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Reactive Navigation based on 2.5D Kinect Data for Safety Improvement in Mobile Assistive Robot Steering

Thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Electrical and Computer Engineering

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University of Coimbra
Faculty of sciences and technology
Departament of Electrical and Computer Engineering

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Coimbra, 2014

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-Bill Cosby.

“In order to succeed, your desire for success should be greater than your fear of failure.”

-Bill Cosby.

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Resumo

A paralisia cerebral (PC) é uma condição médica complexa e não-progressiva, que é caracterizada por perturbações cognitivas e motoras. A PC é também a deficiência mais comum em crianças e a tendência tem sido um aumento da sua prevalência nas últimas décadas. Devido à acessibilidade e melhoria da qualidade da assistência médica prestada aos indivíduos com PC, a esperança média de vida para este grupo aumentou significativamente, o que aumentou a investigação no sentido de compreender a forma como a PC pode afectar a qualidade de vida destes indivíduos, incluindo seus níveis de mobilidade e segurança. Nesta dissertação, foi realizada uma caracterização da mobilidade, acessibilidade e da falta de soluções de mobilidade seguras para pessoas com deficiência motora grave, como os utilizadores de cadeiras de rodas eléctricas que sofrem de PC, a fim de identificar as necessidades nestas áreas e, posteriormente, desenvolver estratégias em conformidade. Através da pesquisa de alguns factores favoráveis, restrições associadas e possíveis melhorias, é possível concluir que a falta de segurança e a dificuldade em navegar a cadeira de rodas eléctrica foram os factores mais limitadores, em geral, e também os mais sugeridos (57,14%) para serem melhorados, validando assim a necessidade de projectar e desenvolver soluções mais adequadas para melhorar a mobilidade, acessibilidade e segurança. Agir perante estes problemas é uma tarefa urgente, uma vez que estes podem causar danos físicos e psicológicos para os utlizadores das cadeiras de rodas eléctricas. Isto define a necessidade de criação de um sistema inteligente capaz de melhorar a navegação dos robôs de assistência (como por exemplo, cadeiras de rodas eléctricas), bem como a segurança destes indivíduos, aumentando a sua qualidade de vida. Uma solução de navegação assistida baseada num algoritmo de Controlo Colaborativo é apresentada nesta dissertação, a fim de responder a estas necessidades. A instalação de um sensor Kinect no robô de assistência vai dar informação adicional do ambiente à sua volta. O novo sistema de navegação irá auxiliar o utilizador a manobrar o robô de assistência de forma segura. Este trabalho começa por analisar o conceito de Segurança, Controlo Semi-Autónomo e Prevenção de Colisões. Para possibilitar a implementação de um sistema de navegação semi-autónomo seguro num robô de assistência, fez-se uso do ROS (Robot Operating System) como plataforma de desenvolvimento e teste de diversos métodos e algoritmos que integram o robô de assistência. O sistema foi testado experimentalmente, validando o seu funcionamento.

Palavras-chave: Segurança, Robô de Assistência, Kinect, Navegação Assistida, Controlo Colaborativo, Navegação Reactiva, Robótica Centrada no Humano, Paralisia Cerebral, Mobilidade, ROS.

Abstract

Cerebral Palsy (CP) is a complex medical and non-progressive condition, that is characterized by cognitive and motor disturbances. CP is also the most common disability in childhood and the trend is to increase its prevalence over the last decades. Due to accessibility and quality improvement of medical care provided to individuals with CP, the average life expectancy for this group has increased significantly, which boosted the research to understand how the CP can affect the quality of life (QOL) of these individuals, including their levels of mobility and safety. In this dissertation, a characterization of mobility, accessibility and lack of safe mobility solutions for individuals with severe motor impairment such as Powered Wheelchair (PW) users suffering from CP was conducted, in order to identify the needs in these fields and subsequently develop strategies accordingly. Through the research of some enabling factors, constraints associated and possible improvements, it can be concluded that the lack of safety and the difficulty in navigating the PW were the most limiting factors, in general, and also the most suggested (57,14%) to be improved, validating the need to design and develop more suitable solutions to improve mobility, accessibility and safety. Act upon these problems is an urgent task, since they might cause physical and psychological damage to the PW users. This defines the need of creating an intelligent system able to improve the navigation of the Mobile Assistive Robots (MARs) as well as the safety of these individuals, enhancing their QOL. An assistive navigation solution based on a Collaborative Control algorithm is presented in this dissertation, in order to address these needs. The installation of a Kinect sensor in the MAR will provide additional information of the surrounding environment. The new navigation system will assist the user maneuvering the wheelchair safely. This work starts by analyzing the concept of Safety, Semi-Autonomous Control and Collision Avoidance. To provide the MAR with the required capabilities for this work, making it a safe semi-autonomous navigation system, ROS (Robot Operating System) is used as a development and test platform for several methods and algorithms integrating the MAR. The system was tested experimentally, validating the effectiveness of its operation.

Key words: Safety, Mobile Assistive Robot, Kinect, Assistive Navigation, Collaborative Control, Reactive Navigation, Human-Centered Robotics, Cerebral Palsy, Mobility, ROS.

Contents

Acknowledgements **i**

Resumo **ii**

Abstract **iv**

List of Figures **ix**

List of Tables **xi**

Nomenclature **xiii**

1 Introduction **1**

1.1 Motivation and context 1

1.2 Goals 2

1.3 Implementations and key contributions 2

2 Background and State of the Art **5**

2.1 Safety 5

2.1.1 Risk Perception 6

2.1.2 Risk Assessment 6

2.2 Related Navigation Systems 7

2.2.1 Navigation Systems using Kinect 7

2.2.2 Robotic Wheelchair for Assistive Navigation 8

2.3 Semi-Autonomous Assistive Navigation System 8

2.3.1 Semi-Autonomous Control 8

2.3.1.1 Shared Control 10

2.3.1.2 Traded Control 11

2.3.1.3 Collaborative Control 12

2.3.1.4 Related Collaborative Control Systems 13

2.4 Collision Avoidance 13

2.4.1 Vector Field Histogram 14

2.4.2 Map Representation 16

2.4.3 Kinect vs other sensors 17

3 User Analysis **19**

3.1 Approach/Methodology 19

3.1.1 Participants 19

3.1.2 Tools 20

3.2 Results 20

3.2.1 Sample characterization 20

3.2.2 Characterization of accessibility, mobility and support 21
3.2.3 Time of use of HMIs and powered wheelchair vs quality of performance 21
3.2.4 Most valued features and limiting factors in the use of assistive technologies for mobility 22
3.2.5 Possible improvements to be implemented in the powered wheelchair 24

4 Assistive Navigation System 27
4.1 System requirements 27
4.2 Generic System Overview 28
4.3 Local Perception Module 28
4.3.1 Multi-level 2.5D data processing 29
4.3.2 Obstacle Detection 31
4.4 Collaborative Control Module 32
4.4.1 Collaborative Control Design 33
4.4.1.1 Key Design Issues 34
4.4.2 Risk Assessment 34
4.4.3 Reactive Collision Avoidance 36

5 ROS Implementation 39
5.1 Local Perception 40
5.1.1 Multi-level 2.5D data processing 40
5.1.2 Obstacle Detection 40
5.2 Collaborative Control 41
5.2.1 Risk Assessment 41
5.2.2 Reactive Collision Avoidance 42
5.3 Mobile Assistive Robot Module 42

6 Experimental Results 45
6.1 Local Perception 45
6.1.1 Multi-level 2.5D data processing 45
6.1.2 Obstacle Detection 48
6.2 Collaborative Control 49
6.2.1 Risk Assessment and Reactive Collision Avoidance 49

7 Conclusion and future work 53
7.1 Conclusion 53
7.2 Future work 54

Bibliography 55

A 63

List of Figures

1.1 Key contributions 3

2.1 Types of Control 8
2.2 a) Shared control loop and b) Traded control loop. 11
2.3 Finding the direction θ to steer the robot when k_{targ} is obstructed by an obstacle [Borenstein and Koren, 1991] 14
2.4 Most common mapping techniques and their representations 16
2.5 A topological map (left) and a discrete metric map [Gonçalves, 2013] (right) 17
2.6 Kinect's Structure 18

4.1 Human-Machine communication channel 28
4.2 Assistive Navigation System Overview 28
4.3 Local Perception Module 29
4.4 Perspective projection [Schindler, 2012] 30
4.5 Kinect 3D depth data condensed into 2D scans of the environment - a) the Kinect's RGB image, b) its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), c) the three 2D scans, d) the top 2D scan (illustrates the shelf outline), e) the middle 2D scan (illustrates the table top) and f) the bottom 2D scan (illustrates the table legs) 31
4.6 Division of Kinect's field-of-view in 5 sectors 31
4.7 Collaborative Control Module 32
4.8 Overview of the Risk Assessment sub-module in the Collaborative Controller 33
4.9 Collaborative Control course of action 33
4.10 Risk Levels 36

5.1 Information flow in the ROS implementation of the ANS 39
5.2 ISRobot (left) and RobChair (right) 39
5.3 Multi-level 2.5D data processing sub-module Nodes 40
5.4 Obstacle Detection sub-module Node 41
5.5 Collaborative Control Module Node 41
5.6 Navigation Module Node 42
5.7 Physical layer components 43
5.8 Data flow in the Mobile Assistive Robot 43

6.1 a) RGB image and b) depth image 45
6.2 Experimental case 1 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan . . . 46

6.3 Experimental case 2 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan . . . 46

6.4 Experimental case 3 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan . . . 47

6.5 Experimental case 4 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan . . . 47

6.6 Test scenario in ISR (left) and MAR navigation trajectory (right) 52

List of Tables

2.1 Recent navigation systems with Kinect 7
2.2 Recent robotic wheelchair platforms [Gonçalves, 2013] 9

3.1 Clinical and sociodemographic data. 21
3.2 Characterization of accessibility, mobility and support. 21
3.3 Level of performance steering the powered wheelchair and with the HMIs. 22
3.4 Most valued features and limiting factors in the use of assistive technologies for mobility. 23
3.5 Powered wheelchair improvement. 24
3.6 Requested powered wheelchair improvements. 24

6.1 Closest points 48
6.2 General Performance Table 49
6.3 Real Experiment Performance Table - Experimental cases 1 and 2 50
6.4 Real Experiment Performance Table - Experimental cases 3 and 4 51

Nomenclature

aLRF	Actuated Laser Range Finders
ANS	Assistive Navigation System
APCC	Coimbra Cerebral Palsy Association (Associação de Paralisia Cerebral de Coimbra)
BIOSTEC	(International Joint Conference on) Biomedical Engineering Systems and Technologies
CC	Collaborative Control
CP	Cerebral Palsy
FCT	Fundação para a Ciência e a Tecnologia
GMFCS-CP	Gross Motor Function Classification System for Cerebral Palsy
HEALTHINF	International Conference on Health Informatics
HMI	Human-Machine Interface
IP	Internet Protocol
IR	Infrared
ISR	Institute of Systems and Robotics
MAR	Mobile Assistive Robot
PC	Paralisia Cerebral
PW	Powered wheelchair
QOL	Quality of Life
RGB	Red, Green, Blue
RGB-D	Red, Green, Blue and Depth
RobChair	Robotic Wheelchair (Referring to the ISR Robotic Wheelchair)
ROS	Robot Operating System
RVIZ	Ruby Visualization Tool
SAANS	Semi-Autonomous Assistive Navigation System

Chapter 1

Introduction

This chapter presents the motivations that led to this work, as well as its main goals and key contributions. It also summarizes the course flow of this dissertation and the content of each chapter.

1.1 Motivation and context

Cerebral palsy (CP) is characterized by cognitive and motor disturbances. It affects body movement, muscle control, muscle coordination, muscle tone, reflex, posture and balance. It can also impact fine motor skills, gross motor skills and oral motor functioning. Individuals with this disability have a more impaired quality of life (QOL) in all domains, especially in the physical domain, when compared with other able-body individuals.

Better conditions and better access to medical care, increased the average life expectancy of individuals with this disease. These factors, along with the fact that CP is considered the most common disability in childhood and the trend shows the increase of its prevalence, were a stimulus in order to start research work to understand how the CP can affect their QOL and how are their levels of mobility and safety. Such trends seem also to lead to a world where robots and intelligent systems will have an evermore important role in integrating and assisting impaired individuals.

Since the life standards of people with motor impairment disabilities, like individuals with CP, are normally reduced due to their motor conditions, the deployment of human-centered robots, such as robotic wheelchairs as an assistive technology, may contribute to help motor impaired people reach a better level of mobility. Furthermore, increasing the mobility levels of people with motor disabilities can also ultimately contribute to improve their social inclusion.

The work developed in this dissertation was justified through a research study where a characterization of mobility, accessibility and lack of safe mobility solutions for individuals with severe motor impairment such as users suffering from CP was conducted. This research was performed in order to identify the needs in these fields and subsequently develop strategies accordingly.

The development of human-centered robots, especially a semi-autonomous navigation system for the motor impaired, to provide a safe and easy navigation of a Mobile Assistive Robot (MAR) commanded by a conventional joystick was the main focus of the work implemented. The local mapping can be achieved by gathering the 3D Kinect data, a sensor that can provide 3D information of the MAR surroundings from a three-dimensional field-of view and condensing that information into multi-level horizontal 2D scans. The MAR navigation system is based on Collaborative Control (CC) in order to assist the user maneuvering the wheelchair safely. To provide the MAR with the required capabilities, ROS (Robot Operating System) was used as a development and test platform for several methods and algorithms developed during the course of this work.

1.2 Goals

This work aims to develop an Assistive Navigation System (ANS) based on CC for a safe and easy navigation of a MAR for people with motor disabilities such as individuals with CP.

The defined goals were:

1. To characterize mobility, accessibility and lack of safe mobility solutions for individuals with CP, through the implementation and analysis of questionnaires on the use of PWs;
2. To develop the system architecture and the appropriate information flow;
3. To transform the 3D Kinect Data into multi-level horizontal 2D scans that provides information of the three-dimensional field-of view;
4. To ensure the safety of MAR users and minimize the effort maneuvering it, through the use of a Collaborative Controller (man-machine collaboration), which is responsible for the fusion of information from the user (via joystick) and reactive collision avoidance navigation algorithm;
5. To conduct tests in order to evaluate the proposed methodology.

1.3 Implementations and key contributions

The development and implementation of a SAANS on ROS framework in a MAR for safety improvement are the key contributions of this dissertation.

The SAANS is composed by three main modules: Local Perception (sub-modules: Multi-level 2.5D data processing and Obstacle Detection), Collaborative Control (sub-modules: Risk Assessment and Reactive Collision Avoidance) and Mobile Assistive Robot, as seen in Figure 1.1.

In order to develop an operational system, some ROS modules were fully implemented and others were modified from a distributed version. Figure 1.1 summarizes the implementations and key contributions described in this dissertation.

The course flow of this work and content of each chapter is the following:

User Analysis (Chapter 3):

- A questionnaire was conducted in order to characterize mobility, accessibility and safety in mobility solutions of individuals with severe motor impairment such as users suffering from CP, in order to identify the needs in these fields. The results were obtained through the analysis of enabling factors, constraints associated and possible improvements, and validate the need to design and develop more suitable solutions to improve mobility, accessibility and safety in the MARs.

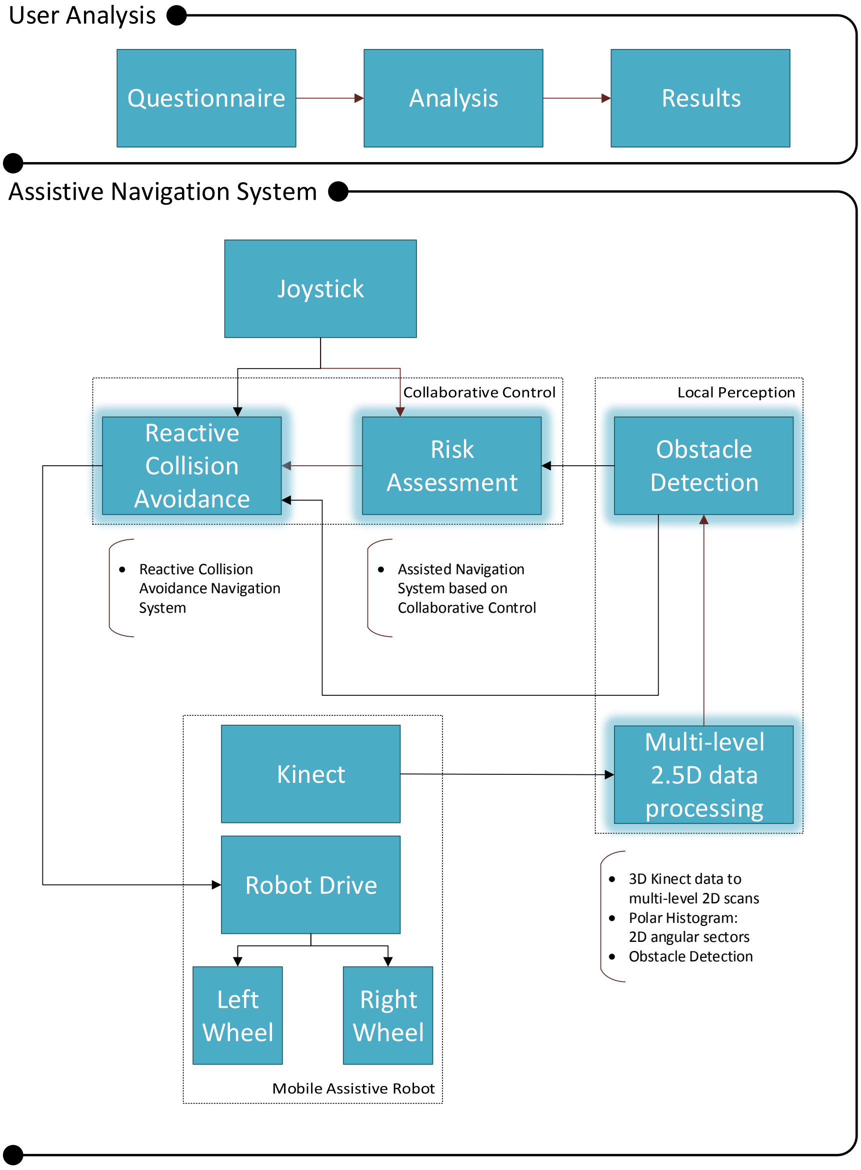

Figure 1.1: Key contributions

Assistive Navigation System (Chapter 4):

- Overview of the ANS software architecture, a contribution that was a result of the work done in this dissertation. All modules are briefly described and the interaction between them is analyzed.

Local Perception (Chapter 4 and 5):

- Multi-level 2.5D data processing:
  - Transformation of the 3D Kinect Data into three horizontal 2D scans that provide information of the three-dimensional field-of view. The 2D depth data was also divided in angular sectors, were in this particular implementation 5 angular sectors were used.

- Obstacle Detection:
  - An algorithm for obstacle detection in the MAR's surrounding environment was implemented.

Collaborative Control (Chapter 4 and 5):

- Risk Assessment: Risk Assessment is a decision sub-module that outputs the risk level of the current situation during robot navigation.
- Reactive Collision Avoidance: An algorithm that integrates the CC module, to allow the MAR to navigate safely in the environment, avoiding collisions. It includes a shared and traded controller that operate according to the risk level of each situation.

In Chapter 6, several experiments for testing and validating the navigation system are described and their results are presented and discussed.

Chapter 2

Background and State of the Art

This chapter introduces the fundamental topics required to understand the work presented in this dissertation. It reviews important background theory and also state of the art on the topics that were required to design and develop the work presented in this dissertation. These topics are Safety, Semi-Autonomous Assistive Navigation System and Collision Avoidance. In this chapter, a brief discussion on navigation systems is carried out.

2.1 Safety

Nowadays, safety is a major concern in many computer-based systems and more particularly, in systems such as service robots that interact with humans [Guiochet et al., 2010]. A system can only be called safe if it is possible to ensure that risks are kept at an accepted level [Voos and Ertle, 2009].

People with motor disabilities have limited mobility, and often rely on the help of assistive technologies to improve it. Sensor systems supporting autonomous or semi-autonomous navigation have been developed for different commercial application areas. These sensor systems have been transferred to PWs to provide systems with obstacle avoidance capacity or systems that assist in the navigation, for people with mobility difficulties.

But not only disabled people need mobility assistance. Elderly people sometimes need the help of a PW for mobility. Many factors not related to the PW's system may compromise their ability to drive it, affecting their safety, such as distraction, reaction time, mental status, visual function and other physical variables.

The time of use of the PW can be a decisive factor for a good level of performance maneuvering it. Therefore, children or new users of these systems can have increased troubles navigating the PW due to the lack of experience, contributing to a more complex navigation and compromised safety, and are more likely to make mistakes that can put them in danger. This leads us to a world where robots and intelligent systems have an increasingly important role in the lives of people that need mobility assistive robots for navigation and safety purposes. It is expected the need to use mobile service robots to provide services, where they have to execute complex tasks in dynamic environments, collaborate with humans in a natural and intuitive way and adapt themselves to varying conditions [Guiochet et al., 2010].

To be an useful assistive navigation technology, these systems must be designed to be able to detect the occurrence of faults, failures or other hazards that can jeopardize the human's safety, evaluate consequences of such occurrences and act accordingly to avoid the identified issues, reducing the amount of risk in different areas. This is called risk assessment.

2.1.1 Risk Perception

Driving a vehicle can somehow be related with driving a PW, since the human's driving ability is an important factor. It is generally estimated that about 90% of driving accidents can be attributed to human error [McKenna, 1993].

Risk is defined as the possibility of injury or loss, because of a technical failure, natural hazard or human error, to an individual, a group of people, etc. The risk level is determined by the probability of an unwanted incident and the severity of the consequences. In any action, people assess the risk of that same action, and consider the probability of losing something or injury. If the probability of occurrence of risk is acceptable, people engage in the risky behavior [Fischhoff et al., 1984].

People respond to a risk or hazard in ways consistent to their perception of that risk. It is their perception that influences behavior or action [Mileti, 1993]. They tend to estimate the general risks to be larger than the personal ones. For example, most people rate themselves as to be a better driver compared to the average driver, which means they can put themselves in more risky situations that can compromise their safety [Oltedal et al., 2005].

[Slovic, 1987] explains why people are relatively unafraid of driving vehicles, even though it has caused many deaths than other more feared events. Because driving accidents are so common, the risk seems familiar and knowable, enabling people to feel that they have the ability of successfully assessing the risk. When an event that causes more damage or deaths occurs, there is worldwide media coverage and warnings about possible future catastrophes, even though they are usually rare events (e.g. natural catastrophes). This is why a lower risk phenomenon like this actually induces much more fear than a higher risk activity (driving a vehicle) [Gorman, 2013].

A similar situation with driving a vehicle is driving a PW, where its users often don't take seriously the risk of navigating it, because they consider themselves good drivers. Being careless with risky situations can cause physical and psychological damage to PW users, validating the need for external unbiased risk perception.

2.1.2 Risk Assessment

There are two types of risk assessment: deliberative and immediate risk assessment [Voos and Ertle, 2009].

The deliberative risk assessment takes into account risks caused by the current goals of the robot. Therefore, the main input variables of this assessment are the goals of the robot and the current sensor information about the environment together with a confidence value. In this risk assessment type, it is evaluated the risk and options for a certain planned action.

Immediate risk assessment focuses on imminent or current risks that can affect human lives, loss of irreplaceable environmental services or resources, expensive economic scenarios or costly loss of property. This type of risk assessment is performed when there is imminent danger of irreversible and dire consequences, that might occur prior to or in the aftermath of an action. It evaluates the risks and options for a certain action that causes imminent danger.

2.2 Related Navigation Systems

2.2.1 Navigation Systems using Kinect

Traditional laser scanners, such as the Hokuyo URG - 04LX, are very expensive and only provide 2D mapping capabilities. The use of Kinect sensor represents a significant reduction of costs and has been proved that for some applications it can replace the use of other sensors, like the very expensive laser scanners. In case of an obstacle detection application the Kinect is more reliable under certain conditions than the common used Hokuyo laser scanner [Zug et al., 2012]. Because of these advantages, its use to provide external sensory information has increased.

In Table 2.1 it can be seen a list of recent applications with Kinect and its purposes.

Table 2.1: Recent navigation systems with Kinect

Institution	Methods used	Purpose
University of São Paulo [Correa et al., 2012]	Artificial neural network (ANN) to recognize different configurations of the environment through image processing and artificial intelligence techniques using Kinect data.	Pioneer P3-AT mobile robot navigation in indoor environments using Kinect sensor for surveillance purposes.
Simón Bolivar University [Ruiz et al., 2013]	Movement control of the robot using velocity vector references generated from the spatial references extracted from de environment using the Kinect sensor.	Control platform for the mobile robot Roomba using ROS and a Kinect sensor, using autonomous navigation strategies such as the Velocity Vector Fields.
Centre of Excellence for Advanced Sensor Technology (CEASTech) - Universiti Malaysia Perlis [Kamarudin et al., 2013]	3D depth data converted into 2D map using the minimum-selection method, to avoid false detection of obstacles and minimize processing.	Kinect's 3D depth data converted into a 2D map for indoor SLAM.
University of Auckland [Oliver et al., 2012]	3D SLAM used to create 3D models of the environment and localize the robot in the environment. 3D point cloud projection into a 2D plane to use a 2D SLAM algorithm.	Kinect sensor for navigation and simultaneous localization and mapping in a Pioneer III (P3-DX) mobile robot.
University of Málaga [Gonzalez-Jimenez et al., 2013]	Two-step post-processing of the Kinect data: i) Projection of the perceived obstacles around the robot on a virtual horizontal scanning plane; ii) Short-term memory of obstacles detected to avoid collisions with obstacles lying in the blind zone.	Reactive navigation with mobile robot SANCHO using Kinect.
Clemson University [Peasley and Birchfield, 2013]	Kinect 3D points projected onto the ground plane to create a 2D occupancy map to determine the presence of obstacles. Translation and rotation velocities computed to perform collision avoidance.	Obstacle detection and avoidance using Kinect in a Pioneer P3-AT mobile robotics platform.

2.2.2 Robotic Wheelchair for Assistive Navigation

Mobile robotics is a broad engineering field, and an important branch of robotics. This field studies the kinematic models, motion control, perception (sensory information processing), planning and navigation.

A robotic wheelchair is a type of MAR and a particular form of wheeled robots. They are an upgrade from standard PWs, with the general goal of simplifying and assist the users in navigation tasks. Most of the MARs aim to provide some type of semi-autonomous control, aiding the patients by easing the hard task of maneuvering it. To achieve such goal, a Human-Machine Interface (HMI) is required to receive the user input. A MAR usually needs to perceive the surrounding environment and requires decision making modules for navigation purposes and a control scheme to connect user inputs.

Research around robotic wheelchairs for assistive navigation purposes has grown consistently over the last few years and many types of intelligent wheelchair platforms have been developed. Some of the developed robotic wheelchairs are presented in Table 2.2, where the main technologies implemented are summarized. Most of the intelligent wheelchairs described in this incorporate a semi-autonomous controller and most of them solely rely on joystick as HMI. A semi-autonomous control system is neither fully autonomous or fully teleoperated, since it requires outside assistance. This type of systems is explained in detail in section 2.3.1.

2.3 Semi-Autonomous Assistive Navigation System

2.3.1 Semi-Autonomous Control

There are many types of control, as seen in Figure 2.1. The focus of this work is in semi-autonomous control, particularly in CC.

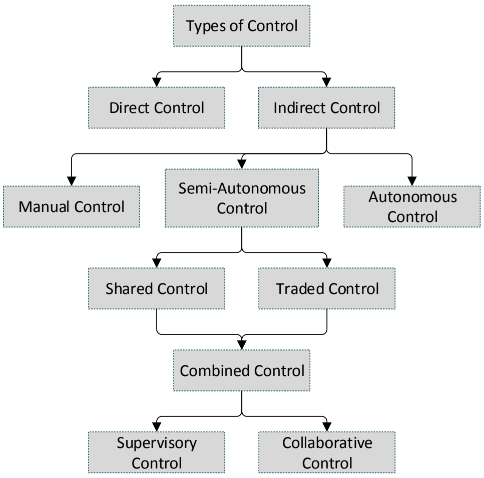

Figure 2.1: Types of Control

Semi-autonomous control comes from two main concepts [Murphy and Rogers, 1996]: the teleoperation concept [Sheridan, 1992] and the autonomous robot concept [Giralt et al., 1993].

Table 2.2: Recent robotic wheelchair platforms [Gonçalves, 2013]

Institution	Main Robotic Technologies	Shared-Control Type and user intention	HMI
University of Technology of Sydney [Patel et al., 2012]	Montecarlo localization Topological mapping.	Hierarchical Hidden Markov Model framework that predicts both the short term (local) and long term (navigational) goals of the user.	Joystick.
VAHM (LASC, University Paul Verlaine-Metz) [Grasse et al., 2010]	Particle filtering approach to implement the recognition of the most frequent paths according to an offline-constructed topological map.	Provides assistance to the user during navigation by proposing the direction to be taken when a path has been recognized.	Joystick.
SHARIOTO (Katholieke Universiteit Leuven) [Vanhooydonck et al., 2010]	Dynamic window approach for obstacle avoidance.	Shared-control with user intention prediction based on a Bayesian network.	Joystick.
LURCH Politecnico di Milano [Bonarini et al., 2012]	Localization based on odometry. Odometry correction is performed based in the detection of passive markers placed in the environment using vision. Trajectory planning based on the fast planner SPIKE (Spike plans In Known Environments).	Control module based on a fuzzy behavior management system, where a set of reactive behaviors, which will be carried out by the robot, are implemented as a set of fuzzy rules. Two set of rules were established: one implementing trajectory following, and the another one implementing obstacle avoidance.	Joystick, touch-screen, electro miographic interface, and Brain Computer Interface (BCI).
University of Michigan [Park et al., 2012]	A static occupancy grid map obtained via SLAM. Global topological map. Position and velocity estimation of new obstacles in the environment based on a Kalman filter.	Model Predictive Equilibrium Point Control (MPEPC) framework, which allows the navigation of a wheelchair in dynamic, uncertain, structured scenarios with multiple pedestrians.	Joystick.

In [Ong et al., 2005], it is referred that according to [Giralt et al., 1993], in the teleoperation concept, both human and machine interact at the human operator station level. In the autonomous robot concept, the focus is to have on-board, in-built intelligence at machine level, to ensure that the robot can adapt its actions autonomously to the task conditions. A semi-autonomous control system, is a system that explicitly requires some kind of outside assistance, be it from a human or another system. It is defined as an evolution from teleoperation by reducing the amount of supervision by the operator and as an approach to autonomous robots, letting the human retain high level operations such as task specification, but handing down routine and safe portions of tasks to be handled autonomously.

Suppose a human and a machine are requested to perform assigned functions for some period of time. The operating environment may change as time passes by, or performance of the human may degrade gradually as a result of psychological or physiological reasons. If the total performance or safety of the system is to be maintained strictly, it may be wise to reallocate functions between the human and the computer.

Semi-autonomous control can be further classified into the following two (and one extra) categories [Ong et al., 2005], with the following design aspects [Inagaki, 2003]:

1. Parallel or shared control type, where a certain task is handled by a machine and a human, at

the same time.

   (a) Extension / Relief - a mechanism is needed to add control force on the other agent's force is needed.
   (b) Partition - the automation is to be designed so that it can cope with every possible partition of functions.

2. Serial or traded control, where the controller decides over time if the control lies on the human side or the machine side completely.
   (a) The automation must be designed so that it can replace the human completely.
3. Mixture of the two previous types, where sharing and trading of a task both occur (Combined Control).
   (a) The CC design is the fusion of the Shared and Traded control design.

Shared and traded control are activated in response to changes in situations or human performance. They may be regarded as physical collaboration between human operators and the automation. Required automation differs, depending on the type of collaboration.

An example of the combined control type is the Supervisory Control (SC) based on the Supervisor-Subordinate role by [Sheridan, 1992] and also the CC, which is an extension of SC based on the Partner-Partner model by [Fong, 2001] for the teleoperation of mobile robot. According to [Fong, 2001], the essential difference between CC and SC is that CC can adjust its method of operation based on situational needs.

Sections 2.3.1.1, 2.3.1.2 and 2.3.1.3 briefly describe each one of these categories.

2.3.1.1 Shared Control

Shared control, classified as a parallel type of semi-autonomous control, is a paradigm of semi-autonomous control that shares the effort involved in the decision task between human and machine. This way, some tasks are made by the user and others by the machine, meaning that the human and the computer work together simultaneously to achieve a determined goal.

Three types of shared control:

1. Extension, where the machine may help the human so that his or her capability may be extended (e.g., the power steering or the power braking of a car), or where the human extends the computer's capability (e.g., "supervisory override", in some types of aircrafts, the pilot may add control force when the maneuver performed by the autopilot was not satisfactory) [Inagaki, 2003].
2. Relief, in which the machine will assist the human so that his or her burden may be reduced. An example of this application is a lane-keeping support system for a car. The system detects white lane markers on the road, and generates torque to assist the driver's steering action for keeping the host vehicle approximately on the center of the lane [Kawazoe et al., 2001]. Assisting the user deviating from obstacles is also a good example.

3. Partitioning, in which a required function is divided into portions so that the human and the computer may deal with mutually complementary parts. A car driver may want to be responsible only for steering by letting the computer control the velocity, or in a military application, where a gun that automatically chooses what to aim and track, and leaves to the human the control of the trigger, leaving each task to the agent that better performs it. Both agents (human and machine) work in a shared, parallel mode. Partitioning is a complementary function allocation.

As compared to manual control, shared control relieves the human of easily automated tasks while allowing him direct control of more hard-to-control activities such as manipulation of parts [Hirzinger, 1993, Lee, 1993] or navigation in cluttered areas [Bourhis and Agostini, 1998, Bruemmer et al., 2003]. It also may simply give the human more flexibility in an automated task.

Figure 2.2 a) illustrates the example of a shared control loop.

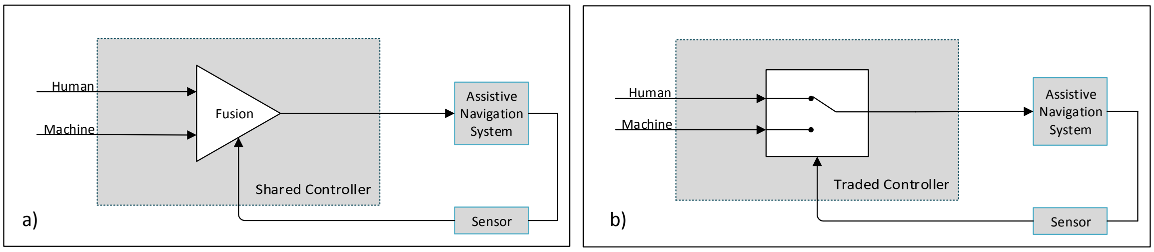

Figure 2.2: a) Shared control loop and b) Traded control loop.

2.3.1.2 Traded Control

Traded Control is classified as a serial type of semi-autonomous control. It is based on a mutually exclusion approach for human and machine, where the control is exchanged between the two. Either manual control or autonomous control can be selected as the operating mode at any one time [Ong et al., 2005, Sheridan, 1992].

For the traded controller to be implemented, an algorithm will decide when the control must be handed over and to which agent. This decision is based on the demand of tasks such as: incompetent performance of tasks/restrictions, nullify potential harmful commands/situations, goal deviations, addition or deletion of goals, and modification of goal's importance.

There are two main conditions when the Traded Control is activated. First, in a navigation task [Bruemmer et al., 2003], if the machine takes a wrong direction, the human may intervene and assume the control of the robot, giving it a new direction movement. The second condition occurs when the human issues commands that could jeopardize his or her safety. In this situation the robot may revoke undesired commands and stop that movement. In a certain way, the traded controller allows both human and robot to support each other [Ong et al., 2005].

In Figure 2.2 b) can be seen the traded control loop.

2.3.1.3 Collaborative Control

A mixture of the previous two types of semi-autonomous control is called CC. Both serial and parallel types interact to an extent, where the tasks within each mode may also be shared and traded [Sheridan, 1992]. This concept tries to break away from the concept of robot as a tool by approaching the robot as a partner by developing a channel of communication between human and machine agents.

A classic example of this combined control is observed, for example, in aircraft autopilot systems [Billings, 1997], where the pilot trades the control over the machine during the cruise phase, but it can also share the control over the aircraft, where while the autopilot is responsible for holding the altitude, the pilot adjusts the heading. This system is a combination of traded and shared control, at the same time.

In CC, the human and the machine collaborate together to perform tasks and to achieve common goals (e.g. avoid obstacles). Instead of a Supervisor-Subordinate role, the human and the robot exchange information and can resolve problems. The CC can adjust its method of operation taking into account the current situation (risk assessment), allowing accurate sharing and trading of control in accordance. This approach enables humans and machines to work better together, what makes it an extremely important feature when success strongly depends on joint task performance [Fong, 2001]. Taking for example a situation where the machine's performance is poor or it doesn't know what to do, it has the possibility to give control to the human, enabling the work to be exchanged between the human or the machine as the tasks take place.

In order to build a successful Collaborative Controller, it must be satisfied both human and machine needs. [Fong, 2001] defines seven key design issues that shouldn't be ignored when developing a system of this kind:

1. Dialogue: A CC system must have a good communication channel. The human and the machine should be able to communicate / dialogue effectively, allowing a good interpretation of the information exchanged.

2. Awareness: The machine should be aware, being capable of detecting limitations (what it can and cannot do). On the other hand, it should also be able to determine the human limitations and be able to decide, in a given situation, if it is better to involve the human or if it is best if the machine intervene to solve a problem.

3. Self-Reliance: The machine must be self-reliant. It should not rely 100% on the human since it might not be available or provide accurate information. It must avoid hazards, maintaining its own safety.

4. Adaptiveness: By design, the collaborative controller is equipped with a framework in order to prepare it for certain changes in its working environment. The machine needs to adapt its own behavior accordingly. Because CC allows for variable human response (in terms of accuracy, speed, etc.), the machine must also able to dynamically adjust its autonomy. It should also be prepared for different characteristics of the human with whom it shares control: differences in experience, knowledge, skill and training.

5. Human-Robot Interaction (HRI): In conventional systems, the robot is considered a "tool", where HRI follows a fixed pattern: the human generates a command and the robot performs

the action. In CC, the robot is considered a partner. While building a CC, we need to enable humans and machines to understand each other through interaction.

6. User Interface Design (UID): Communication has a key role in the CC. UIDs has to support dialogue and to serve the machine in situations where the machine may need to attract the user's attention. UIDs can also serves the operator, providing information for human decision making.

7. Control and Data Flow: As opposed to conventional teleoperation systems, where the operator retains ultimate authority, in CC systems the control is allowed to be negotiated. With this in mind, there must exist rules to solve situations where the machine and the human do not agree. On the other hand, it requires flexible data handling, to prevent misunderstanding between the machine and the human.

2.3.1.4 Related Collaborative Control Systems

Since Fong's research work on CC has been published [Fong, 2001], several other works have been done using this concept of joint task performance between human and machine. CC in multi-robots is studied in [Fong et al., 2003].

There has been several works [Monferrer and Bonyuet, 2002, Zeng et al., 2008, Montesano et al., 2010, Urdiales et al., 2011, Lopes et al., 2013a, Lopes et al., 2013b] focused on the implementation of collaborative controllers in wheelchairs.

The interaction between humans and social robots in a collaborative manner has been a subject of research of Breazeal for years [Breazeal et al., 2003, Breazeal et al., 2004, Hoffman and Breazeal, 2004a, Hoffman and Breazeal, 2004b, Breazeal et al., 2008].

2.4 Collision Avoidance

As discussed in section 2.1, safety of PW users is crucial. Collision avoidance technology has the capacity to provide a safer and easier navigation for motor disabled people, thus increasing the mobility independence. Because of the reasons mentioned previously, collision avoidance approaches have become increasingly used in MARs.

Reactive or collision avoidance approaches, which are the core of this dissertation, are able to generate robot control using only a small part of the world model. They map the robot's surrounding environment, through the use of sensory information, obtained for example, with Kinect sensor, laser scanners or sonars. The disadvantage of these approaches is that they are not able to produce optimal solutions. These approaches are easily trapped in local minima (such as deadlocks like U-shaped obstacles). They are an integral part of robotics and there are numerous methods for achieving this. The most used methods are: the Potential Field Methods [Khatib, 1985], the Vector Field Histogram [Borenstein and Koren, 1991] or the Dynamic Window Approach [Fox et al., 1997]. Since these three methods typically consider only obstacles close to the robot, they are very fast. Local methods quickly adapt to unexpected changes in the environment, unlike the global techniques. The DWA approach is the opposite of the potential field and the VFH methods, incorporating the dynamics of the robot and can be used for high speed navigation.

Next, we will discuss the Vector Field Histogram (VFH) for obstacle detection and collision avoidance, map representation types and the use of a Kinect sensor to provide information about the environment.

2.4.1 Vector Field Histogram

The VFH method allows obstacle detection and collision avoidance of obstacles while navigating a mobile robot toward an object or to a predetermined target position. This method uses a histogram based on a 2-D Cartesian grid as world model. The world model is continuously updated using range-type sensors (laser, sonar, etc). Thus, three levels of data representation exist [Borenstein and Koren, 1991]:

Highest level: The highest level of VFH provides a detailed description of the robot's environment. The VFH method uses a two-dimensional cartesian histogram grid, which is continuously updated in real-time with range data provided by range sensors installed on the robot.

Intermediate level: The histogram grid is reduced to a one-dimensional polar histogram, that is built around the robot's current location. As a result, each sector has a value that represents the polar density of obstacles in the direction of the sector.

Lowest level: At the lowest level of data representation is set the output of the VFH algorithm, which are the reference values for the drive (lowest polar obstacle densities) and steer controllers of the robot, to be able to rotate it in that direction.

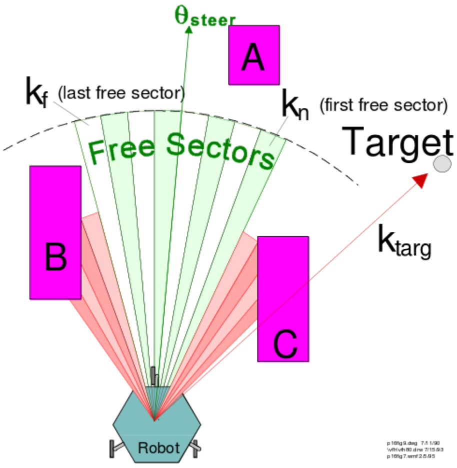

Figure 2.3: Finding the direction θ to steer the robot when k_{targ} is obstructed by an obstacle [Borenstein and Koren, 1991]

In order to compute the desired control commands for the robot, this method employs a two-stage data-reduction process:

- Initially, the histogram grid is reduced to a polar histogram that is built around the current location of the robot. Each sector of the polar histogram contains a value representing the density of obstacles in that direction.

  - The contents of each cell are treated as a vector of obstacles, whose direction is determined by β, which is defined between the current cell and the center of the robot

    $$\beta_{i,j} = \tan^{-1} \frac{y_i - y_0}{x_i - x_0} \tag{2.1}$$

    and whose amplitude is

    $$m_{i,j} = (c^*_{i,j})^2 (a - b d_{i,j}) \tag{2.2}$$

    where:a and b are positive constants, $c_{i,j}$ is the value of certainty for the active cell (i, j), $d_{i,j}$ is the distance between the active cell and the center of the robot, $m_{i,j}$ is the amplitude of the vector of the obstacle at the cell, x_0 and y_0 are the center of the robot coordinates, x_i and y_i are the active cell coordinates and finally, $\beta_{i,j}$ is the direction from active cell to the center of the robot.

  - The closer to the robot the occupied cells are, the higher the obstacle vector amplitudes produced are.

  - The value of a is chosen so that

    $$a - b d_{max} = 0; \; d_{max} = \frac{\sqrt{2 \times w_s - 1}}{2} \tag{2.3}$$

    where d_{max} is the distance between the center of the robot and the furthest active cell. Therefore, for the most distant cell, $m_{i,j} = 0$ and increases linearly for the nearest cell.

  - The histogram has an angular resolution α such that

    $$n = \frac{360^{o}}{k} \tag{2.4}$$

  - Each sector k corresponds to an angle ρ which depends of α as follows

    $$\rho = k \times \alpha \tag{2.5}$$

  - For each sector k, the polar obstacle density is

    $$h_k = \sum_{i,j} m_{i,j} \tag{2.6}$$

- In the second phase, the algorithm is responsible for determining the most appropriate direction for the robot. It selects the most appropriate sector, which is the one that has a lower density of obstacles, rotating the robot in that direction θ. A polar histogram typically has peaks which correspond to areas with high densities of obstacles and valleys that correspond to lower densities. Any valleys that have density inferior than a certain pre-defined threshold, correspond to possible directions to follow. Typically there are several possible directions to follow and the objective is to choose the one that is closest to the target direction k_{targ}.

- After choosing the valley is necessary to choose the most appropriate sector within this valley. This algorithm defines two different types of valleys: narrow and wide. A valley is considered large if it has more than s_{max} sectors. This constant is chosen according to the width of the sector.
- The wide valleys result from having big gaps between obstacles. To determine the direction that the robot should follow:
  - Determine k_n which corresponds to the nearest sector k_{targ} and that is below the preset limit - this sector is the next frontier of the valley;
  - Moreover, k_f determine that corresponds to the far boundary and is calculated in accordance with

    $$k_f = k_n + s_{max} \tag{2.7}$$

  - The desired direction is given by

    $$\theta = \frac{(k_f + k_n)}{2} \tag{2.8}$$

    the implementation of this method can be seen in figure 2.3.
- The narrow valleys occur when the robot navigates between obstacles close to each other:
  - In this case the most distant border k_f is less than s_{max} sectors, but the driving direction is calculated through equation 2.8;
  - One should only consider narrow valleys that have a width greater than a certain value.

It is proved that this algorithm, although simple, is effective in detecting and preventing collisions. It is also appropriate for the type of perception data of the proposed system.

2.4.2 Map Representation

There are two main types of maps in mobile robotics: metric and topological maps [Thrun, 1998], which are illustrated in Figure 2.4.

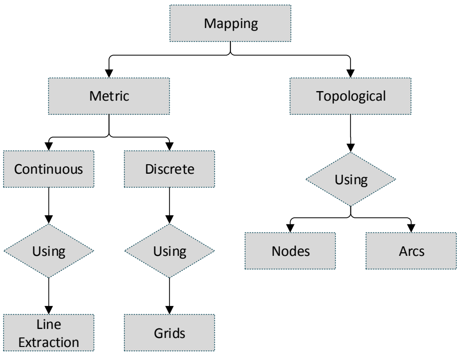

Figure 2.4: Most common mapping techniques and their representations

Metric maps are the most simple and easy to understand by humans. They illustrate the environment directly from the data provided by sensors [Dudek and Jenkin, 2000]. There are continuous or discrete metric maps.

The continuous map is an interpolation of the real world from discrete measures. Line extraction is where best-fit lines are extracted from the provided sensory data [Siegwart and Nourbakhsh, 2004].

Discrete maps (e.g. occupancy grid maps), are represented by a matrix of cells. Each cell has attached to it a occupancy value, which indicates the type of environment in that place. A cell can represent an empty space, an obstacle, an unknown space, or just a value of the probability of that area being occupied. In the most common mapping techniques, each cell just has a binary occupancy value, indicating occupied or free states for the cell. An occupancy grid map can divide the space into a finite number of cells small grid cells, making it possible to have a detailed map, but more computationally complex. The number of cells and cell size for each map should be balanced [Thrun et al., 2005].

Topological maps, describe the connectivity of different places, making use of graphs to represent the environments. It uses a list of significant places or nodes, connected via arcs, in order to represent the environment. The nodes in a topological map represent places, landmarks or other distinct situations. In comparison to metric maps, these maps are much more easy to store and use by a computer, improving performance greatly in large environments, but difficult to keep consistent [Thrun, 1998].

In Figure 2.5 is illustrated a topological map of a corridor (B, D, F, H) and some rooms (A, C, E, G, I), on the left, and a 2D metric map to the right, also called occupancy grid map.

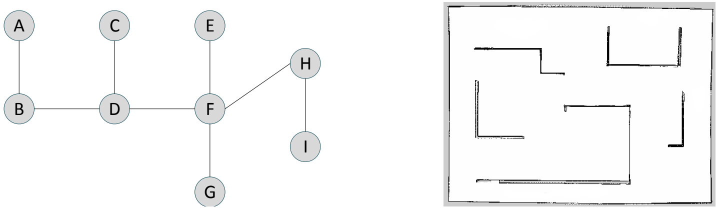

Figure 2.5: A topological map (left) and a discrete metric map [Gonçalves, 2013] (right)

2.4.3 Kinect vs other sensors

Sensing data from the external environment is the key requirement to enable localization, mapping and navigation. Most successful mobile robots rely on 2D radial laser scanners for perceiving the environment, which are very expensive. Using these 2D scanners for reactive navigation applications presents a serious limitation: the obstacles will only be detected if they are on the plane scanned by the laser scanner, which typically is a plane parallel to the floor. The obstacles at a different height or with salient parts that aren't on the scanned plane, will not be seen and therefore increasing the risk of collision. This problem can only be tackled by gathering 3D information of the surrounding environment of the robot from a three-dimensional field-of-view [Gonzalez-Jimenez et al., 2013]. Before Kinect, actuated laser range finders (aLRF) were used to obtain 3D data. These sensors are expensive and not quick enough for navigation purposes [Holz et al., 2008, Marder-Eppstein et al., 2010]. These limitations can be overcome through the use of RGB-D cameras, like Kinect, a sensor developed as a natural interface for videogames, that provides 3D information of the environment. The Xbox Kinect is a 3D depth sensor with two cameras and a laser-based infrared (IR) projector. One camera is a standard RGB camera and the other is an IR camera. Both IR projector and IR camera can be called 3D depth sensors. Kinect's structure can be seen in Figure 2.6.

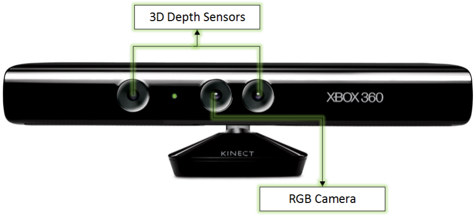

Figure 2.6: Kinect's Structure

The IR camera will look for a certain pattern projected onto a scene by the laser-based IR projector. The Kinect sensor compares the appearance of the projected pattern with the expected pattern at various depths and calculates the disparity of each pixel [Peasley and Birchfield, 2013]. It has certain features that makes it an interesting and useful device to use:

- Compact and lightweight sensor which provides both RGB and range images;
- Gathers 3D information of the robot's surrounding from a three-dimensional field-of view;
- Low cost solution (around 150€);
- Works real-time at a frequency of 30 Hz;
- The operation range goes from 0.6 to 5m, which is acceptable for indoor environments.

The use of Kinect to feed a reactive navigator based on a 2D space representation presents two difficulties [Gonzalez-Jimenez et al., 2013]:

- Provides huge amount of data, which is more than 300.000 measurements per frame at 30Hz;
- The existence of a blind zone both at short distance and because of the narrow horizontal field-of-view (in comparison to laser radial scanners).

The main disadvantage of a Kinect sensor related to comparable laser scanner systems is the small monitoring angle. It limits the capabilities for mapping and localization tasks significantly.

In this dissertation we explore Kinect's potential in a perception system for obstacle detection.

Chapter 3

User Analysis

A characterization of mobility, accessibility and lack of safe mobility solutions for individuals with severe motor impairment such as users suffering from CP was conducted, in order to identify the needs in these fields and subsequently develop strategies accordingly. The results are obtained through the research of enabling factors, constraints associated and possible improvements. The need to design and develop more suitable solutions to improve mobility, accessibility and safety is validated through this study and the obtained results.

This research and the proposed solution led to a conference paper in BIOSTEC 2015 - International Joint Conference on Biomedical Engineering Systems and Technologies.

With the overall goal to characterize all three factors referred above, this research work was organized as follows:

1. Characterization of subject's mobility, public transportation use and HMI;
2. Relation between HMIs and PW time of use and the quality of performance;
3. Identification of most valued features and limiting factors in the use the PW;
4. Analysis of possible solutions to be implemented in a PW.

3.1 Approach/Methodology

3.1.1 Participants

The sample for this study included 16 individuals and was collected at APCC, between December 2013 and March 2014, based on the following inclusion criteria:

- Clinical diagnosis of CP;
- Ability to understand questions and provide answers accordingly;
- Use of a PW;
- Minimum age of 15 years.

After obtaining APCC's formal authorization, participants were selected by their teams of clinical follow-up, based on the inclusion criteria listed above. Before filling out the questionnaires, all participants gave informed consent.

3.1.2 Tools

The evaluation protocol of this study was composed of the following tools:

1. Clinical and sociodemographic data form: questionnaire filled out jointly by the researcher and the technician responsible for monitoring the subject, which contains the following information: age, gender, type of CP and associated problems;

2. Gross Motor Function Classification System for Cerebral Palsy (GMFCS-CP) [Palisano et al., 1997]: grading scale of the degree of impairment, structured in five levels, in which the Level 1 is the lowest and level 5 the highest. The grading is based on functional limitations, the need of use of mobility aids or wheelchairs and also on the quality of movement. Level 1 and 2 are for manual wheelchair users. Since in this research we are studying PW users, we are only interested in level 3, 4 and 5. Level 3 is for individuals that need to use a PW in more complicated places, but for short distances or for places nearby to navigate, a manual wheelchair will be enough to ensure their mobility. Level 4 is for users that can only get their autonomous mobility with the help of a PW. Level 5 is for users whose mobility is seriously compromised. Physical problems limit voluntary control of the movements and the control of the head and trunk. Even with the use of a PW, they have mobility problems;

3. Questionnaire for mobility, accessibility and safety characterization: questionnaire filled out by the subject or with the researcher's help, with multiple choice questions, organized into four parts which will be analyzed further ahead:

   (a) Characterization of:
      i. subject's mobility;
      ii. use of public transportation;
      iii. HMIs.
   (b) Characterization of the use of assistive mobility technologies;
   (c) Most valued features and limiting factors in the use of the PW;
   (d) Possible solutions to be implemented in the PW for its improvement.

3.2 Results

3.2.1 Sample characterization

In Table 3.1 we can see the clinical and sociodemographic characterization of the sample.

The collected sample (n = 16) had an average age of 29,80.

The most observed type of CP was spastic (68,75%), followed by dystonic (25,00%) and ataxic (6,25%). Analyzing other health problems associated with CP (besides motor impairment), 37,50% of the cases do not present any additional associated problems, although 31,25% experience visual deficits, 12,50% intellectual deficits, 12,50% hearing deficits and 12,50% epilepsy.

According to the inclusion criteria associated with the use of an assistive technology to improve mobility, most individuals (68,75%) are level 4 in the grading scale of the degree of impairment, 18,75% of the individuals are level 5 and the rest (12,50%) of the subjects are level 3.

Table 3.1: Clinical and sociodemographic data.

Age (M)	29,80
Gender	Frequency (n/%)
Male	13/81,25
Female	3/18,75
Type of Cerebral Palsy	
Spastic	11/68,75
Dystonic	4/25,00
Ataxic	1/6,25
Additional associated Problems	
No additional associated problems	6/37,50
Visual problems	5/31,25
Hearing problems	2/12,50
Intellectual problems	2/12,50
Epilepsy	2/12,50
Degree of Impairment (GMFCS-CP)	
Level III	2/12,50
Level IV	11/68,75
Level V	3/18,75

3.2.2 Characterization of accessibility, mobility and support

Almost all individuals with CP (93,75%) reported being able to move autonomously with the help of a PW.

The number of individuals who reported not using public transportation (although they wanted to) is very high (87,50%). This somehow reflects the inadequacy in the access to public transportation, in which individuals with CP are particularly vulnerable.

Finally, a relatively small percentage (25,00%) of people in the group of subjects need HMIs for computer use.

These results can be verified in Table 3.2.

Table 3.2: Characterization of accessibility, mobility and support.

	Yes (n/%)	No (n/%)
Do you have the possibility of moving autonomously with the powered wheelchair?	15/93,75	1/6,25
Do you use public transportation?	2/12,50	14/87,50
Do you use HMIs for computer use?	4/25,00	12/75,00

3.2.3 Time of use of HMIs and powered wheelchair vs quality of performance

All subjects participating in this study were considered experienced users steering a PW since they have several years of experience using it.

Analyzing Table 3.3, it is possible to see that all the users of HMIs for computer use and most individuals (62,50%) using the HMIs required for steering the PW, considered themselves in a level 5 of performance. Most of the subjects (81,25%) in this research use a joystick to help the navigation of the PW. Many of these users (43,75%) were classified as level 4 in terms of steering performance of the PW and also, that a significant percentage (37,50%) were classified as level 5.

Table 3.3: Level of performance steering the powered wheelchair and with the HMIs.

Level of steering performance in the powered wheelchair	Frequency (n/%)
Level 3	3/18,75
Level 4	7/43,75
Level 5	6/37,50
HMIs for powered wheelchair navigation	
Joystick	13/81,25
Pedal Technology	1/6,25
Head interface with sensors	1/6,25
Chin Technology	1/6,25
Level of performance with HMIs for powered wheelchair navigation	
Level 3	3/18,75
Level 4	3/18,75
Level 5	10/62,50
HMIs for computer use	
Chin Pointer	2/50,00
Pedal Technology	1/25,00
SmartNav - Infrared Technology	1/25,00
Missing=12 (n=4)	
Level of performance with HMIs for computer use	
Level 5	4/100,00
Missing=12 (n=4)	

3.2.4 Most valued features and limiting factors in the use of assistive technologies for mobility

In Table 3.4 we can see that the most valued features of a PW are its comfort and structure (68,75%), easy navigation and wheelchair control (56,25%) and finally, safety (43,75%). The main limiting factors in a PW are the difficulty in reverse drive (37,50%) and building/vehicle access (31,25%). Also 12,50% of the individuals complained about the lack of safety.

The architectural barriers were identified as the main factor limiting the PW use at home (75,00%) and in the outdoors (87,50%). Another relevant limiting factor is again the difficulty in reverse drive at home (18,75%) and lack of safety in public places (31,25%).

Table 3.4: Most valued features and limiting factors in the use of assistive technologies for mobility.

Most valued features in a wheelchair	Frequency (n/%)
Comfort/Positioning	11/68,75
Easy navigation and wheelchair control	9/56,25
Safety	7/43,75
Dimension	2/12,50
Not specified	2/12,50
Limiting factors of powered wheelchair use	
Difficulty in reverse drive	6/37,50
Building/vehicle access	5/31,25
Mechanical aspects	3/18,75
Dimension	3/18,75
Safety	2/12,50
Design	1/6,25
Complicated interfaces	1/6,25
Control and navigation of the wheelchair	1/6,25
Impractical belt	1/6,25
Not specified	3/18,75
Limiting factors of the powered wheelchair use at home	
Architectural barriers	12/75,00
Reverse drive	3/18,75
Strain caused by the powered wheelchair use	2/12,50
Fatigue	1/6,25
Powered wheelchair inadequacy	1/6,25
No limitation	2/12,50
Limiting factors of the outdoor access	
Architectural barriers	14/87,50
Safety	5/31,25
Strain caused by the powered wheelchair use	1/6,25
Fatigue	1/6,25
No limitation	1/6,25
Limiting factors in the private transportation use	
Powered wheelchair inadequacy	12/75,00
Vehicle limitation	5/31,25
Vehicle adaptation costs	4/25,00
Difficulty placing the powered wheelchair in the vehicle	3/18,75
No limitation	2/12,50
Limiting factors in the public transportation use	
Complexity of the usage	2/100,00
Shortage of transportation	2/100,00
Missing=14 (n=2)	

The powered wheelchair inadequacy (75,00%), the limitations of the vehicles (31,25%) and the vehicle adaptation costs (25,00%) on one hand, and the lack of adapted transports and complexity of its use (both referred by all the public transportation users), on the other hand, were the main limiting factors mentioned for the use of private and public transportation, respectively.

We were able to get a perception of the mobility and accessibility difficulties and also concluded that many of the complaints were related with the lack of safety and how relevant this issue is or related with the lack of an appropriate assistive navigation system to help maneuvering the PW.

3.2.5 Possible improvements to be implemented in the powered wheelchair

Since one of the goals of this research is to help improve the QOL of people with CP, the subjects of this study were asked if their PW could be improved in any way, and almost all of them answered positively (93,75%), as seen in Table 3.5.

Table 3.5: Powered wheelchair improvement.

	Yes (n/%)	No (n/%)
The powered wheelchair can be improved in any way?	15/93,75	1/6,25

In Table 3.6 is possible to see the requested improvements. The most requested improvements suggestions were: aid for reverse drive (40,00%), collision avoidance (26,67%), reverse driving information (26,67%), a warning during reverse driving (26,67%), comfort/structure improvement (20,00%), assistance in navigation in more complicated places (13,33%).

Table 3.6: Requested powered wheelchair improvements.

Possible improvements	Frequency (n/%)
Aid for reverse drive	6/40,00
Collision avoidance	4/26,67
Reverse driving information	4/26,67
Warning during reverse	4/26,67
Comfort/structure improvement	3/20,00
Assistance in navigation in more complicated places	2/13,33
Wheelchair that lifts	1/6,67
Rear camera/mirror	1/6,67
Wheelchair that lies down	1/6,67
Retracting pedal	1/6,67
Bumper (soften ball impact in football)	1/6,67
Chance of driving the wheelchair vertically	1/6,67
Flashers	1/6,67
Autonomous wheelchair	1/6,67
Wheelchair with lights	1/6,67
Buttons design improvement	1/6,67
Improvement of speed control with the joystick	1/6,67
Missing=1 (n=15)	

With these results we can conclude that most of the suggested improvements (57,14%) affect safety and are related with the difficulty in navigating the PW. These were also, pointed out as the most limiting factors, in general, which means there is the need to develop more suitable solutions to improve navigation and safety.

The results suggest that the time of use of the PW can be a decisive factor for a good level of performance. Since in this research work, the subjects were all adults with a good level of expertise driving the PW, where the level of performance in which more individuals are in is level 4 and almost as many are in level 5, this means that this is close to the best case scenario. Younger PW users can have increased troubles driving the PW due to the lack of experience, therefore contributing to a more complex navigation and compromised safety.

A solution to address both of these problems is to install sensors in the PW, providing additional information of the environment and to introduce a new navigation system based on a collaborative controller that shares the information of the user and the machine.

In this dissertation, a SAANS to increase safety is proposed, in order to attain the goals of increased safety and easier navigation in structured indoor environments.

Chapter 4

Assistive Navigation System

This chapter presents the architecture of the proposed Assistive Navigation System (ANS) as well as an explanation of the used methods to implement each sub-module. The system's architecture is described in a conceptual level, trying to attain the predefined goals. To do so, the requirements needed to achieve the goals are examined.

4.1 System requirements

The ANS is designed to assist the user maneuvering the MAR safely. With the solution presented in this Chapter, we can solve the problems pointed out in Chapter 3, such as the need for increased user safety and MAR navigation improvement. The proposed solution can also solve other referred problems, such as the difficulty in reverse drive and the lack of information while moving backwards. Placing the Kinect in the back of the MAR and applying the same algorithm, the MAR can provide assistance in reverse drive and increase the user's safety.

To achieve the goals mentioned in Chapter 1, several requirements have been identified.

- The users are able to communicate with the wheelchair through a Joystick, since the majority of the cases that were studied in Chapter 3 had a Joystick as HMI.

- To map the environment, the 3D depth data retrieved from Kinect is condensed into multi-level horizontal 2D scans that contain the information of the three-dimensional Kinect's field-of view in order to decrease computational complexity and let the user approach certain obstacles. This is explained in detail in the Multi-level 2.5D data processing sub-module (described in section 5.1.1). Taking into account that assisting the user navigating the MAR safely is our aim, an Obstacle Detection sub-module (described in section 6.1.2) was developed. In this sub-module, the 2D depth data was divided in 5 angular sectors for obstacle detection.

- In the Collaborative Control module, the Risk Assessment, a decision sub-module, was developed in order to, as the name suggests, assess the risk. The Reactive Collision Avoidance sub-module uses the risk assessment information in order to avoid the detected obstacles. This module is described in section 4.4.

Figure 4.1 shows the essential role of communication between human and machine in this architecture. The human uses a Joystick to interact with the machine, and the machine communicates through ROS with the MAR.

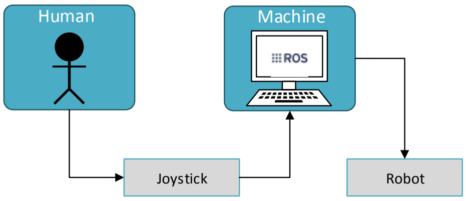

Figure 4.1: Human-Machine communication channel

4.2 Generic System Overview

The system overview, the information flow between the system's modules and how they interact with each other, is illustrated in Figure 4.2.

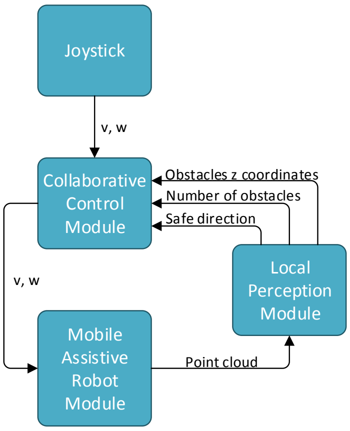

Figure 4.2: Assistive Navigation System Overview

The two fundamental modules (Collaborative Control and Local Perception) of the designed system architecture and its sub-modules (Multi-level 2.5D data processing, Obstacle Detection, Risk Assessment and Reactive Collision Avoidance) will be explored in detail in the following sections. The physical layer design and the Mobile Assistive Robot Module are explained in the next Chapter.

4.3 Local Perception Module

The Local Perception module is composed by two sub-modules: Multi-level 2.5D data processing and Obstacle Detection. The implementation of these two sub-modules is explained in detail in the next two sections.

In the Multi-level 2.5D data processing sub-module, the 3D depth data (point cloud) is received from Kinect in the MAR module, which is condensed into three horizontal 2D scans in order to decrease computational complexity. The 2D scans contain only the relevant information of the 3D depth data. This module provides the 2D environment information that is transmitted to the Obstacle Detection sub-module.

The Obstacle Detection sub-module does, as the name implies, the detection of obstacles the MAR surrounding environment. It is done through the analysis of the three 2D scans provided by the Multi-level 2.5D data processing sub-module. The module outputs the distance of the obstacles to the CC module, as well as the number of detected obstacles and a safe direction.

Figure 4.3 shows the components of the Local Perception Module and the interaction with other modules.

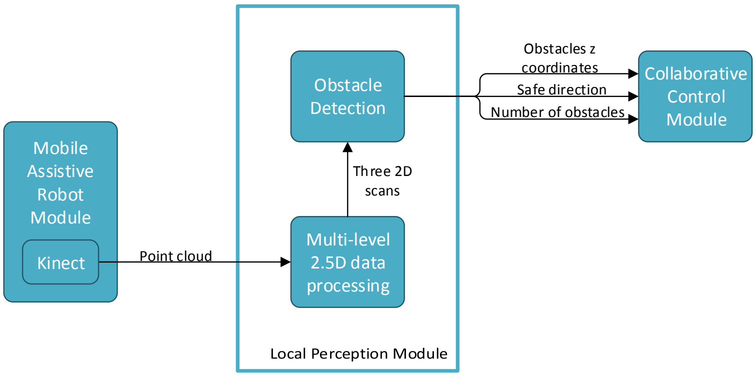

Figure 4.3: Local Perception Module

4.3.1 Multi-level 2.5D data processing

Our solution to overcome the intense flow of data provided by Kinect is to condense the 3D Kinect data into 2D scans. We need to reduce the huge amount of data that this sensor provides, while keeping the relevant 3D sensorial information about obstacles. D*epthimage_to_laserscan* [Rockey, 2013] is a ROS package that converts the Kinect's 3D depth data to provide a 2D scan, resembling a laser scanner. Any advantage that might come with the use of Kinect is not explored in this package, since it only scans one plane of the environment.

The purpose of this work was to use the Kinect sensor and explore all its advantages and the benefits of its use instead of a laser scanner. To do that, we had to, after performing a careful analysis, modify this package according to our needs.

To condense the 3D Kinect data into 2D scans, it is selected the minimum measured distance in each column of the Z-array (depth pixel), as can be seen in equation 4.1. The minimum distance was selected such that

$$Z' = \min(Z_{0,j}, Z_{1,j}, \ldots, Z_{479,j}) \tag{4.1}$$

where j is the respective column number. The Y locations for the corresponding Z-elements were modified to provide a 480x1 array, instead of a 1x1 array. This way, we can make use of the 3D data of Kinect and scan its 47 degree field-of-view, instead of just one plane. This array along with the array indicated in equation 4.1, represent the 2D obstacle locations (Z and X coordinates) as obtained when using a laser scanner. Also note that the Y coordinate was ignored as the robot can only move in X and Z direction (see Figure 4.4). The arrays have already represented the nearest obstacle locations no matter where their vertical positions are, since the Kinect vertical field-of-view covers obstacles of the same height as the MAR.

Kinect is not reliable when the obstacles are closer than 0.6 meters and is blind at distances inferior to 0.5 meters. If the user's intent is to approach an obstacle, it would be hard to let the user get closer and maintain its safety. To overcome this problem, we changed the *depthimage_to_laserscan* package, so it could provide three 2D scans (3D depth data from Kinect condensed into 2D scans) of the environment: one for the top, one for the middle and one for the bottom.

This method is needed to identify key situations like approaching tables or desks, for example. Through the features of these situations, the algorithm operates accordingly, allowing the user to get closer than it normally would get. Tables and desks have the top scan free and the middle and bottom scans occupied.

Since in this method we are condensing the 3D depth data into three 2D scans, each one of them has 2D information of $\frac{1}{3}$ of the data that Kinect provides.

To simulate the laser scanner, this package will by default scan the plane of the image where the center row is, which can be obtained through the pinhole camera model. It describes the mathematical relationship between the coordinates of a 3D point and its projection onto the image plane of an ideal pinhole camera [Sciammarella and Sciammarella, 2012]. In Figure 4.4 we can see C_X and C_Y, which are the coordinates of center of radial lens distortion and also the piercing point of the camera coordinate frame's Z axis with the camera's sensor plane. C_Y is also the position and orientation of the camera in the Y axis.

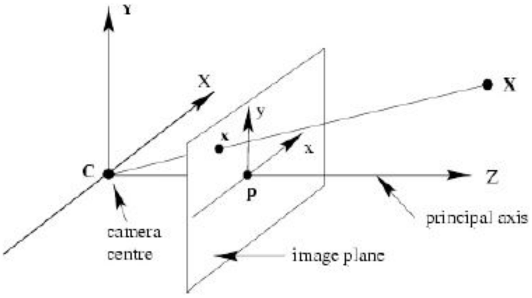

Figure 4.4: Perspective projection [Schindler, 2012]

Each scan performed has a height of $\frac{1}{3}$ of the Kinect's image height.C_Y points to the center row of the image, and therefore, the center row of the middle scan area. To allow the package to scan 3 different areas at the same time, we use the value of C_Y and the scan height to change the location of each scan by creating pointers to remaining areas to scan: the top and bottom areas.

In Figure 4.5 we can see the comparison between the original package and the modified one. The axis orientation in these figures is illustrated in Figure4.4.

This algorithm maintains its efficiency since all the relevant data is considered and decreases the computational complexity since we aren't constantly using and analyzing the 300.000 measurements per frame at 30Hz.

The minimum-selection method in equation 4.1 was implemented to avoid false detection of obstacles and minimize processing power and time.

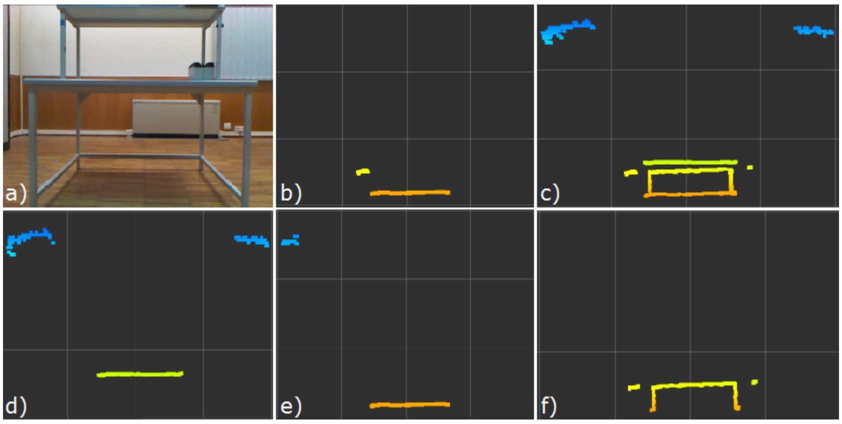

Figure 4.5: Kinect 3D depth data condensed into 2D scans of the environment - a) the Kinect's RGB image, b) its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), c) the three 2D scans, d) the top 2D scan (illustrates the shelf outline), e) the middle 2D scan (illustrates the table top) and f) the bottom 2D scan (illustrates the table legs)

4.3.2 Obstacle Detection

To perform obstacle detection, we developed a local planner based on the VFH approach, determined by the data provided by Kinect. A histogram is created by dividing the 2D scans obtained directly from the data provided by the Kinect's 3D field-of-view into 5 angular sectors, which will be analyzed in order to find the closest obstacle. We decided to use 5 sectors since it has been proved to be effective when the goal is to provide a safe navigation for the robot [Correa et al., 2012]. For example, in Figure 4.6 we can see the 5 sectors are highlighted in the Kinect's 2D scan image.

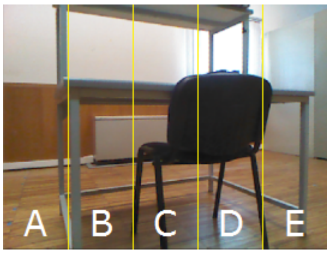

Figure 4.6: Division of Kinect's field-of-view in 5 sectors

The number of obstacles and the distance of each obstacle is obtained through the analysis of the 2D scan. Only the closest obstacle in each angular sector is relevant, since if the robot crashes with an obstacle in a certain sector, it will be the closest one. If the closest obstacle in a section has a value (distance) inferior than a given threshold, it will be considered a potential obstacle or an actual obstacle that can compromise the user's safety. The evaluation of the risk of the detected obstacles is done in the risk assessment sub-module. After finding the closest obstacle in each sector, it's possible to know the distance in meters through the *depthimage_to_laserscan* package. The values returned by this sub-module are the sector in which there are obstacles and their distance to the MAR.

Following this, a second analysis is performed in order to understand which side of the MAR is populated with more obstacles. To do so, we calculate the weight distribution of the obstacles. For example, if there are obstacles in sections A, B and D, we can see that the left side of the MAR has more weight because there are more obstacles in that side. With this information, the reactive collision avoidance knows which side is the safest.

The similarities with the VFH method consist in the fact that we build a histogram of the Kinect's field of view. For each section in this histogram, there is a value that represents the existence of an obstacle in that direction. Afterwards, in the presence of a high risk obstacle or when in imminent danger, we analyze the safest side of the Kinect's field-of-view and steer the robot in that direction.

4.4 Collaborative Control Module

The CC module has a central role in the ANS. It decides, according to the perceived situation, whether to give all the power to the user or to the machine, or to merge user's and machine's inputs. It has two sub-modules: Risk Assessment and Reactive Collision Avoidance. In the next sections, the CC design and implementation is described, as well as the Risk Assessment and the Reactive Collision Avoidance.

This module receives information from the Local Perception module in order to update the current situation and to know where the safest direction is, and from the user through the HMI, in our case, through the Joystick. This information is used in the two sub-modules. With the information obtained, the Risk Assessment sub-module will analyze the current situation and if an object is closer than a given threshold, it is considered an obstacle that may or may not compromise the user's safety. This sub-module outputs the navigation risk level according to the faced risk.

The main objective for the Reactive Collision Avoidance sub-module is to avoid the obstacles found in the environment. It receives information from the Joystick, from the Local Perception module, and it also receives the risk level of the perceived situation determined in the Risk Assessment sub-module. This sub-module returns a linear velocity $v\left(t\right)$ and/or an angular velocity $w\left(t\right)$, which can be mixed with the velocities returned by the user through the joystick, in case of shared control. This velocities are delivered to the MAR.

It can be seen in Figure 4.7 the components that compose the CC module and its interactions with other modules.

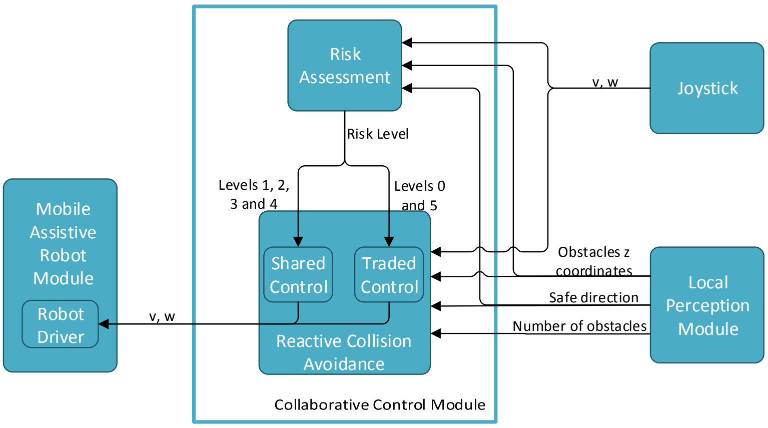

Figure 4.7: Collaborative Control Module

4.4.1 Collaborative Control Design

The Collaborative Controller is a mediator between human and machine. Figure 4.8 shows its design and information flow. The module is updated with the current perceived situation (obstacle location and distance, and also the user's behavior) by the Local Perception module and with the user intent through the joystick commands. Taking into account the current situation, the CC makes a decision based on risk assessment, of whether to share the control between the human agent and the machine agent or to give full control of the MAR to just one of them.

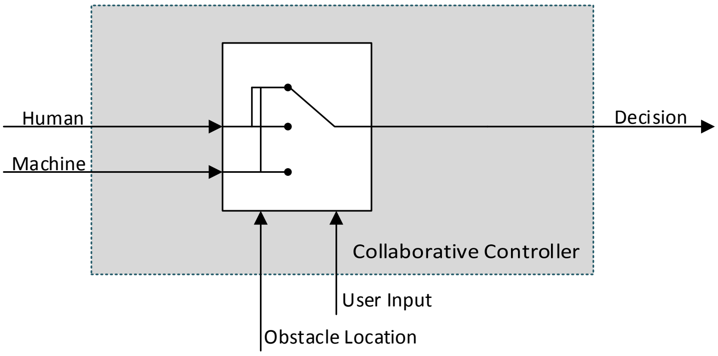

Figure 4.8: Overview of the Risk Assessment sub-module in the Collaborative Controller

Figure 4.9 shows a finite-state machine that illustrates the expected work of the system, taking into account some of the issues that will be discussed in section 4.4.1.1.

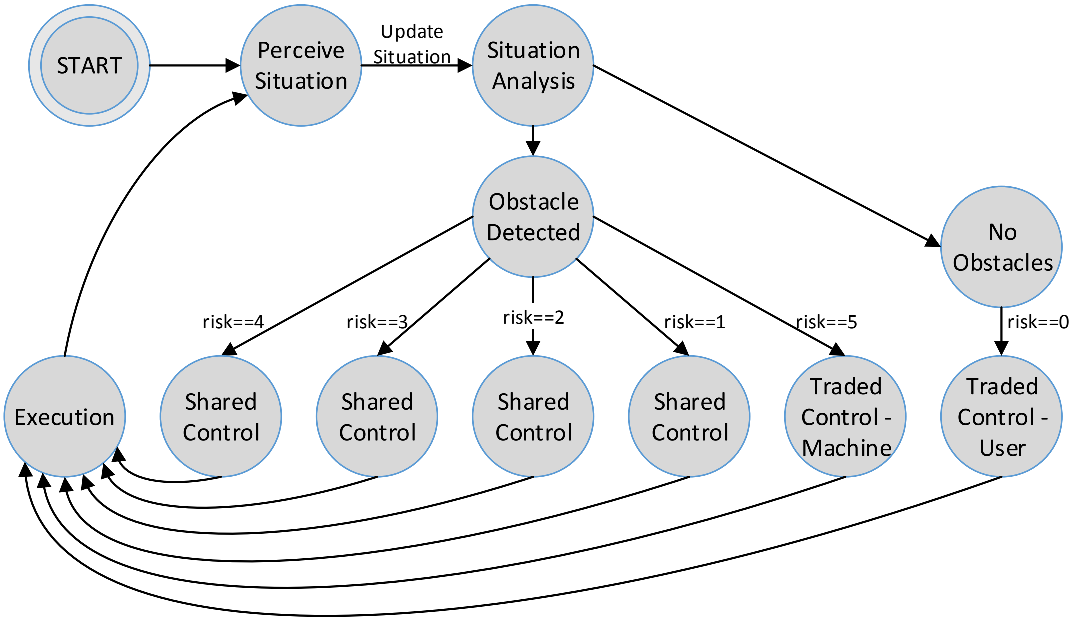

Figure 4.9: Collaborative Control course of action

4.4.1.1 Key Design Issues

The Collaborative Controller can be considered a mediator between human and machine. In Chapter 2, it was described the seven key design issues established in [Fong, 2001] that shouldn't be ignored during design phase of a system of this kind.

Design begins by defining key situations where the Collaborative Controller will intervene, as seen in Figure 4.9. The implementation and solution for the key design issues in order to design a successful CC system is discussed in this section:

- The first key design issue to consider is *Dialogue*. Since there is the need of a communication channel between the human and the robot, the user should communicate with the MAR through the use of an appropriate HMI, in our case, through a Joystick, which is adequate for some people with motor impairment and was also the most used HMI in the user analysis (Chapter 3).

- In *Awareness* the Collaborative Controller must understand the situation and act accordingly. The robot identifies situations where the user needs help and assist in such situations.

- The robot must have *Self-reliance*, having the ability to maintain the human and its own safety. The primary concern of this design will be navigation and collision avoidance problems. *Self-Reliance* is tackled by allowing the robot to act on its own, when a key situation is encountered, for example, when the user's safety is severely compromised and the robot has to intervene and take over the MAR control.

- *Adaptiveness* is the ability of the controller to be prepared for users with different characteristics (differences in experience, knowledge, skill and training). A possible solution to this problem consists in defining a list of skill levels, and attribute a skill level to each user. The machine should be prepared for certain changes in its working environment. The MAR adapts it's behavior accordingly, when changes in the environment appear, like for example, a crowded space. This issue was not tackled in this work.

- *Human-Robot Interaction* key design issue focuses on the improvement of the definition of HRI to a more natural, partner-partner interaction. The collaborative controller automatically applies this concept allowing this a partnership between the human and the machine.

- *User Interface Design* has the role of boosting system's usability. A possible solution is providing information for human decision making or attract the user's attention when a key situation is encountered. This issue is under development.

- Finally, the *Control and Data Flow* of the CC is where the rules to solve situations where the machine and the human do not agree are applied (where control is negotiated). These rules are described in the next two sections.

4.4.2 Risk Assessment

In order to make decisions according to the accessed risk, this sub-module has to evaluate the current situation. If an obstacle in a certain sector has a distance value inferior than a given threshold, a classification of the current situation can be done:

- Obstacles further than 0.9 meters present no risk to the user (risk level 0).
- Obstacles located between 0.6 and 0.9 meters from the MAR are categorized as potential obstacles that can come in the way of the trajectory, being afterwards sub-categorized as high risk obstacles (risk level 3 or 4 - located between 0.6 and 0.75 meters) and medium risk obstacles (risk level 1 or 2 - located between 0.75 and 0.9 meters).
- We considered that the MAR is in imminent danger (risk level 5) when an obstacle is less than 0.6 meters away.

The algorithm selects the sector that presents more danger to the user from among all the other sections, and classifies the current situation according to that sector. The classification also depends on the user's behavior regarding the safe direction to follow.

The traded control is activated when:

- Risk level 0 - In case of no obstacles found in the way, the control will be on the user's side completely (control on the human's side).
- Risk level 5 - In case of immediate risk to the user's safety, the collaborative controller will remove the MAR control from the user and let the machine fully handle the situation (control on the machine's side).

The shared control is activated when:

- Risk level 1 - in a medium risk situation, the linear velocity is limited to prevent a fast approach to the obstacles. In this risk level, the user has a correct behavior and therefore, has plenty of control over the MAR, but not full control.
- Risk level 2 - the user is navigating the MAR the direction of a potential obstacle in a medium risk situation, their freedom to navigate the MAR will be more restricted. At this stage, the user has control over the MAR, but does not fully control it. It is just a little more limited than the case in risk level 1.
- Risk level 3 - in a high risk situation, the user is trying to deviate from the obstacle, but although it is on the right direction, isn't turning enough to avoid the collision. This is the most balanced case of shared control.
- Risk level 4 - a potential obstacle in a high risk situation is located, but the user is having a behavior that can jeopardize his safety. The user's control over the MAR will be very compromised.

The risk levels mentioned above are illustrated in Figure 4.10. What defines correct and wrong behavior, is if the user is moving away from the obstacles or towards them, respectively. The closer the obstacles are, the bigger the risk. If the user's behavior is wrong, the risk is bigger. In the minimum risk situation, there are no obstacles and therefore, the user's behavior is indifferent. In the maximum risk situation, since the user's safety is too compromised, the user's behavior doesn't matter.

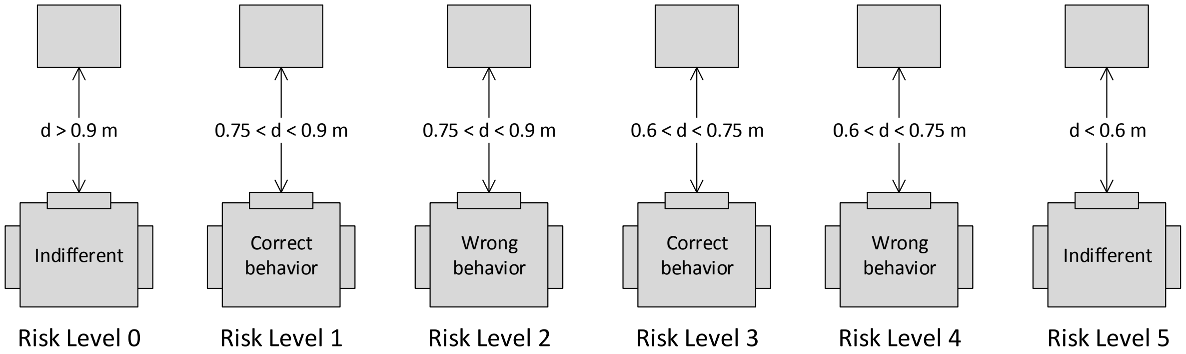

Figure 4.10: Risk Levels

4.4.3 Reactive Collision Avoidance

The algorithm developed for the Reactive Collision Avoidance Navigation, will take into account the weight of the sectors (number of obstacles) and the safest direction to follow. Another factor that this algorithm has into account, is the distance of the obstacle and the angular and linear velocities that the user is providing to the MAR.

It acts as a Traded Controller, effectively denying or allowing the enforcement of user commands or acts as a Shared Controller by combining the MAR navigation commands with the user's commands. It provides assistance to the user maneuvering in more complicated places as well as avoiding collision in order to achieve a better level of safety.

The rules of the reactive navigation are:

- Traded Control - When no obstacles are found, there is no navigation limitation, except for the maximum velocity attainable. It is limited for safety reasons;
- Shared Control - When in a medium risk situation, the maximum linear velocity attainable will be limited for the same reason referred in the previous topic, and will vary with twice the distance from the obstacle to the MAR;
    - An exception to this rule is when the user is moving in the direction of an obstacle, in this same situation. The linear velocity is more limited in this case and varies with the distance;
- Shared Control - In a high risk situation, both linear and angular velocities will be affected by the reactive navigation. Linear velocity is reduced in accordance with the user going against the obstacle or not, varying with half the distance and with the distance, respectively). The angular velocity applied in the MAR also depends on the behavior of the user. If going against the obstacle, the reactive navigation will offset the turning angle faster than if the user if moving away from the obstacle. It offsets the angle in order to rotate the MAR to a safe direction, helping in the maneuver. A safe direction is the side of the Kinect's field-of-view with less weight. The robot turns in that direction until it has no high risk obstacles in the way;
- Traded Control - If the obstacle is jeopardizing the user's safety (imminent danger situation), the

MAR is stopped and rotated the opposite direction of the obstacle found, until a safe situation is encountered, with no obstacles in the way;

- If there are obstacles in just section A and E, they will not be relevant because they are not considered a risk to the user's safety, since the MAR will not hit them when passing close by.

The Reactive Navigation was developed in a way to avoid the MAR to be stuck in deadlocks (U-shaped obstacle configurations), since we created a short-term memory, that will temporally recall the number of perceived obstacles around the MAR, which will allow it not to be stuck.

In case the robot is in deadlock, the algorithm saves the maximum number of obstacles found in the location where the robot is stuck, and every time that number increases, it changes the direction of rotation, since it means it is a more crowded area. It will eventually get out of that situation since the maximum obstacles found will stop increasing and it will keep rotating until it is in a free direction.

Chapter 5

ROS Implementation

The first four sections of this chapter explain in detail the software implementations in ROS environment of the multi-level 2.5D data processing and obstacle detection, in the Local Perception module and of the risk assessment and reactive collision avoidance, in the Collaborative Control module. The final section describes the physical layer and the Mobile Assistive Robot module components.

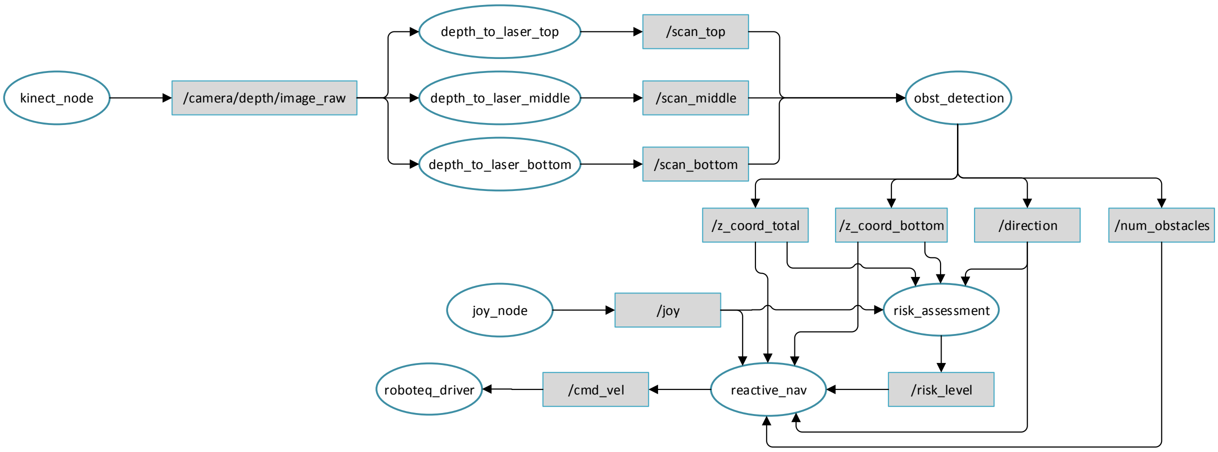

Figure 5.1: Information flow in the ROS implementation of the ANS

Figure 5.2: ISRobot (left) and RobChair (right)

After defining the ANS architecture design and the methods used to achieve the goals of this dissertation, the development and implementation of the defined methods and algorithms were carried out, using ISRobot and RobChair, a mobile robot and a robotic wheelchair, respectively, both from ISR. Figure 5.1 shows the interaction between all ROS nodes and topics of the ANS. ROS operation is explained in [Coleman, 2013]. All of the ANS software designed was written in C++. The setups used can be seen in figure 5.2.

5.1 Local Perception

The local perception of the environment is performed in the Multi-level 2.5D data processing and Obstacle Detection sub-modules. An introduction on these modules design is given and the nodes that compose them are described in detail.

In this module we focus on overcoming one of the issues related with using Kinect for mapping purposes, referred in Chapter 2, by adapting the 3D Kinect data to the needs of the ANS. It also does obstacle detection and localization, so that the remaining modules work properly.

5.1.1 Multi-level 2.5D data processing

The Multi-level 2.5D data processing sub-module is responsible for the gathering and processing the information. Three ROS nodes are implemented - *depth_to_laser_top*, *depth_to_laser_middle* and *depth_to_laser_bottom* - which are explained in detail in the next section.

These nodes receive the 3D depth data from Kinect through the topic */camera/depth/image_raw* and return 2D scans of the environment in the topics */scan_top*, */scan_middle*, */scan_bottom*. These nodes and related topics can be seen in Figure 5.3.

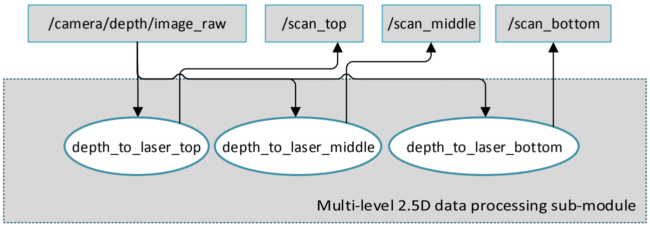

Figure 5.3: Multi-level 2.5D data processing sub-module Nodes

5.1.2 Obstacle Detection

The Obstacle Detection sub-module can be viewed as a system perceiver. It subscribes to the topics */scan_top*, */scan_middle*, */scan_bottom* (2D Kinect sensor data), which will be analyzed in the node *obst_detection*, in order to find obstacles that may compromise the user's safety.

It publishes:

- the topics */z_coord_total* and */z_coord_bottom* (depth of the obstacles in the z axis, from the Kinect's 47 degree field-of-view and from the bottom scan area, respectively), which are the distances of the detected obstacles that allow collision avoidance and allows to approach tables and desks;
- the topic */direction*, where the side of the MAR where less obstacles can be found;

- the topic */num_obstacles*, which tells the reactive collision avoidance sub-module the number of obstacles found, used in the deadlock avoidance strategy.

Figure 5.4 illustrates the general view of the Obstacle Detection sub-module implementation.

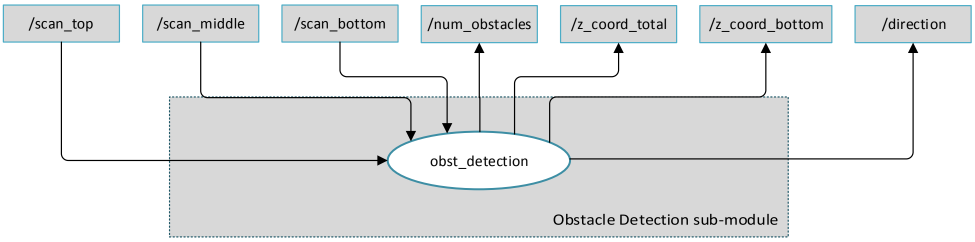

Figure 5.4: Obstacle Detection sub-module Node

5.2 Collaborative Control

In this section, an introduction to the Collaborative Controller sub-modules design is given, highlighting its requirements and operation, and the nodes that compose them are described in detail. The main goal of this module is to allow the MAR to navigate safely in the environment, avoiding collisions and assist the user in difficult places. Decisions regarding the current situation are taken in this module and a shared or traded controller is activated according to the risk level of each situation.

5.2.1 Risk Assessment

The Risk Assessment sub-module is implemented as a ROS node, *risk_assessment*, and is where the risk levels are defined. This node subscribes to:

- the topic */joy* (user's input) and the topic */direction* (safest direction), to analyze the user's behavior;
- the topics */z_coord_total* and */z_coord_bottom* (distance of the obstacles found in the Kinect's 47 degree field-of-view and in the bottom scan) in order to understand the current situation.

It publishes the risk level according to the situation in the topic */risk_level*. Figure 5.5 depicts the topic published and subscribed topics.

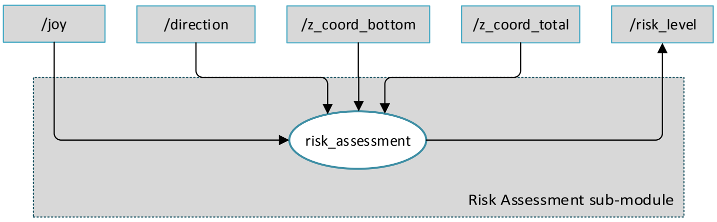

Figure 5.5: Collaborative Control Module Node

5.2.2 Reactive Collision Avoidance

The Navigation module implements the *reactive_nav* node. It receives data from:

- the risk assessment sub-module through the topic */risk_level* (in order to enforce the type of semi-autonomous control and also the navigation rules according to the risk);
- the obstacle detection sub-module through the topics */z_coord_*total, */z_coord_bottom* and */direction*, in order to calculate the right direction to rotate the MAR until there are no obstacles in the way, and through the topic */num_obstacles* in order to avoid deadlock situations;
- the joy_node through the topic */joy* (so that when the user has total or partial control over the MAR, the user's commands are transmitted).

This data allows the node to calculate the velocities and return them to the *roboteq_driver* which communicates to the MAR, through the topic */cmd_vel*. Figure 5.6 illustrates this node and its related topics.

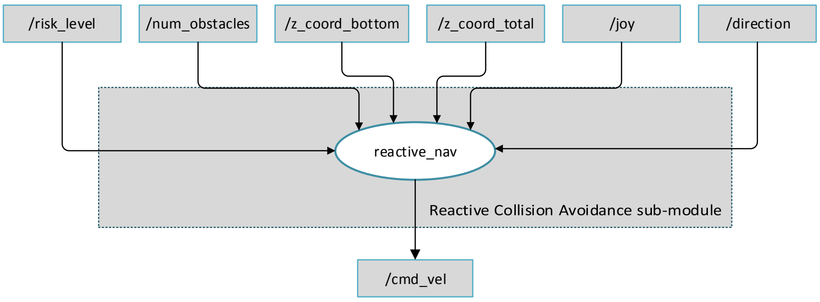

Figure 5.6: Navigation Module Node

5.3 Mobile Assistive Robot Module

To allow the system to be tested in real scenarios, a physical layer is needed. The MAR is the physical layer of the ANS. It is the link between the surrounding environment and the ANS.

To incorporate the physical layer in the ANS, its components must operate at the hardware level and then there must be a viable link between hardware and software layers, known as drivers. In the described implementation, the MAR includes a Microsoft Kinect as 3D depth sensor and the user commands the MAR with a joystick.

The robot driver was implemented in [Perdigão, 2014]. The sensor drivers used in this work were obtained in the distributions available for the ROS community.

Figure 5.7 illustrates the integration physical layer in the ROS environment.

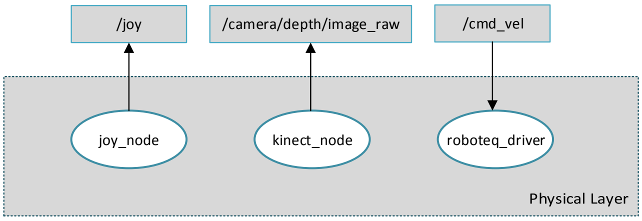

Figure 5.7: Physical layer components

The MAR used to implement this system has differential driving, which simplifies the navigation task. It receives from the Reactive Collision Avoidance (in the Collaborative Control module) a linear velocity $v(t)$ and/or an angular velocity $w(t)$, which are converted to speeds of the left and right wheel. It provides the 3D depth data that is obtained from the Kinect sensor.

Figure 5.8 shows the data flow from and to the MAR.

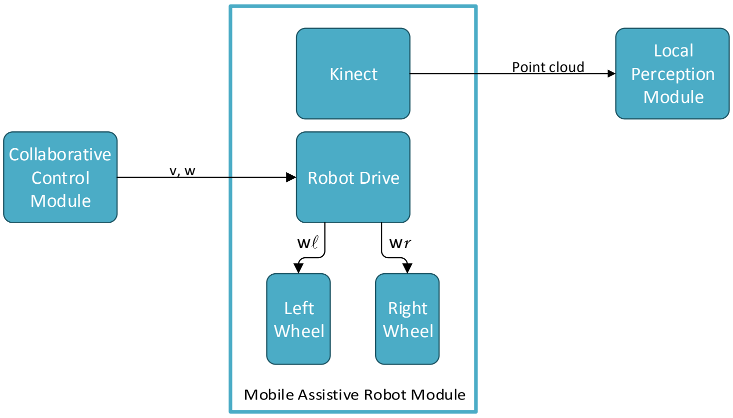

Figure 5.8: Data flow in the Mobile Assistive Robot

Chapter 6

Experimental Results

In this chapter, experiments assessing key parts of the system performance are described in order to validate the current software and hardware implementation of the ANS. There will be a section dedicated to each tackled issue.

6.1 Local Perception

6.1.1 Multi-level 2.5D data processing

In Figure 6.1 we can see the RGB image (left) obtained from the Kinect's RGB camera and the depth image (right) obtained through the infrared sensors of the Kinect.

The RGB image is displayed only for the purpose of showing the view of the Kinect Sensor on the robot and the depth image helps to understand the depth of the obstacles. Note that the darker the pixels, the nearer the object is. The white pixels represent invalid data because they are out of the Kinect's valid range, shadow, reflection or transparency problem. Sometimes it can be seen some surfaces with dark pixels. This happens due to the reflectance of those surfaces.

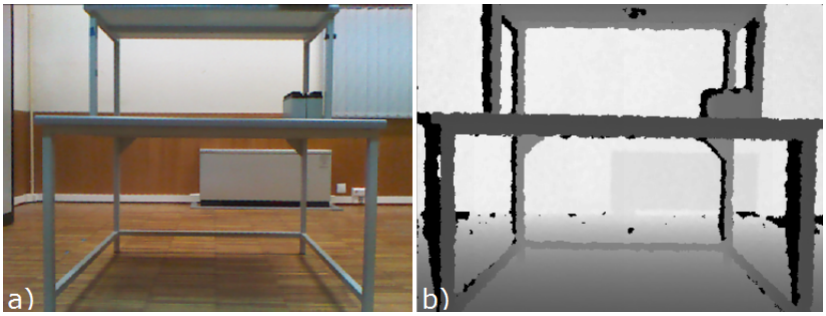

Figure 6.1: a) RGB image and b) depth image

Figures 6.2, 6.3, 6.4 and 6.5 are composed by 8 different perception images of the environment, obtained through Rviz, a visualization tool from ROS. The axis orientation in these figures is illustrated in Figure 4.4.

The colors in which the Kinect's 2D scans are represented are with gradient effect, from red to purple (hot and cold, respectively). Red represents a very close obstacle (0.5 meters) and purple represents an obstacle that is very far away (5 meters).

These figures represent four different situations that will be analyzed shortly. The 4 experimental cases are all from the same scenario, in which the Kinect and the Hokuyo laser scanner are positioned on the same vertical axis. In this experiment, from case to case, the two sensors maintained the same position in the x and y axis, but they were rotated upon themselves in order to obtain diverse situations.

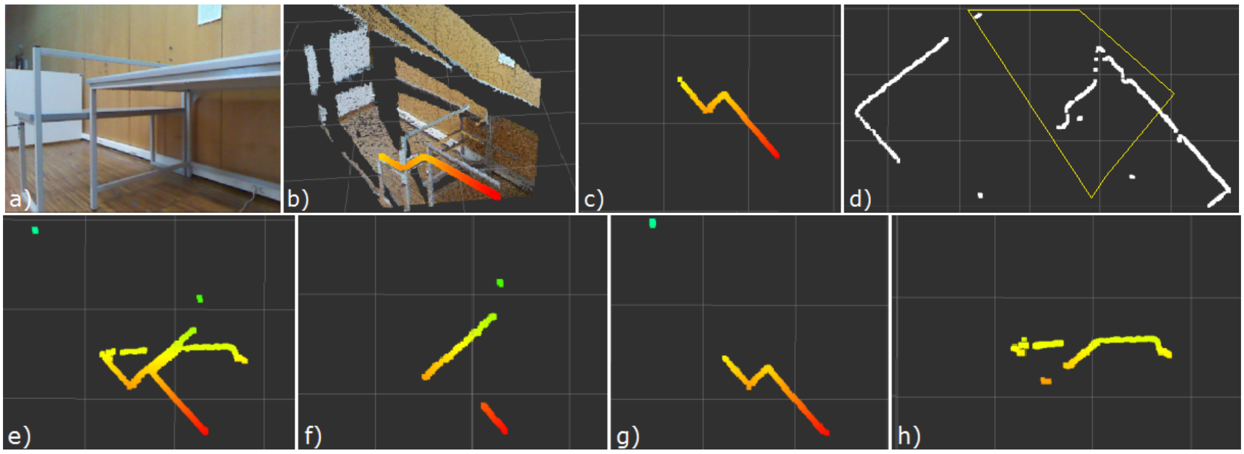

Figure 6.2: Experimental case 1 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan

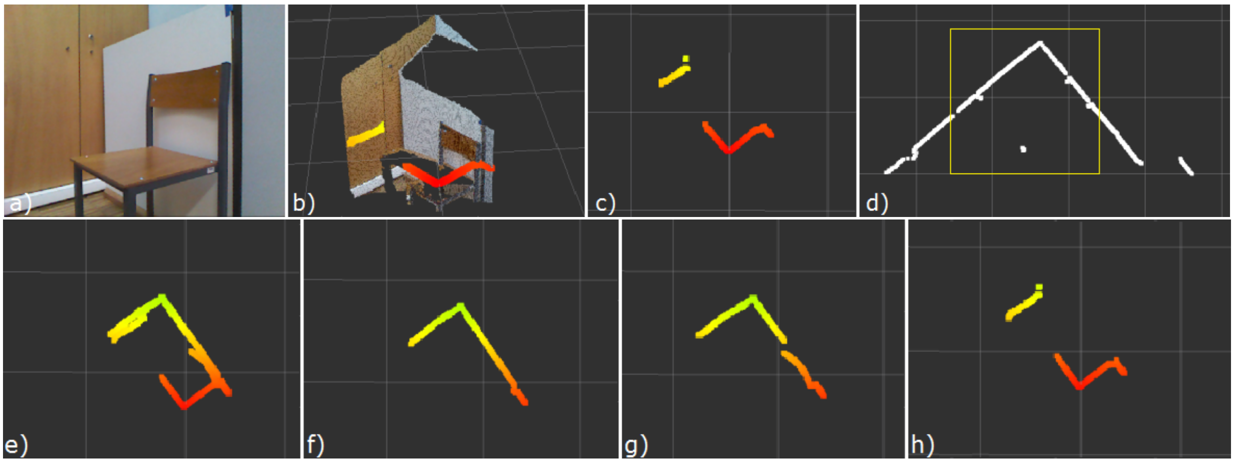

Figure 6.3: Experimental case 2 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan

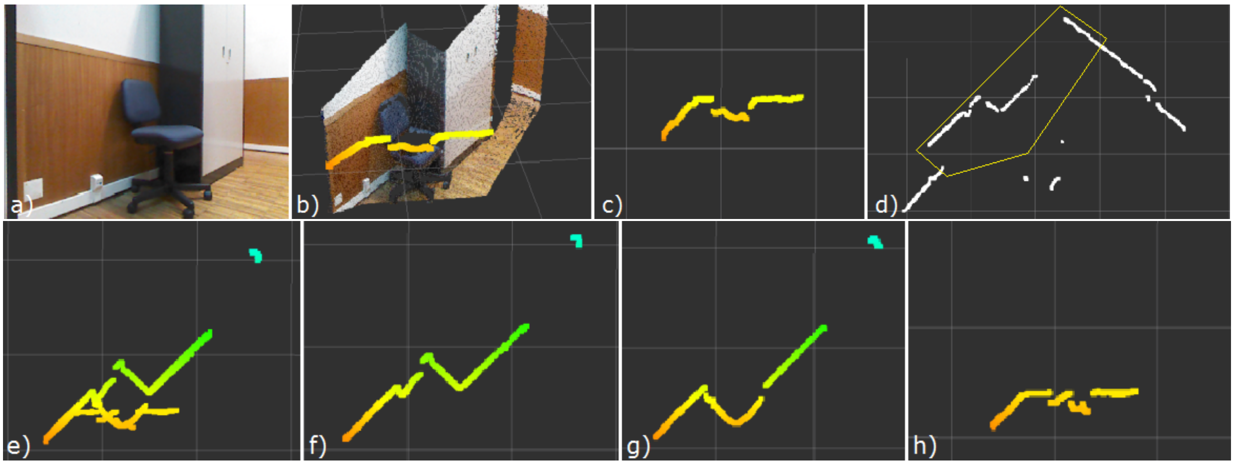

Figure 6.4: Experimental case 3 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan

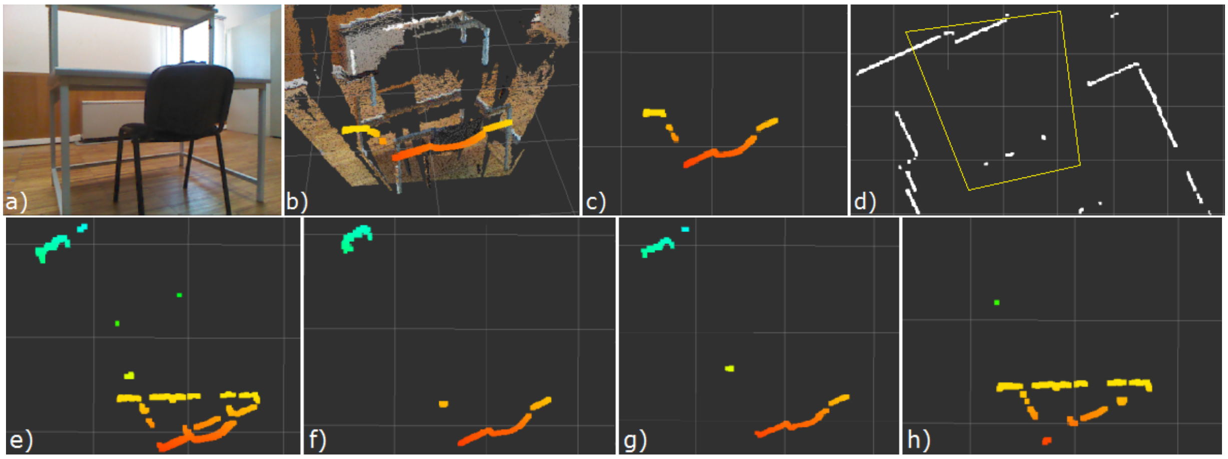

Figure 6.5: Experimental case 4 - (a) Kinect RGB image, (b) Kinect's pointcloud and its 2D scan of the 3D field-of-view (3D depth data from Kinect condensed into 2D scan), (c) the Kinect's 2D scan of the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) three 2D scans provided by Kinect, f) the top 2D scan, g) the middle 2D scan and h) the bottom 2D scan

Analyzing the four figures, it is possible to do the comparison between the actual part of the scenario being scanned, the depth data retrieved from Kinect, the 2D scan obtained from it, the 2D scan from the Hokuyo laser scanner and the Kinect's multi-level 2D scans, and prove some advantages of the use of Kinect, as well as some disadvantages.

Advantages:

- The table and the chairs are fully detected with Kinect (images (c)), while Hokuyo laser, in most cases, only detects the legs of these obstacles (images (d)). This happens because it can only detect objects that are in the plane scanned and Kinect retrieves 3D information of the environment.

- With the three 2D scans, it is possible to acquire certain typical features from objects, and allow the user to approach it, by not considering them obstacles.
- With the algorithm that condenses the relevant 3D information into 2D scans, it is possible to have a reliable scan, as shown in all the figures and it decreases the computational complexity that the use of Kinect causes.

Disadvantages:

- Kinect can only scan 58 degrees horizontally, while Hokuyo has a 180 degree field-of-view.
- Because the laser scanner only scans in one plane, typically parallel to the floor, it can scan obstacles located up to its maximum distance reachable, if there are no barriers. Kinect scans 47 degrees vertically. Since we can't have it at a very high height, the ground will be at some point, closer than some obstacles. An example of that is the experimental case 3 (Figure 6.4), where in images (b), (c) and (h), can be seen that Kinect detects the ground instead of the cabinet, which is further away. It can also be seen in experimental case 4 (Figure 6.5), that in the left side of the table, it is detecting the ground. For this application it is not relevant since the ground will not be considered an obstacle.

6.1.2 Obstacle Detection

The obstacle detection in the experimental cases shown in Figures 6.2, 6.3, 6.4 and 6.5 is qualitatively defined as successful. The closest points in each of the defined 5 vertical sections, for each experimental case are shown in Table 6.1.

Table 6.1: Closest points

	Vertical section distances (m)				
Experimental Case	A	B	C	D	E
1	1.21	1.02	0.80	0.69	0.63
2	1.43	0.91	0.57	0.56	0.84
3	1.21	1.35	1.25	1.24	1.55
4	0.87	0.89	0.94	0.96	1.05

These values can be confirmed with the help of the gradient colors of the outline of the obstacles, where the warmer the color is, the closer the object is, and vice versa.

Analyzing the vertical section distances for each experimental case (except vertical sections A and E, since obstacles in those sections don't put the user's safety at risk), we can conclude that:

- In experimental case 1, 1 section is detecting close obstacles that may come in the way of the MAR (section D - more weight to the right).
- In experimental case 2, there are 2 sections detecting actual obstacles that are compromising the user's safety (section C and D - more weight to the right).

- In experimental case 3, none of the sections are occupied with an obstacle or potential obstacles.
- In experimental case 4, 1 probable obstacle was found in section B (more weight to the left).

This algorithm can also successfully detect and react to moving parts (e. g. people) in real-time if they walk in front of the MAR (across the user's trajectory).

6.2 Collaborative Control

6.2.1 Risk Assessment and Reactive Collision Avoidance

To ensure the functionality of the ANS, the risk assessment and reactive collision avoidance were both tested in the scenario illustrated in section 6.1.1. The commands outputted to the robot vary according to the experimental case and according to the user's input on the MAR. A general performance of the algorithm can be seen in Table 6.2 and the results of a real experiment can be seen in Tables 6.4 and 6.4.

Table 6.2: General Performance Table

		Type of behavior	
Experimental Case	Risk Assessment	Moving against the obstacle	Moving away from the obstacle
1	High risk	Maximum linear velocity varies with half the distance from the closest obstacle ($\max v\,(t) = \frac{0{,}69}{4}$ m/s)	Maximum linear velocity varies with the distance from the closest obstacle ($\max v\,(t) = \frac{0{,}69}{3}$ m/s)
		Increase angular velocity (angular velocity $+= \frac{\Pi}{8}$ m/s)	Increase angular velocity (angular velocity $+= \frac{\Pi}{10}$ m/s)
2	Imminent danger	Stop the MAR (linear velocity = 0 m/s)	
		Turn the MAR in the opposite direction of the obstacle (angular velocity $= \frac{\Pi}{8}$ m/s)	
3	No risk	Limit maximum linear velocity to 0.5 m/s	
4	Medium risk	Maximum linear velocity varies with the distance from the closest obstacle ($\max v\,(t) = \frac{0{,}89}{3}$ m/s)	Maximum linear velocity varies with twice the distance from the closest obstacle ($\max v\,(t) = \frac{0{,}89}{2}$ m/s)

Experimental Case 1: This is considered a high risk situation, since the closest obstacle is between 0.6 and 0.75 meters away. The maximum linear velocity is very limited to ensure that the user doesn't approach the obstacles too fast. It varies with the quarter of the distance from the closest obstacle, when the user is moving towards the obstacle ($w \leq 0$) and varies with the third of the distance (less limited than the other case), if the user is trying to move away from the obstacle ($w > 0$). When this high risk situation is reached, the user is assisted by the machine, which increases the angular velocity by$\frac{\Pi}{8}$ or $\frac{\Pi}{10}$, if the it is moving towards or away from the obstacles, respectively. This is a shared control situation.

Experimental Case 2: The closest obstacle is putting the user's safety at risk, so this is an imminent danger situation. The user will lose the control over the MAR immediately and the linear velocity will be reduced to 0 m/s (the MAR is stopped). The angular velocity will be equal to $\frac{\Pi}{8}$ m/s (rotating in the direction that has less obstacles - less weight). This is a traded control situation, where the Collaborative Controller decided that the control lies on the machine side completely.

Experimental Case 3: In this case, the user isn't facing any safety issue while navigating the MAR, since there aren't any potential obstacles on the way. The only limitation that the reactive navigation imposes, is to limit the maximum linear velocity to 0.5 m/s, which has been proven to be a safe and ideal navigation velocity. This is a traded control situation just like in experimental case 2, but this time the Collaborative Controller gives the full control of the MAR to the user.

Experimental Case 4: This is considered a medium risk situation, since the closest obstacle is located between 0.75 and 0.9 meters away from the MAR. The maximum linear velocity is limited for precaution. It varies with the third of the distance from the closest obstacle, if the user is moving against the obstacle ($w \geq 0$) and with half the distance (less limited than the other case), if the user is moving away from the obstacle ($w < 0$). The algorithm doesn't affect the angular velocity since this is a medium risk situation and the user can still deviate from the obstacles by himself. This is a shared control situation.

Table 6.3: Real Experiment Performance Table - Experimental cases 1 and 2

Experimental Case	User's behavior	v_{User} (m/s)	w_{User} (rad/s)	v_{MAR} (m/s)	w_{MAR} (rad/s)
1	Moving against obstacle	0.15	0	0.15	$\frac{\Pi}{8}$
	Moving against obstacle	0.30	$-\frac{\Pi}{8}$	0.173	$\frac{\Pi}{8}$
	Moving away from the obstacle	0.50	$\frac{\Pi}{8}$	0.23	$\frac{\Pi}{10}$
2	Moving against obstacle	0.15	0	0	$\frac{\Pi}{8}$
	Moving against obstacle	0.30	$-\frac{\Pi}{8}$	0	$\frac{\Pi}{8}$
	Moving away from the obstacle	0.50	$\frac{\Pi}{8}$	0	$\frac{\Pi}{8}$

Experimental Case 1: Since the closest obstacle is 0.69 meters away, the maximum linear velocity was limited to 0.23 m/s. In the third case, the user applied a linear velocity superior than allowed, so the reactive navigation limited it. In the first and second case, the user was going against the obstacles, since there were obstacles found in front and to the left of the MAR. In these cases the maximum linear velocity was limited to 0.173 m/s, more limited than the first case. In those 3 situations, since this was a high risk situation, the Collaborative Controller helped the user maneuvering the MAR by incrementing the angular velocity by $\frac{\Pi}{10}$ if the user was moving away from the obstacle and by $\frac{\Pi}{8}$ if it was moving towards.

Experimental Case 2: In this experimental case, the obstacle putting the user's safety at risk was 0.56 meters away. No matter what the angular or linear velocity from the user was, the Collaborative Controller gave full control over the MAR to the machine. The MAR was stopped and rotated in the opposite side of the obstacles by being applied an angular velocity of $\frac{\Pi}{8}$.

Table 6.4: Real Experiment Performance Table - Experimental cases 3 and 4

Experimental Case	User's behavior	v_{User} (m/s)	w_{User} (rad/s)	v_{MAR} (m/s)	w_{MAR} (rad/s)
3	No obstacles - moving freely	0.80	0	0.50	0
	No obstacles - moving freely	0.30	$\frac{\Pi}{8}$	0.30	$\frac{\Pi}{8}$
	No obstacles - moving freely	0.15	$-\frac{\Pi}{8}$	0.15	$-\frac{\Pi}{8}$
4	Moving against obstacle	0.15	0	0.15	0
	Moving against obstacle	0.30	$\frac{\Pi}{8}$	0.297	$\frac{\Pi}{8}$
	Moving away from the obstacle	0.50	$-\frac{\Pi}{8}$	0.445	$-\frac{\Pi}{8}$

Experimental Case 3: The only limitation imposed by the reactive navigation was to limit the maximum linear velocity to 0.5 m/s. In the first situation, the linear velocity was limited since the user was sending a linear velocity of 0.80 m/s to the MAR. In the other two situations, there was no need to limit the linear velocity. Since there were no obstacles in the way, the angular velocity imposed by the user wasn't limited or adjusted in any of these three situations.

Experimental Case 4: The closest obstacle was 0.89 meters away from the MAR. The Collaborative Controller allowed the user to rotate the MAR according to its will, since this wasn't a high risk situation yet. In cases one and two, the user is considered to be going against the obstacles (when going to the left or in front, since it is the direction of the obstacles), so the linear velocity was limited to 0.297 m/s, being more restrained than when the user was going in a safe direction. In the last case the user was moving away from the obstacles, but had the linear velocity limited, since it was above the 0.445 m/s or less limit.

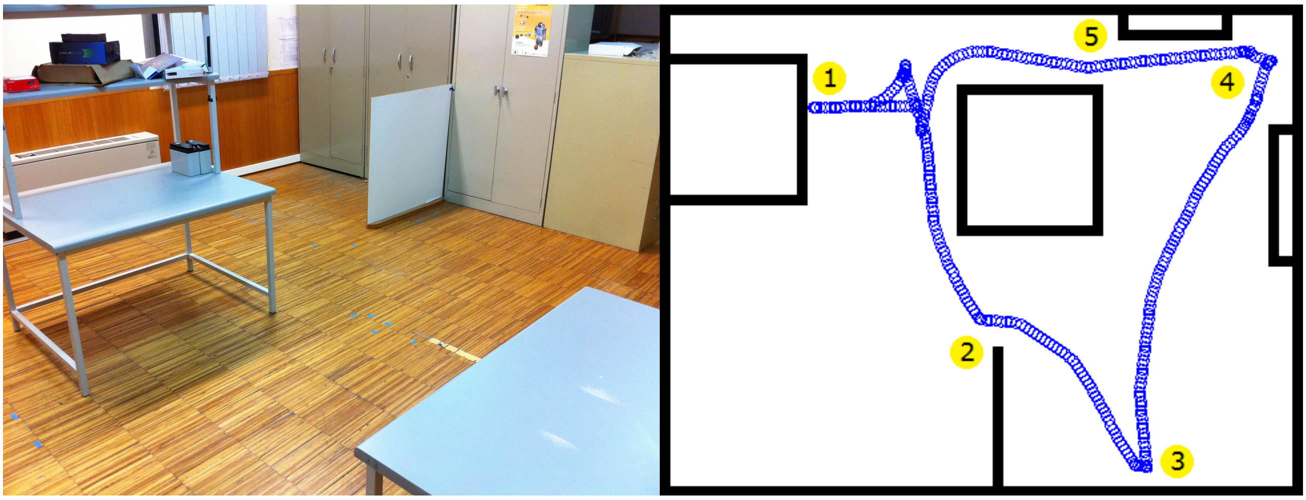

Figure 6.6: Test scenario in ISR (left) and MAR navigation trajectory (right)

In Figure 6.6 it is possible to see a trajectory done by the MAR (right) in a real test scenario in ISR (left). In this experiment, several key situations are highlighted:

Situation 1: In this situation, the user successfully approached the table. The MAR identified it as a safe situation since this obstacle had the features of a table and therefore, it did not intervene.

Situation 2, 3 and 4: The user tried to approach obstacles and the MAR successfully avoided them. Because the user was quickly navigating towards the obstacles, the traded control was activated almost immediately in order to prevent a collision. The user lost all control over the MAR.

Situation 5: Shared control was activated in this situation since the user tried to approach the side of a table. Because the user was navigating slower than in the previous situations, traded control wasn't activated since the shared controller commands were able to deviate the MAR in time, avoiding a collision with the obstacle.

This system was tested both in simulated environment conditions and in real conditions. Comparing the results presented in Figure 6.6, Table 6.4 with the expected general performance of the algorithm, we can see that the system is functional and that the collaborative controller fulfilled its role in the ANS.

Chapter 7

Conclusion and future work

7.1 Conclusion

In this dissertation, a characterization of mobility, accessibility and lack of safe mobility solutions for individuals with severe motor impairment such as users suffering from CP was performed. With this research we were able to identify the needs in these fields, in order to later develop strategies accordingly. The lack of safety and the difficulty in navigating the PW were the most limiting factors, in general, and also the most suggested to be improved. This results validate the need to design and develop more suitable solutions, in order to assist individuals with disabling conditions that need their mobility, accessibility and safety improved.

In this work, a SAANS composed by Local Perception (Multi-level 2.5D data processing and Obstacle Detection) and Collaborative Control modules (Risk Assessment and Reactive Collision Avoidance), fully integrated in ROS, was designed and implemented. This system will assist the user maneuvering the MAR to improve safety and make navigation easier.

The proposed SAANS is modular and versatile, which allows an easy integration of new modules and functionalities in the global architecture. It is a real functioning system that is currently showing promising results. It proved to be reliable during all the performed tests carried out during the course of this dissertation.

The Kinect may be used as sensor for environment perception in some situations. However, in crowded environments (populated with many obstacles), one must not solely rely on Kinect since it is blind at distances inferior to 0.5 meters.

Regarding the goals initially proposed in this dissertation, it is possible to conclude that:

- it was done a characterization of mobility, accessibility and lack of safe mobility solutions for individuals with CP;
- a system architecture and the appropriate information flow were successfully developed;
- the 3D Kinect data was transformed into multi-level horizontal 2D scans used for perceiving the environment;
- the safety of MAR users was ensured with the help of an obstacle avoidance algorithm;
- the navigation of the MAR was successfully assisted through CC;
- tests were performed validating the proposed ANS.

7.2 Future work

In the future, the SAANS should be tested by individuals with severe motor impairment.

In order to improve the perception system, short range sensors, like laser scanners or sonars, may be added. This would solve Kinect's blind zone at short distances. Also, a path suggestion module can be added, based on the analysis of the probability of occupation and on the analysis of the entropy (a measure of uncertainty), that suggest the freest path (safest direction) that the user should follow.

To continue this work, the remaining issues pointed by the PW users can be solved, possibly by implementing the desired wheelchair improvements.

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Appendix

Appendix A

Mobility, Accessibility and Safety of People with Cerebral Palsy

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Keywords: Cerebral Palsy, Mobility, Accessibility, Safety, Powered Wheelchair, Improvement, Assistive Navigation.

Abstract: This research characterizes mobility, accessibility and lack of safe mobility solutions for individuals with severe motor impairment such as users suffering from Cerebral Palsy (CP) into specific groups, as well as some enabling factors, constraints associated and the search of possible improvements, in order to identify the needs in these fields and subsequently develop strategies accordingly. The sample was collected in Coimbra Cerebral Palsy Association (APCC) and it included 16 individuals with CP. To these individuals we gave an evaluation protocol with a form with clinical and sociodemographic data and a questionnaire. The main limiting factors include building/vehicle access, difficulty in reverse drive and lack of safety. The most valued features of a powered wheelchair are comfort and structure, easy navigation and wheelchair control and safety. The lack of safety in the outdoors was a relevant limiting factor. Almost all of the individuals wanted to improve the powered wheelchair. The most requested improvements were safety related or related with navigation problems. An assistive navigation solution based on a shared control algorithm is presented, where a powered wheelchair is equipped with the Kinect sensor, in order to help the user maneuvering the wheelchair safely.

1 INTRODUCTION

Cerebral palsy (CP) is a complex medical and non-progressive condition, that is characterized by cognitive and motor disturbances, and it is a consequence of the damage of specific brain areas caused before, during or shortly after birth (Koman et al., 2003). According to the data obtained from the National Health Interview Survey from 1988 (Health Statistics and Health & Human Services, 1988), CP appears as the most disabling clinical situation, involving the largest number of annual medical contacts and also the largest number of hospital admissions during the year.

CP is also the most common disability in childhood and the trend is to increase its prevalence over the last decades (Vargus-Adams, 2003). Due to accessibility and quality improvement of medical care provided to individuals with CP, the average life expectancy for this group has increased significantly. Therefore, before 1950 few people with CP survived until adulthood and now is expected that 65% to 90% of children with CP can live past adulthood (Zaffuto-Sforza, 2005). However, despite the increasing prevalence of CP, the medical innovation and development, observed in the 1970s and 1980s, contributed to a significant increase in average life expectancy, which boosted the research to understand how the CP can affect the quality of life (QOL) of these individuals, including their levels of mobility and participation (Kennes et al., 2002; Wake et al., 2003).

Research results show that children with CP have a more impaired QOL in all domains when compared with other able-body children (Vargus-Adams, 2003; Varni et al., 2007), but another study concludes that the QOL of this group is only lower in the physical domain and not in the psychological and social domains (Dickinson et al., 2007). The QOL of adults with CP is significantly affected in all domains assessed by The World Health Organization Quality of Life (WHOQOL-BREF): Physical, Psychological, Social Relationships and Environment (Carona et al., 2010). More specifically, when compared to other able-body adults, they reported a lower QOL in the physical domain (mobility) and in the environment domain (participation and/or opportunities for recreation and leisure and transportation).

This research aims to study new technologies that can contribute to the mobility, accessibility and safety improvement of individuals with CP. With this study we aim to be able to provide results to support the design and development of more suitable solutions to improve mobility, accessibility and safety.

With the overall goal to characterize all three factors referred above, this research work was organized as follows: (1) Characterization of subject's mobility, public transportation use and Human-Machine Interface (HMI); (2) Relation between HMIs and powered wheelchair time of use and the quality of performance; (3) Identification of most valued features and limiting factors in the use the powered wheelchair; (4) Analysis of possible solutions to be implemented in a powered wheelchair.

Further in this paper, we will see that the lack of safety and the difficulty in navigating the powered wheelchair were generally pointed out as the most limiting factors, which means there is the need to develop more suitable solutions to improve navigation and safety.

A solution to address both of these problems is to install more sensors in the powered wheelchair, providing additional information of the environment and to introduce a new navigation system based on a shared controller that shares the information of the user and the machine. In our case, we decided that the Kinect, a sensor that provides 3D information of the environment, had certain features that made it an interesting and useful device to use:

- It is a compact and lightweight sensor which provides both RGB and range images;
- It gathers 3D information of the powered wheelchair's surrounding from a three-dimensional field-of view;
- It is a low cost solution (around 150 €);
- It works at a frequency of 30 Hz;
- Operation range acceptable for indoor environments: from 0.6 to 3.5m.

The use of Kinect to feed a reactive navigator based on a 2D space representation presents two difficulties: (a) the huge amount of data it provides and (b) the existence of a blind zone both at short distance and because of the narrow horizontal field-of-view (in comparison to laser radial scanners) (Gonzalez-Jimenez et al., 2013). We will present solutions to overcome these difficulties in Section 4.

The current research was based on the work done previously under the research project Interface10 - Emergent Interfaces for Improving Accessibility of Persons with Cerebral Palsy (Carona et al., 2012).

2 APPROACH / METHODOLOGY

2.1 Participants

The sample for this study included 16 individuals and was collected at APCC, between December 2013 and March 2014, based on the following inclusion criteria: (1) clinical diagnosis of CP; (2) ability to understand questions and provide answers accordingly; (3) use of a powered wheelchair; (4) minimum age of 15 years.

After obtaining APCC's formal authorization, participants were selected by their teams of clinical follow-up, based on the inclusion criteria listed above. Before filling out the questionnaires, all participants gave informed consent.

2.2 Tools

The evaluation protocol of this study was composed of the following tools:

1. Clinical and sociodemographic data form: questionnaire filled out jointly by the researcher and the technician responsible for monitoring the subject, which contains the following information: age, gender, type of CP and associated problems;
2. Gross Motor Function Classification System for Cerebral Palsy - GMFCS-CP (Palisano et al., 1997): grading scale of the degree of impairment, structured in five levels, in which the Level 1 is the lowest and level 5 the highest. The grading is based on functional limitations, the need of use of mobility aids or wheelchairs and also on the quality of movement. Level 1 and 2 are for manual wheelchair users. Since in this research we are studying powered wheelchair users, we are only interested in level 3, 4 and 5. Level 3 is for individuals that need to use a powered wheelchair in more complicated places, but for short distances or in easier places to navigate, a manual wheelchair will be enough to ensure their mobility. Level 4 is for users that can only get their autonomous mobility with the help of a powered wheelchair. Level 5 is for users whose mobility is seriously compromised. Physical problems limit voluntary control of the movements and the control of the head and trunk. Even with the use of a powered wheelchair, they have mobility problems;
3. Questionnaire for mobility, accessibility and safety characterization: questionnaire filled out by the subject or with the researcher's help, with multiple choice questions, organized into four parts which will be analyzed further ahead: (1) characterization of (a) subject's mobility, (b) use of public transportation and (c) HMIs; (2) characterization of the use of assistive

mobility technologies; (3) most valued features and limiting factors in the use of the powered wheelchair; (4) possible solutions to be implemented in the powered wheelchair for its improvement.

3 RESULTS

3.1 Sample characterization

In Table 1 we can see the clinical and sociodemographic characterization of the sample.

Table 1: Clinical and sociodemographic data

Age (M)	29,80
Gender (n/%)	
Female	3/18,75
Male	13/81,25
Type of Cerebral Palsy (n/%)	
Spastic	11/68,75
Dystonic	4/25,00
Ataxic	1/6,25
Additional associated Problems (n/%)	
No additional associated problems	6/37,50
Visual problems	5/31,25
Epilepsy	2/12,50
Intellectual problems	2/12,50
Hearing problems	2/12,50
Degree of Impairment (GMFCS-CP) (n/%)	
Level III	2/12,50
Level IV	11/68,75
Level V	3/18,75

The collected sample (n = 16) had an average age of 29,80. The most observed type of CP was spastic (68,75%), followed by dystonic (25,00%) and ataxic (6,25%). Analyzing other health problems associated with CP (besides motor impairment), 37,50% of the cases do not present any additional associated problems, although 31,25% experience visual deficits, 12,50% intellectual deficits, 12,50% epilepsy and 12,50% hearing deficits. According to the inclusion criteria associated with the use of an assistive technology to improve mobility, most individuals (68,75%) are level 4 in the grading scale of the degree of impairment, 18,75% of the individuals are level 5 and the rest (12,50%) of the subjects are level 3.

3.2 Characterization of accessibility, mobility and support

Almost all individuals with CP (93,75%) reported being able to move autonomously with the help of a powered wheelchair. The number of individuals who reported not using public transportation (although they wanted to) is very high (87,50%). This somehow reflects the inadequacy in the access to public transportation, in which individuals with CP are particularly vulnerable. Finally, a relatively small percentage (25,00%) of people in the group of subjects need HMIs for computer use. These results can be verified in Table 2.

Table 2: Characterization of accessibility, mobility and support.

	Yes (n/%)	No (n/%)
Do you have the possibility of moving autonomously with the powered wheelchair?	15/93,75	1/6,25
Do you use public transportation?	2/12,50	14/87,50
Do you use HMIs for computer use?	4/25,00	12/75,00

3.3 Time of use of HMIs and powered wheelchair vs quality of performance

All subjects participating in this study were considered experienced users steering a powered wheelchair since they have several years of experience using it.

Table 3: Level of performance with the HMIs.

HMIs for powered wheelchair navigation (n/%)	
Joystick	13/81,25
Pedal Technology	1/6,25
Head interface with sensors	1/6,25
Chin Technology	1/6,25
Level of performance with HMIs for powered wheelchair navigation (n/%)	
Level 3	3/18,75
Level 4	3/18,75
Level 5	10/62,50
HMIs for computer use (n/%)	
Chin Pointer	2/50,00
Pedal Technology	1/25,00
SmartNav - Infrared Technology	1/25,00
Missing=12 (n=4)	
Level of performance with HMIs for computer use (n/%)	
Level 5	4/100,00
Missing=12 (n=4)	

Analyzing Table 3, it is possible to see that all the users of HMIs for computer use and most individuals (62,50%) using the HMIs required for steering the powered wheelchair, considered themselves in a level 5 of performance.

Most of the subjects (81,25%) in this research use a joystick to help the navigation of the powered wheelchair.

Table 4: Level of performance steering the powered wheelchair.

Level of steering performance in the powered wheelchair (n/%)	
Level 3	3/18,75
Level 4	7/43,75
Level 5	6/37,50

Analyzing Table 4 is possible to see that many of these users (43,75%) were classified as level 4 in terms of steering performance of the powered wheelchair and also, that a significant percentage (37,50%) were classified as level 5.

3.4 Most valued features and limiting factors in the use of assistive technologies for mobility

Table 5: Most valued features and limiting factors in a powered wheelchair.

Most valued features in a wheelchair	Frequency (n/%)
Comfort/Positioning	11/68,75
Easy navigation and wheelchair control	9/56,25
Safety	7/43,75
Dimension	2/12,50
Not specified	2/12,50
Limiting factors of powered wheelchair use	**Frequency (n/%)**
Difficulty in reverse drive	6/37,50
Building/vehicle access	5/31,25
Mechanical aspects	3/18,75
Dimension	3/18,75
Safety	2/12,50
Design	1/6,25
Complicated interfaces	1/6,25
Control and navigation of the wheelchair	1/6,25
Impractical belt	1/6,25
Not specified	3/18,75

In Table 5 we can see that the most valued features of a powered wheelchair are its comfort and structure (68,75%), easy navigation and wheelchair control (56,25%) and finally, safety (43,75%). The main limiting factors in a powered wheelchair are the difficulty in reverse drive (37,50%) and building/vehicle access (31,25%). Also 12,50% of the individuals complained about the lack of safety.

Table 6: Limiting factors in the use of assistive technologies for mobility.

Limiting factors of the powered wheelchair use at home	Frequency (n/%)
Architectural barriers	12/75,00
Reverse drive	3/18,75
Strain caused by the powered wheelchair use	2/12,50
Fatigue	1/6,25
Powered wheelchair inadequacy	1/6,25
No limitation	2/12,50
Limiting factors of the outdoor access	
Architectural barriers	14/87,50
Safety	5/31,25
Strain caused by the powered wheelchair use	1/6,25
Fatigue	1/6,25
No limitation	1/6,25
Limiting factors in the private transportation use	
Powered wheelchair inadequacy	12/75,00
Vehicle limitation	5/31,25
Vehicle adaptation costs	4/25,00
Difficulty placing the powered wheelchair in the vehicle	3/18,75
No limitation	2/12,50
Limiting factors in the public transportation use	
Complexity of the usage	2/100,00
Shortage of transportation	2/100,00
Missing=14 (n=2)	

The architectural barriers were identified as the main factor limiting the powered wheelchair use at home (75,00%) and in the outdoors (87,50%). Another relevant limiting factor is again the difficulty in reverse drive at home (18,75%) and lack of safety in public places (31,25%).

The powered wheelchair inadequacy (75,00%), the limitations of the vehicles (31,25%) and the vehicle adaptation costs (25,00%) on one hand, and the lack of adapted transports and complexity of its use (both referred by all the public transportation users), on the other hand, were the main limiting factors mentioned for the use of private and public transportation, respectively.

The results above can be seen in Table 6.

We were able to get a perception of the mobility and accessibility difficulties and also concluded that many of the complaints were related with the lack of safety and how relevant this issue is or related with the lack of an appropriate assistive navigation system to help maneuvering the powered wheelchair.

3.5 Possible improvements to be implemented in the powered wheelchair

Since one of the goals of this research is to help improve the QOL of people with CP, the subjects of this study were asked if their powered wheelchair could be improved in any way, and almost all of them answered positively (93,75%), as seen in Table 7.

Table 7: Powered wheelchair improvement.

	Yes (n/%)	No (n/%)
The powered wheelchair can be improved in any way?	15/93,75	1/6,25

In Table 8 is possible to see the most requested improvements: aid for reverse drive (40,00%), collision avoidance (26,67%), a warning during reverse driving (26,67%), reverse driving information (26,67%), comfort/structure improvement (20,00%), assistance in navigation in more complicated places (13,33%).

Table 8: Most requested powered wheelchair improvements.

Possible improvements	Frequency (n/%)
Aid for reverse drive	6/40,00
Collision avoidance	4/26,67
Warning during reverse driving	4/26,67
Reverse driving information	4/26,67
Comfort/structure improvement	3/20,00
Assistance in navigation in more complicated places	2/13,33
Missing=1 (n=15)	

Table 9 shows the least requested powered wheelchair improvements.

With the results mentioned in Table 8, we can conclude that most of the suggested improvements (57,14%) affect safety and could be solved by installing more sensors in the powered wheelchair and by introducing a new navigation system.

Table 9: Least requested powered wheelchair improvements.

Possible improvements	Frequency (n/%)
Wheelchair that lifts	1/6,67
Rear camera/mirror	1/6,67
Wheelchair that lies down	1/6,67
Retracting pedal	1/6,67
Bumper (soften ball impact in football)	1/6,67
Chance of driving the wheelchair vertically	1/6,67
Flashers	1/6,67
Autonomous wheelchair	1/6,67
Wheelchair with lights	1/6,67
Buttons design improvement	1/6,67
Improvement of speed control with the joystick	1/6,67
Missing=1 (n=15)	

4 TECHNICAL PROPOSAL OF SAFETY SYSTEM

A solution to the problems identified in the previous section, as well as the implementation of some of the suggestions for the powered wheelchair improvements, will be presented in this section. The block diagram of the system's architecture is illustrated in Figure 1. Each block is described in the following subsections.

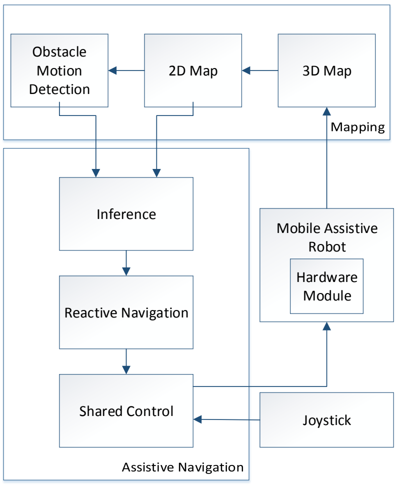

Figure 1: Block diagram of the system's architecture.

For the navigation of Mobile Assistive Robot (MAR), there is the need to develop a model of the environment. The installation of a Kinect sensor in the

MAR will provide additional information of the surroundings. Through the analysis of the Kinect data and the analysis of the data provided by the Obstacle Motion Detection block, it is possible to assist in the navigation of the MAR. A set of rules is defined which will, along with the information previously obtained, affect the reactive navigation of the MAR. The new navigation system is based on shared control in which the machine will share the control of the wheelchair with the user.

4.1 Mapping

The Mapping container includes the 3D Map block, where the Kinect scans the environment and returns the depth ranges. In the 2D Map block, 3D Kinect data is transformed into 2D scans. The Obstacle Motion Detection block is capable of finding the dynamic regions of the environment. It detects moving parts rapidly. All of this works in real time.

4.1.1 3D Mapping

In Figure 2 we can see the RGB image (left) obtained from the Kinect's RGB camera and the depth image (right) obtained through the infrared sensors of the Kinect. The RGB image is displayed only for the purpose of showing the view of the Kinect Sensor on the robot and the depth image helps to understand the depth of the obstacles. Note that the darker the pixels, the nearer the object is. The white pixels represent invalid data because they are out of the Kinect's valid range, shadow, reflection or transparency problem. It can be seen that some surfaces have dark pixels. This happens due to the reflectance of those surfaces.

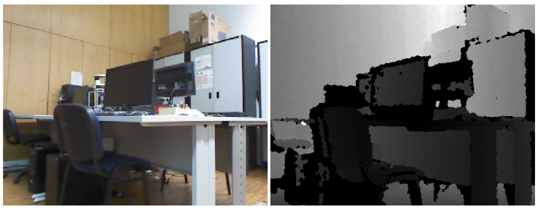

Figure 2: Kinect's RGB image (left) and depth image (right).

4.1.2 2D Mapping

Our solution to overcome the intense flow of data provided by Kinect is to condense the 3D Kinect data into a 2D scan by selecting the minimum measured distance in each column of of the Z-array (depth pixel), as can be seen in equation 1. The minimum distance was selected such that

$$Z' = min(Z_{0,j}, Z_{1,j}, \ldots, Z_{479,j}) \qquad (1)$$

where j is the respective column number (Rockey, 2013). The Y locations for the corresponding Z-elements were provide a 480x1 array, while the X locations provide a 640x1 array. These two arrays indicate the 2D obstacle locations (Z and X coordinates) as obtained when using a laser scanner. Also note that the Y coordinate was ignored as the robot can only move in X and Z direction. The arrays have already represented the nearest obstacle locations no matter where their vertical positions are, since the Kinect vertical field-of-view covers obstacles of the same height as the MAR.

The comparison of the 2D scan obtained with the method explained above with the pointcloud from Kinect is shown in Figure 3.

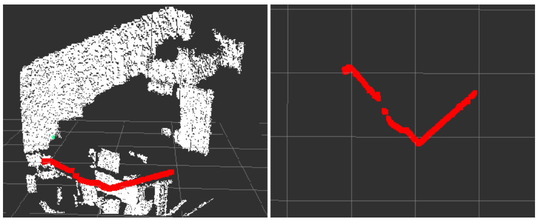

Figure 3: 3D Kinect data mixed with 2D scan (left) and 2D scan seen from above (right).

4.1.3 Obstacle Motion Detection

The MAR should be able to respond correctly in a dynamic environment. The Obstacle Motion Detection block will help in this task. Since the MAR undergoes a position and rotation change, the motion detection module requires internal information from the vehicle. The Inertial Measurement Unit (IMU) is used for this propose, which provides velocity and orientation of the MAR at time t. The information provided by IMU is used to find transformation to match the corresponding regions between map t and map t-1. The pose estimation between two maps may not be exact but the error does not accumulate over time because only two consecutive maps are considered. Any significant change between two consecutive maps (t and t-1) signifies a moving object. Subtraction process is applied to provide moving objects. This process is still under development and can be seen in Figure 4.

4.2 Assistive Navigation

The Assistive Navigation container includes the Inference block, Reactive Navigation block and the Shared Control Block. The information obtained from the 2D

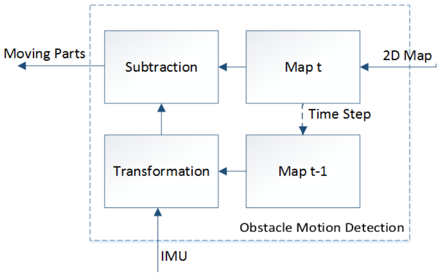

Figure 4: Obstacle Motion Detection block architecture.

Map block along with the information from the Obstacle Motion Detection and the set of rules defined in the Inference block, will affect the reactive navigation of the MAR. In the Reactive Navigation block is where decisions are made for the MAR navigation.

To improve safety and at the same time provide assistance when navigating the MAR in more complicated places while avoiding collisions, we developed a shared control based algorithm. In this algorithm, we considered that the MAR is about to collide with an obstacle when they are less than 0.6 meters away. Obstacles located between 0.6 and 0.9 meters from the MAR are considered potential obstacles that can come in the way of the trajectory. The shared controller allows the user to freely steer the MAR unless it is in danger of colliding with an obstacle, in which case, the shared control is activated.

The Shared Control block will receive the user's commands from the Joystick and it is where is decided which commands to follow, the MAR commands or the user's. This decision is communicated to the Hardware Module that is located in the MAR block. This cycle will repeat itself continuously.

The MAR lets its user navigate freely when:

- there are no obstacles near the MAR;

- the user is moving towards a potential obstacle, but it isn't yet at risk of collision, which means that there is still room for the user to change the MAR trajectory;

- a potential obstacle is located, and the user is having the correct behavior, moving away from the obstacle (there is no limitation, except for the maximum velocity attainable which is limited for safety reasons).

The assistive navigation will intervene when:

- the user is navigating the MAR in the direction of the obstacle. In this case the shared control is activated, in which the MAR will turn in the opposite direction;

- the user is trying to deviate from the obstacle, but although it is on the right direction, isn't turning enough to avoid the collision. In this case the assistive navigation will offset the turning angle, helping in the maneuver;

- the user is at risk of collision. The assistive navigation will stop the MAR, and turn to the opposite side of the obstacle.

To help guide the users during the navigation, we use entropy values of the surrounding environment to analyze the user's behavior. The user will receive real-time information of the obstacles in the environment in a 1.5 meter distance of the MAR. The algorithm will inform the user if he's having a less correct behavior by going to a more complicated place to navigate the MAR and will also suggest a better behavior. If the user is going in a more crowded space (higher probability of occupancy), the value of the entropy will be higher as well. These values should ideally be as close to zero as possible. This human-robot interaction is an important feature to be implemented in the MAR, and is still being developed.

With this solution, the user's safety is improved as well as the MAR navigation. This solution can also solve other referred problems, such as the difficulty in reverse drive and the lack of information while moving backwards. Placing the Kinect in the back of the MAR and applying the same algorithm, the MAR can provide assistance in reverse drive and at the same time provide information and suggest the best direction to follow.

5 CONCLUSIONS AND FUTURE WORK

The main goals of this study were the characterization of mobility, accessibility and safety in a group of individuals with CP and to find possible improvements to be implemented in the powered wheelchairs.

The results suggest that the time of use of the powered wheelchair can be a decisive factor for a good level of performance. Since in this research work, the subjects were all adults with a good level of expertise driving the powered wheelchair, where the level of performance in which more individuals are in is level 4 and almost as many are in level 5, this means that this is close to the best case scenario. Younger powered wheelchair users can have increased troubles driving the powered wheelchair due to the lack of experience, therefore contributing to a more complex navigation and compromised safety.

Combining these results with the suggested improvements to implement in the powered wheelchairs, we concluded that the lack of safety and the difficulty in navigating the powered wheelchair were the most limiting factors, in general, and also the most suggested (57,14%) to be improved.

Future work can be adding short range sensors for close distances and also solving the remaining issues pointed by the powered wheelchair users, possibly by implementing the desired wheelchair improvements. Getting a larger sample could point us toward future research directions. After solving the problems pointed out in the present research, it is possible to continue the research by looking for new ways to improve the powered wheelchairs.

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