



**HAL**  
open science

# Solutions robotiques bas coût pour l'aide à la navigation en fauteuil roulant électrique : vers une contribution dans le champ de la rééducation neurologique

Louise Devigne

## ► To cite this version:

Louise Devigne. Solutions robotiques bas coût pour l'aide à la navigation en fauteuil roulant électrique : vers une contribution dans le champ de la rééducation neurologique. Ordinateur et société [cs.CY]. INSA de Rennes, 2018. Français. NNT : 2018ISAR0024 . tel-02122535

**HAL Id: tel-02122535**

**<https://theses.hal.science/tel-02122535>**

Submitted on 7 May 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# THESE DE DOCTORAT DE

L'INSTITUT NATIONAL DES SCIENCES

APPLIQUEES RENNES

COMUE UNIVERSITE BRETAGNE LOIRE

ECOLE DOCTORALE N° 601

*Mathématiques et Sciences et Technologies  
de l'Information et de la Communication*

Spécialité : Informatique

Par

**Louise DEVIGNE**

**Low-cost robotic solutions for safe assisted power wheelchair  
navigation: towards a contribution to neurological rehabilitation**

Thèse présentée et soutenue à « Rennes », le « 06 décembre 2018 »

Unité de recherche : Laboratoire IRISA UMR6074

Thèse N° : 18ISAR 33 / D18 - 33

## Composition du Jury :

Président :	Guy Bourhis	Professeur des Universités, LCOMS, Université de Lorraine
Examineurs :	Tom Carlson Olivier Remy-Neris	Associate professor, Aspire CREATE, University College of London Professeur des Universités Praticien Hospitalier, CHU de Brest
Rapporteurs :	El Mustapha Mouaddib Rachid Alami	Professeur des Universités, MIS, Université de Picardie Jules Verne Directeur de recherche, LAAS, CNRS
Dir. de thèse :	Marie Babel	Maître de conférences HDR, IRISA UMR6074, INSA Rennes
Co-dir. de thèse :	Philippe Gallien	Médecin médecine physique et réadaptation HDR, Pôle Saint Hélier

**Intitulé de la thèse :**

Solutions robotiques bas coût pour l'aide à la navigation en fauteuil roulant électrique : vers une contribution dans le champ de la rééducation neurologique

**Louise DEVIGNE**

**En partenariat avec :**

				
---	---	--	--	--

*Document protégé par les droits d'auteur*





# Contents

<b>Table of contents</b>	<b>1</b>
<b>1 Introduction: Clinical and social motivations</b>	<b>17</b>
1.1 Introduction . . . . .	17
1.2 Powered mobility clinical and social perspectives . . . . .	18
1.2.1 Defining disability . . . . .	19
1.2.2 Disability and mobility . . . . .	20
1.2.2.1 Power wheelchair mobility aids . . . . .	20
1.2.2.2 Visual and cognitive functions involved in wheelchair driving . . . . .	21
1.2.2.3 Visual/and or cognitive impairments preventing safe power wheelchair driving . . . . .	23
1.2.3 Motivations for this work . . . . .	24
1.3 Thesis outline . . . . .	24
<b>2 Assisting power wheelchair navigation</b>	<b>27</b>
2.1 Mechanical design solutions . . . . .	27
2.2 Smart power wheelchair solutions . . . . .	28
2.2.1 Sensing . . . . .	29
2.2.1.1 Vision sensors . . . . .	29
2.2.1.2 Laser rangefinders . . . . .	30
2.2.1.3 Ultrasonic sensors . . . . .	30
2.2.1.4 Infrared sensors . . . . .	31
2.2.1.5 Which sensor(s) for a smart power wheelchair ? . . . . .	31
2.2.2 Control . . . . .	32
2.2.2.1 Autonomous navigation assistance . . . . .	32
2.2.2.2 Semi-autonomous navigation assistance . . . . .	34
2.3 Smart power wheelchairs requirements . . . . .	35
2.4 Robotics tools for smart power wheelchair design . . . . .	37
2.4.1 Power wheelchair modeling . . . . .	37
2.4.2 Sensor-based modeling . . . . .	38
2.4.3 Sensor-based control . . . . .	39
2.5 Towards user-centered smart powered mobility design . . . . .	39

<b>3</b>	<b>An assisted powered mobility simulator</b>	<b>41</b>
3.1	Why design a powered mobility driving simulator ? . . . . .	41
3.1.1	Virtual reality benefits . . . . .	41
3.1.2	Powered mobility simulation: related work . . . . .	42
3.2	An assisted powered mobility simulator . . . . .	45
3.2.1	Generic driving simulator framework . . . . .	45
3.2.2	Wheelchair driving simulation . . . . .	45
3.2.3	Assisted navigation within the virtual environment . . . . .	46
3.3	Simulator validity assessment . . . . .	47
3.3.1	Study design . . . . .	47
3.3.2	Data collection . . . . .	49
3.3.3	Results . . . . .	50
3.3.3.1	Presence . . . . .	51
3.3.3.2	Perceived Workload . . . . .	51
3.3.3.3	Simulator sickness . . . . .	51
3.3.3.4	Driving assistance . . . . .	51
3.3.4	Discussion . . . . .	52
3.4	Simulator experiential validity assessment . . . . .	54
3.4.1	Assessment protocol . . . . .	54
3.4.1.1	Objectives . . . . .	54
3.4.1.2	Assessed criteria . . . . .	54
3.4.1.3	Population . . . . .	54
3.4.1.4	Driving task . . . . .	55
3.4.1.5	Procedure . . . . .	55
3.4.2	Results . . . . .	57
3.4.3	Discussion . . . . .	57
3.5	Conclusion . . . . .	60
<b>4</b>	<b>Indoor power wheelchair navigation assistance</b>	<b>63</b>
4.1	Generic shared control approach . . . . .	64
4.1.1	Objective . . . . .	64
4.1.2	Modeling . . . . .	64
4.1.2.1	Interaction matrix computation . . . . .	66
4.1.2.2	Practical consideration . . . . .	66
4.1.2.3	Case of frontal and lateral sensors, $\theta_i \in \{0, \frac{\pi}{2}, \pi, -\pi, -\frac{\pi}{2}\}$ . . . . .	67
4.1.2.4	Particular case of corner sensors, $\theta_i \notin \{0, \frac{\pi}{2}, \pi, -\pi, -\frac{\pi}{2}\}$ . . . . .	67
4.2	Autonomous robotic wheelchair control . . . . .	70
4.2.1	Autonomous control framework . . . . .	70
4.2.1.1	Simulation . . . . .	71
4.3	Sensor-based servoing for semi-autonomous navigation . . . . .	72
4.3.1	Semi-autonomous control framework . . . . .	72
4.3.1.1	Computing shared control values . . . . .	74
4.4	Simulations . . . . .	77
4.5	Evaluation and validation with regular power wheelchair users . . . . .	78

4.5.1	Study design . . . . .	80
4.5.1.1	Primary objective . . . . .	80
4.5.1.2	Main assessed criteria . . . . .	80
4.5.1.3	Secondary objective . . . . .	80
4.5.1.4	Secondary assessed criteria . . . . .	80
4.5.1.5	Participants . . . . .	81
4.5.2	Study conduct . . . . .	81
4.5.2.1	Procedure . . . . .	81
4.5.2.2	Practical setup . . . . .	83
4.5.3	Results . . . . .	85
4.5.3.1	Driving circuit condition . . . . .	85
4.5.3.2	Ecological circuit condition . . . . .	85
4.5.3.3	Subjective assessment . . . . .	86
4.5.4	Discussion . . . . .	86
4.6	Conclusion . . . . .	88
<b>5</b>	<b>Navigation assistance for outdoor power wheelchair</b>	<b>89</b>
5.1	Introduction . . . . .	90
5.1.1	Context and motivations . . . . .	90
5.1.2	How to lessen power mobility issues, especially outdoors ? . . . .	90
5.1.3	Related works . . . . .	91
5.1.4	Objective . . . . .	92
5.2	Methods . . . . .	93
5.2.1	How to detect relevant information ? . . . . .	93
5.2.2	Modeling . . . . .	93
5.3	Curbside avoidance method . . . . .	94
5.3.1	Method . . . . .	94
5.3.2	Control method . . . . .	97
5.3.3	Simulations . . . . .	99
5.3.3.1	Simulation framework . . . . .	99
5.3.3.2	Simulation results . . . . .	99
5.4	Experiment . . . . .	100
5.4.1	Experimental setup . . . . .	100
5.4.2	Experiment environment . . . . .	102
5.4.3	Experiment results . . . . .	102
5.4.4	Conclusion . . . . .	103
5.5	Outdoor navigation assistance method . . . . .	104
5.5.1	Modeling . . . . .	105
5.5.2	Detection method and features extraction . . . . .	106
5.5.3	Velocity regulation controller design . . . . .	107
5.5.3.1	Interaction matrix computation . . . . .	107
5.5.3.2	Shared control method . . . . .	107
5.5.4	Simulations . . . . .	109
5.5.4.1	Simulation framework . . . . .	109

5.5.4.2	Simulation results . . . . .	109
5.6	Discussion . . . . .	110
5.7	Conclusion . . . . .	110
<b>6</b>	<b>Augmented experience: a promising tool for rehabilitation</b>	<b>113</b>
6.1	Introduction . . . . .	114
6.1.1	Context and motivations . . . . .	114
6.1.2	Related works and clinical motivations . . . . .	114
6.1.3	Objective . . . . .	115
6.2	Method . . . . .	116
6.2.1	Framework . . . . .	116
6.2.2	Haptic guidance algorithm . . . . .	116
6.3	Simulations . . . . .	117
6.3.1	Simulation conditions . . . . .	118
6.3.2	Simulation results . . . . .	118
6.4	Experiment . . . . .	119
6.4.1	Experimental setup . . . . .	120
6.4.2	Experiment protocol . . . . .	121
6.4.3	Data Collection . . . . .	122
6.4.3.1	Haptic guidance solution data . . . . .	122
6.4.3.2	User feedback . . . . .	122
6.4.4	Experiment results . . . . .	122
6.4.4.1	User performance . . . . .	122
6.4.4.2	User feedback . . . . .	123
6.5	Discussion . . . . .	123
6.6	Conclusion . . . . .	124
	<b>References</b>	<b>147</b>
	<b>List of figures</b>	<b>149</b>

# Thesis related publications

## Journal Articles

**J.1 Louise Devigne**, François Pasteau, Nicolas Le Borgne, Marie Babel, Tom Carlson, Philippe Gallien, Assisting power wheelchair driving on a sidewalk: a proof of concep. In: AMSE, Modelling, Measurement & Control, 2018.

## Refereed Conference Papers

**C.1 Louise Devigne**, Marie Babel, Florian Nouviale, Vishnu Narayanan, François Pasteau, and Philippe Gallien. Design of an immersive simulator for assisted power wheelchair driving. In IEEE Int. Conf. on Rehabilitation Robotics, ICORR'17, 2017.

**C.2 Louise Devigne**, Vishnu K Narayanan, François Pasteau, and Marie Babel. Low complex sensor-based shared control for power wheelchair navigation. In Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on, pages 5434-5439. IEEE, 2016.

**C.3 Louise Devigne**, François Pasteau, Marie Babel, Vishnu Narayanan, Sylvain Guegan, and Philippe Gallien. Design of a haptic guidance solution for assisted power wheelchair navigation. In IEEE Int. Conf. on Systems, Man, and Cybernetics, SMC 2018, 2018.

**C.4** Chinemelu Ezeh, Pete Trautman, **Louise Devigne**, Valentin Bureau, Marie Babel, and Tom Carlson. Probabilistic vs linear blending approaches to shared control for wheelchair driving. In IEEE Int. Conf. on Rehabilitation Robotics, ICORR'17, 2017.

**C.5 Louise Devigne**, Marie Babel, Florian Nouviale, François Pasteau, Aline Baudry, Philippe Gallien, “Conception d’un simulateur immersif pour la conduite assistée de fauteuil roulant électrique” In: Colloque Jeunes Chercheuses, Jeunes Chercheurs In: “Colloque Jeunes Chercheuses, Jeunes Chercheurs”, Université Paris 8-Vincennes -Saint-Denis, 8 Juin 2017.

**C.6 Louise Devigne**, Philippe Gallien, François Pasteau, Bastien Fraudet, Marie Babel, Benoît Nicolas, Luc Le Pape, Amélie Colin, Sophie Achille-Fauveau « Simulateur de conduite en réalité virtuelle pour l'accélération de la recherche sur les solutions d'aide à la navigation en fauteuil roulant électrique », SOFMER 2017, Nancy, France.

**C.7 Louise Devigne**, François Pasteau, Nicolas Le Borgne, Marie Babel, Tom Carlson, and Philippe Gallien. Assistance à la conduite de fauteuil roulant électrique (FRE) sur un trottoir: une preuve de concept. In IFRATH 2018-10ème Conférence sur les Aides Techniques pour les Personnes en Situation de Handicap, Handicap, pages 1-6, 2018.

# Résumé en Français

## Introduction

L'utilisation d'un fauteuil roulant permet aux personnes en situation de handicap de compenser une perte de mobilité. Cependant, alors qu'environ 70 millions de personnes dans le monde auraient besoin d'un fauteuil roulant, seulement 5 à 15 % ont accès à ce type d'aides techniques [O<sup>+</sup>15]. Pour certaines personnes, il est impossible de conduire un fauteuil roulant électrique sans être accompagnées ou supervisées par un tiers. En effet, certaines personnes lourdement handicapées ne peuvent pas manœuvrer un fauteuil roulant électrique en toute sécurité. Les personnes particulièrement concernées sont celles atteintes de troubles visuels, visuo-spatiaux et/ou cognitifs. En effet, ces troubles peuvent altérer la capacité à utiliser un fauteuil roulant de manière autonome et sécurisée [CVM16]. Il en résulte pour bon nombre de personnes en situation de handicap un manque d'autonomie corrélé à des difficultés dans la vie quotidienne. Ces difficultés peuvent avoir des répercussions sur les personnes elles-mêmes mais également sur les soignants, les accompagnants et les membres de leur famille. En effet, les personnes en situation de handicap lourd vivent généralement à domicile accompagnées par des aidants familiaux ou dans des établissements spécialisés avec du personnel aidant. La vie au domicile peut également avoir un impact négatif sur la vie sociale des aidants familiaux eux-mêmes. En effet, un rapport britannique publié en 2009 sur le handicap intellectuel et physique, la mobilité sociale et l'inclusion sociale & la santé [EMR<sup>+</sup>09] souligne que les aidants familiaux sont plus susceptibles d'être sujets à une réduction des possibilités d'emploi. D'autre part, ce rapport souligne que l'isolement social vécu par les personnes en situation de handicap se retrouve exacerbé par ce qui est désigné comme une "ségrégation" dans des structures telles que les écoles spécialisées ou les établissements de soins. Enfin, on observe généralement que les personnes en situation de handicap sont désavantagées dans leur vie sociale, notamment en ce qui concerne les expériences de la petite enfance, l'éducation, l'emploi et le marché du travail, la vie sociale et culturelle, la santé et le bien-être [EMR<sup>+</sup>09].

Dans ce contexte où les limitations de mobilité peuvent réduire l'accès aux différentes activités sociales et professionnelles et conduire à une forme d'exclusion sociale [CSU05], des améliorations significatives doivent être apportées pour la mobilité des personnes en situation de handicap. La question des facteurs qui impactent la mobilité a d'abord été étudiée en termes de barrières architecturales dans l'environnement physique [SD97]. De multiples facteurs tels que l'environnement physique, social ou

politique peut avoir un impact positif ou négatif sur la capacité des individus à vivre de manière autonome et à participer pleinement à tous les aspects de la vie quotidienne [WBM99]. La mobilité en fauteuil roulant peut évidemment être améliorée par la réduction des obstacles environnementaux physiques en construisant des structures adaptées ou en modifiant l'architecture des structures existantes. Cependant, les modifications de l'environnement physique nécessitent des politiques appropriées et des investissements financiers conséquents de la part des localités mais aussi de la part des acteurs privés du bâtiment. Enfin, la difficulté d'aborder ces problématiques dans une telle perspective macroéconomique repose sur la pluralité des handicaps et sur les limites et les désavantages qu'ils impliquent. En effet, un même environnement peut contenir des éléments qui constituent des obstacles à la mobilité d'une personne tout en facilitant la mobilité d'une autre.

C'est dans ce contexte que les freins relatifs à la mobilité peuvent également être adressés d'un point de vue individuel. En effet, des aides technologiques peuvent être conçues pour améliorer la mobilité dans tous types d'environnements. Par exemple, l'utilisation d'un fauteuil roulant dit "intelligent" prenant en compte les contraintes de l'environnement pourrait aider l'utilisateur à conduire un fauteuil au quotidien.

C'est dans cette perspectives que de nombreux travaux de recherche ont été menés sur le développement de solutions innovantes d'aide à la mobilité. Plusieurs laboratoires de recherche ont développé des solutions dites de "fauteuils roulants intelligents". Certains projets ont inclus les utilisateurs dans la fabrication de leur prototype en collaborant avec des centres de rééducation. Ces 20 dernières années, la recherche scientifique s'est concentrée sur de nombreux projets selon deux axes majeurs : l'assistance à la navigation (autonome ou semi-autonome) et la création d'interfaces de retour d'information (feedback). Cependant, il n'existe à ce jour aucune solution d'assistance à la navigation en fauteuil roulant électrique à destination du grand public sur le marché, ou même dans les centres de rééducation pour aider à l'apprentissage ou à la rééducation des patients.

L'objectif de ce travail de thèse est alors de développer des solutions tenant compte des besoins et attentes des utilisateurs finaux. Il s'agit principalement de développer un système bas coût qui assiste l'utilisateur dans la conduite du fauteuil. Les solutions techniques proposées devront également être peu encombrantes et facilement adaptables sur n'importe quel fauteuil roulant électrique standard afin de faciliter la diffusion sur le marché pour un accès au plus grand nombre. Ce travail de thèse s'inscrit dans le cadre d'une collaboration unique entre l'INSA Rennes et le centre de Médecine Physique et de Réadaptation Pôle Saint Hélier alliant connaissances robotiques, expertise des thérapeutes et conseils d'utilisateurs. Les solutions proposées dans ce travail sont donc développées selon une approche centrée sur l'utilisateur final. En effet, le processus d'élaboration des solutions proposées implique dès le départ des personnes en situation de handicap en hospitalisation de courte ou de longue durée, des neuropsychologues, des ergothérapeutes, et des neurologues spécialisés en médecine physique et en réadaptation.

## Mobilité motorisée : perspectives cliniques et sociales

Selon les derniers chiffres de l'Organisation Mondiale de la Santé (OMS), 110 à 190 millions d'adultes éprouvent des difficultés de mobilité [KOA<sup>+</sup>18]. En France, on estime à environ 850 000 le nombre de personnes à mobilité réduite. La motivation de ce travail est alors de concevoir des solutions intelligentes et adaptées d'aide à la mobilité visant à améliorer la qualité de vie de ces personnes ainsi qu'à fournir un outil de rééducation. Dans les pages qui suivent, nous présenterons un aperçu des défis liés à la mobilité et au handicap dans une perspective clinique mais aussi sociale. Pour ce faire, les compétences nécessaires à la conduite d'un fauteuil roulant seront décrites en détail, de même que les déficiences pouvant empêcher une personne de conduire un fauteuil roulant électrique en toute sécurité. De plus, nous soulignerons les fortes motivations pour ce travail, principalement l'impact positif que peuvent avoir les aides techniques à la mobilité sur la vie quotidienne des utilisateurs.

### Handicap et mobilité

En général, la mobilité est affectée par des handicaps orthopédiques ou neurologiques. Les troubles orthopédiques impliquent une déformation du système squelettique résultant soit d'une anomalie congénitale (*e.g.* pied bot, spina bifida), soit d'une maladie (*e.g.* dystrophie musculaire, arthrite), soit d'un accident (*e.g.* lésions médullaires). Les handicaps neurologiques touchent le système nerveux qui affecte la capacité de bouger, d'utiliser ou de contrôler certaines parties du corps. De telles incapacités peuvent être le résultat d'une maladie (*e.g.* sclérose en plaques, maladie de Lyme) ou d'une lésion cérébrale (paralysie cérébrale, lésions cérébrales, accident vasculaire cérébral). Une telle altération de la mobilité peut survenir après un accident vasculaire cérébral, une fracture ou une amputation d'un membre, ou un traumatisme (*e.g.* lésion cérébrale, lésion de la moelle épinière). Les personnes en situation de handicap peuvent éprouver des problèmes de mobilité physique sous la forme d'une réduction de la force musculaire ou de la mobilité des membres. Une perte ou une diminution de la mobilité peut également être associée à un état progressif comme le vieillissement ou une maladie dégénérative (*e.g.* sclérose en plaques ou maladie de Parkinson). Afin de surmonter ces limitations de mobilité, des aides à la mobilité telles que les fauteuils roulants électriques peuvent être envisagées.

### Aides à la mobilité motorisées

Plusieurs appareils peuvent être utilisés pour aider à la mobilité selon le handicap, les problèmes de mobilité et les besoins spécifiques de chaque individu. Les aides à la mobilité les plus courantes comprennent les aides à la marche comme les cannes et les béquilles et les aides au transport comme les fauteuils roulants et les monte-escaliers. Des appareils de mobilité motorisés peuvent, par exemple, être prescrits dans le cas d'une utilisation à long terme pour les personnes ayant une déficience lourde ou progressive, ou pour compenser les problèmes de fatigue éprouvés lors de la propulsion d'un fauteuil roulant manuel.

Contrairement aux scooters, les fauteuils roulants électriques permettent d'adapter la configuration des sièges et de la mettre à niveau au fur et à mesure que la condition physique de l'utilisateur évolue. En effet, l'utilisation d'un fauteuil roulant électrique est particulièrement cruciale pour les personnes souffrant de handicaps lourds ou progressifs car elle permet de se déplacer tout en se reposant confortablement pendant la journée avec le moins de transferts multiples (par exemple, au lit, sur une chaise). En effet, certaines personnes peuvent utiliser leur fauteuil roulant électrique quotidiennement avec un temps d'occupation moyen de 12 heures par jour [SS11]. En outre, il a été signalé que le passage des fauteuils roulants manuels aux fauteuils roulants électriques pourrait améliorer les performances professionnelles, avec un sentiment accru de compétence, d'adaptabilité et d'estime de soi [BAS01]. De plus, l'utilisation d'un fauteuil roulant électrique a été associée à de nombreux avantages psychologiques et physiques. En effet, les appareils de mobilité motorisés comme les fauteuils roulants offrent un meilleur accès aux activités de la vie quotidienne comme le shopping, les rendez-vous chez le médecin, les visites chez des parents ou les activités sociales [EFNDS07]. En outre, plusieurs revues systématiques portant sur les résultats de plusieurs études ont souligné le fait que la mobilité motorisée peut améliorer l'activité et la participation des utilisateurs et accroître la mobilité (8 études incluses) [SBS<sup>+</sup>09]. Elle a également un impact positif sur l'indépendance, la qualité de vie, la mobilité et l'engagement des adultes (11 études incluses) [FRMM13], mais aussi sur le développement global et la mobilité indépendante des enfants et adolescents (29 études incluses) [LF14]. Conformément à ces conclusions, l'Organisation mondiale de la santé (OMS) recommande de concevoir des technologies d'assistance pour favoriser l'égalité des chances pour les personnes en situation de handicap [OO<sup>+</sup>05].

Cependant, certains handicaps peuvent aussi avoir un impact sur les fonctions visuo-spatiales et/ou cognitives. La présence de déficiences visuelles ou cognitives peut compromettre la capacité d'une personne à conduire un fauteuil roulant électrique en toute sécurité. Dans la prochaine section, nous donnerons un aperçu de ces fonctions ainsi que de la façon dont elles peuvent compromettre la sécurité de la conduite en fauteuil roulant.

### **Fonctions visuelles et cognitives impliquées dans la conduite en fauteuil roulant**

Les personnes en situation de handicap peuvent présenter des déficiences visuelles qui réduisent leur capacité à percevoir leur environnement, ce qui réduit leur capacité à conduire un fauteuil roulant électrique en toute sécurité. Par exemple, les déficiences visuelles consistant en une perte de vision (perte de vision périphérique, cécité, hémianopsie, diminution de l'acuité visuelle) entraînent plus de difficultés lors de la manœuvre d'un fauteuil roulant électrique. D'autres déficiences visuelles telles que la diplopie (vision double) ou une altération de la perception stéréoscopique peuvent induire une perte partielle ou totale de la perception des formes et des distances, compromettant ainsi la sécurité en fauteuil roulant.

Bien que l'implication des fonctions physiques et visuelles semble évidente lors de la

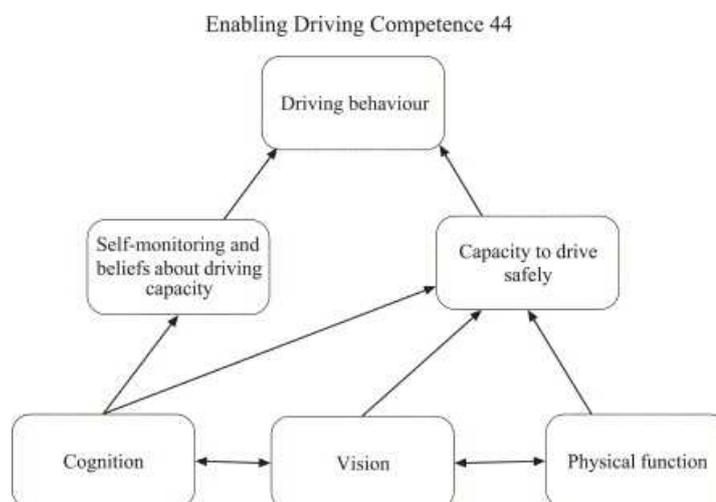


Figure 1 – Autoriser la conduite de fauteuil roulant [AWLW05].

tâche de conduite, les fonctions cognitives sont également impliquées. (Figure 1).

Les fonctions cognitives sont la capacité d’interagir avec le monde qui nous entoure. Elles comprennent la perception, l’attention, la communication/langage, la mémoire, les fonctions exécutives, la gestualité/praxies. Les déficiences cognitives sont généralement le résultat de lésions neurologiques. Les principales capacités cognitives mobilisées par la tâche de conduite reposent sur la mémoire, l’attention, les fonctions exécutives et les fonctions cognitives de perception [AWLW05].

**Perception** La perception est une capacité individuelle à reconnaître, voir et donner un sens à quelque chose. C’est la capacité de reconnaissances et d’identifications sensorielles (visuelle, auditive, tactile, gustative, olfactive) ainsi que la perception de soi dans l’environnement (*i.e.* où je suis, où sont les parties du corps). En particulier, les fonctions visuo-spatiales constituent la capacité de comprendre les représentations visuelles ainsi que leurs relations spatiales (*i.e.* la perception de l’espace, des distances et des directions). En d’autres termes, les fonctions visuo-spatiales concernent la perception visuelle, c’est-à-dire l’organisation mentale et l’interprétation de l’information sensorielle visuelle.

**Attention** L’attention est fortement sollicitée lors de la tâche de conduite. Cette fonction cognitive permet de trier toutes les informations sensorielles qui atteignent notre cerveau afin de nous concentrer uniquement sur les informations perçues les plus pertinentes. Certains troubles neurodéveloppementaux (comme le trouble déficitaire de l’attention avec hyperactivité - TDAH), ou des troubles neurodégénératifs (comme la maladie de Parkinson ou la maladie d’Alzheimer), ou des lésions neurologiques aiguës (p. ex. à la suite d’un AVC) peuvent entraîner des déficits graves et invalidants dans cette fonction. Plusieurs niveaux d’attention requis pour la conduite d’un fauteuil roulant électrique peuvent être distingués :

- **Intensité**
  - **Alerte.** Il s'agit de la capacité du cerveau à atteindre et à maintenir un état de grande sensibilité aux stimuli entrants, c'est-à-dire la capacité d'un individu à réagir à un événement, par exemple, un temps de réaction suffisamment court pour arrêter un véhicule lorsque quelqu'un traverse devant le véhicule de façon imprévue. Lorsqu'un tel événement se produit, il désengage l'individu de l'activité en cours en captant son attention. Si l'événement n'a pas d'importance ou de priorité, la personne peut utiliser des mécanismes d'inhibition pour négliger cet événement et se réengager dans la tâche de conduite.
  - **L'attention soutenue** concerne au moins la vigilance et est typiquement impliquée dans le maintien d'un itinéraire sans être entièrement concentré sur la tâche de conduite elle-même.
- **Sélectivité**
  - **L'attention ciblée** est la capacité du cerveau à concentrer son attention sur un stimulus cible pendant n'importe quelle période de temps tout en inhibant les stimuli secondaires pour rester concentré.
  - **L'attention divisée** correspond au niveau d'attention le plus élevé. C'est la capacité du cerveau à gérer plusieurs stimuli en même temps tout en inhibant d'autres stimuli. Un tel niveau d'attention est nécessaire pour conduire un fauteuil roulant électrique en toute sécurité.

**Mémoire** La mémoire est composée de 5 catégories : mémoire épisodique, mémoire de travail, mémoire sémantique, représentations perceptuelles et mémoire procédurale [EVD16]. Un fonctionnement sûr des fauteuils roulants électriques nécessite en particulier une bonne mémoire à court terme et une mémoire de travail adéquate (stockage temporaire des informations à traiter) pour que les informations pertinentes puissent être prises en compte pendant le processus de prise de décision [AWLW05].

**Fonctions exécutives** Les fonctions exécutives sont sollicitées dans tous les aspects de la vie quotidienne. Ils représentent la capacité d'un individu à utiliser les fonctions de mémoire et d'attention, mais aussi les processus de contrôle inhibiteurs, la stratégie, la planification, la prise de décision, le raisonnement, la gestion des priorités ou la résolution de problèmes dans la vie quotidienne [Dia13]. Tous ces processus cognitifs sont nécessaires pour planifier et coordonner les réponses sensorimotrices et cognitives requises pour conduire un véhicule [AWLW05].

### **Déficiences visuelles et/ou cognitives empêchant la conduite sécurisée d'un fauteuil roulant électrique**

Alors qu'un fauteuil roulant électrique est un outil essentiel pour la mobilité au quotidien et peut avoir un impact positif sur l'autonomie de l'utilisateur ainsi que sur

son inclusion sociale [DSF03][EFNDS07], conduire un tel véhicule peut être difficile car l'environnement est souvent inadapté aux fauteuils roulants électriques. De plus, une telle tâche nécessite de bonnes capacités visuelles, cognitives et visuo-spatiales.

L'utilisation d'un fauteuil roulant électrique peut être compromise par des facteurs techniques (liés au fauteuil lui-même) [Eva00], environnementaux (obstacles physiques), sociaux ou personnels (troubles cognitifs et/ou sensoriels) [Har04]. En effet, bien que la conduite sécurisée d'un fauteuil roulant électrique nécessite des fonctions physiques, visuelles et cognitives, les personnes en situation de handicap peuvent présenter des troubles de ces fonctions, ce qui les empêche de conduire en toute sécurité tout type de véhicule motorisé, y compris un fauteuil roulant électrique. Dans ce contexte, les cliniciens peuvent décider de ne pas prescrire d'aide à la mobilité motorisée lorsque la conduite est trop dangereuse (*i.e.* au-dessus d'un niveau de risque subjectif)[MCB13].

Il est facilement concevable qu'une déficience visuelle puisse entraver la conduite d'un véhicule du fait d'une perception réduite ou incomplète de l'information visuelle. En effet, les déficiences visuelles peuvent affecter la quantité et la qualité de l'information visuelle reçue. Or, l'altération des fonctions visuo-spatiales et cognitives peut compromettre la conduite. Ces fonctions définissent respectivement la capacité de comprendre les représentations visuelles ainsi que leurs relations spatiales (c'est-à-dire la perception de l'espace, des distances et des directions) et la faculté de traiter cette information et de développer la compréhension et d'initier des réponses [CATT<sup>+</sup>09].

En particulier, les personnes souffrant de troubles de la perception ou de l'attention, ou du syndrome dysexécutif (c'est-à-dire des déficiences des fonctions exécutives) ne peuvent généralement pas se faire prescrire un fauteuil roulant électrique. Par exemple, la négligence unilatérale, un syndrome de négligence visuo-spatiale faisant généralement suite à une lésion cérébrale unilatérale, rend impossible le traitement d'un stimulus dans la moitié de l'espace environnant, empêchant ainsi de conduire un fauteuil roulant électrique de manière sécurisée.

De plus, les utilisateurs possédant déjà un fauteuil roulant électrique rencontrent eux aussi des difficultés de sécurité lors de la conduite. Par exemple, une étude évaluant la perception des obstacles environnementaux au moyen du questionnaire CHIEF [WHFM<sup>+</sup>04] rempli par 100 utilisateurs de fauteuils roulants a rapporté que 52% des utilisateurs de fauteuils roulants sont confrontés quotidiennement à des problèmes d'accessibilité, dont 77% ont déclaré considérer ces questions comme un problème majeur [DGR13]. Une autre étude menée en 2014 au Québec auprès de 12 utilisateurs de fauteuils roulants électriques et de 4 soignants a révélé que les problèmes les plus fréquemment cités sont les espaces étroits (*c.-à-d.* le passage des portes, les manœuvres de demi-tour, les manœuvres de levage), la navigation dans des endroits bondés et les changements de niveau du sol [KRA<sup>+</sup>14]. Les résultats de cette étude ont souligné que les technologies des fauteuils roulants intelligents peuvent aider les utilisateurs à surmonter les difficultés liées à la conduite tout en soulignant la nécessité d'inclure les utilisateurs dans le processus de développement des technologies des fauteuils roulants intelligents.

## Motivations pour ce travail

Pour résumer ce qui a été fait auparavant, la mobilité motorisée est une question importante à aborder. En effet, s'il n'est pas totalement maîtrisé en raison de handicaps lourds, un appareil de mobilité motorisé peut causer des dommages matériels et/ou représenter un danger de blessure pour autrui ou pour soi-même [MMB<sup>+</sup>05]. Par conséquent, il est courant d'empêcher les personnes ayant une déficience visuelle, visuo-spatiale ou cognitive de conduire un fauteuil roulant électrique. Dans ce contexte, certaines études ont examiné les avantages potentiels de la technologie des fauteuils roulants intelligents avec des utilisateurs, des soignants ou des thérapeutes. Le résultat général de ces études est que les technologies de fauteuils roulants électriques intelligents seraient un outil pertinent pour l'aide à mobilité motorisée ainsi qu'un outil de formation et de rééducation.

En outre, une étude menée en 2008 a évalué que 61% à 91% de personnes pourraient bénéficier de telles technologies d'ici 2010 [SLC08]. Cette estimation incluait non seulement les personnes ayant des incapacités importantes, mais aussi une plus grande partie de la population qui pouvaient bénéficier ponctuellement de l'utilisation de fauteuils roulants électriques intelligents. Si l'on considère le vieillissement de la population, on estime que le nombre de personnes ayant des déficiences liées à l'âge augmentera d'ici 2030, augmentant ainsi le nombre de personnes qui pourraient avoir besoin d'aide à la mobilité.

Ce travail a ensuite été fortement motivé par les défis cliniques et sociaux que représente la mobilité motorisée. Les utilisateurs, les soignants et les thérapeutes attendent avec impatience les technologies de fauteuils roulants électriques intelligents pour faciliter la mobilité des personnes dans de nombreux aspects de leur vie quotidienne. Leurs attentes m'ont fortement motivé à participer à ce projet. En effet, je crois que des solutions technologiques pertinentes peuvent être apportées à ces personnes. Je crois également que la combinaison des connaissances de la robotique avec l'expertise des thérapeutes et les conseils des utilisateurs est la formule gagnante pour finalement aboutir à une solution de mobilité électrique abordable qui peut profiter au plus grand nombre de personnes. La motivation de ce travail a été, et est toujours, que je crois que de telles solutions amélioreraient la qualité de vie des personnes en situation de handicap en fournissant non seulement la mobilité à ceux qui ont déjà un fauteuil roulant, mais aussi en ouvrant de nouvelles possibilités en rééducation neurologique.

## Aperçu de la thèse

Dans ce chapitre, les motivations cliniques et sociales de ce travail de thèse ont été présentées. L'objectif général de ce travail de thèse est ensuite la conception en collaboration avec des utilisateurs et des thérapeutes de solutions robotiques pour la mobilité assistée motorisée. Ce chapitre a mis en évidence le besoin de telles solutions. Pour être utilisée par le maximum de personnes qui auraient besoin d'une aide à la navigation dans leur vie quotidienne ou à des fins de rééducation, la conception de solutions de mobilité assistée appliquées à la navigation motorisée en fauteuil roulant électrique représente un défi robotique important. En effet, les solutions d'assistance visent à utiliser des

méthodes de détection innovantes, à fournir des méthodes de contrôle partagé tenant compte de l'intention de l'utilisateur et à être conformes à l'intégration de matériel industriel nécessitant du matériel petit, robuste, peu coûteux et à faible consommation d'énergie.

Le reste de ce manuscrit présente les solutions conçues dans le cadre de cette thèse en collaboration avec les utilisateurs finaux et les cliniciens pour relever ce défi. Il est organisé comme suit.

**Chapitre 2 :** Ce chapitre s'ouvre sur une vue d'ensemble des solutions mécaniques qui peuvent améliorer la navigation des appareils d'aide à la mobilité motorisés dans des environnements constitués de barrières physiques. Ensuite, un aperçu des solutions d'aide à la navigation pour fauteuils roulants est présenté. Nous proposons ensuite de résumer les exigences technologiques issues des projets passés. Enfin, les outils génériques de robotique et les principes d'asservissement par capteurs qui ont été appliqués aux solutions proposées tout au long de ce travail de thèse sont présentés.

**Chapitre 3 :** Ce chapitre présente la conception d'un simulateur de mobilité assistée. Alors que la réalité virtuelle propose de nombreux avantages, nous appliquons cette technologie à la simulation de conduite de fauteuil. Plus particulièrement, les domaines visés par le simulateur proposé sont l'évaluation écologique des capacités de conduite, l'utilisation par les cliniciens pour la rééducation et l'apprentissage, le design rapide et collaboratif de nouvelles solutions d'assistance. Bien que certains simulateurs de conduite soient utilisés dans certains laboratoires de recherche, même dans des contextes d'évaluation clinique, aucun simulateur n'intègre des méthodes de navigation assistée ni la possibilité de développer facilement de nouvelles solutions robotiques. L'objectif de ce travail est alors de proposer un tel simulateur standardisé et facile à utiliser, d'une part pour la recherche et le développement et d'autre part pour l'évaluation des compétences de conduite, l'apprentissage et la rééducation. Ensuite, deux études menées en collaboration avec la centre de rééducation Pôle Saint Hélier avec des personnes valides et permettant d'évaluer la validité du simulateur proposé sont présentées.

**Chapitre 4 :** Ce chapitre présente une solution d'aide à la navigation semi-autonome dans un environnement intérieur. Une méthode de commande partagée basé capteurs permettant une correction en douceur de la trajectoire du fauteuil roulant à l'approche d'un obstacle est présentée. Ensuite, des simulations démontrent les propriétés de la solution de contrôle partagée proposée et valident le cadre mathématique. Enfin, une étude ayant pour objectif le test d'un fauteuil roulant électrique standard équipé de la solution d'assistance sur circuit. L'évaluation de la satisfaction et les performances de conduite avec et sans assistance permet de valider la méthode mathématique employée. Cette étude a été menée au Pôle Saint Hélier en collaboration avec des cliniciens et incluant 23 usagers.

**Chapitre 5 :** Ce chapitre présente les travaux réalisés sur l'assistance à la navigation en présence d'obstacles "négatifs" tels que les bordures de trottoir, les marches, les rampes. Deux méthodes d'asservissement basé capteurs sont proposées. Contrairement à la méthode présentée au chapitre 4, la détection des obstacles "négatifs" repose sur la mesure de distances par des capteurs fixés sur le châssis du fauteuil orientés vers le sol. La première méthode proposée est une application directe de la méthode introduite au chapitre 4 pour la navigation en environnement intérieur. En effet, celle-ci consiste à utiliser la définition de seuils sur la distance au sol mesurée par chaque capteur et de considérer un dénivellement trop important comme un obstacle à éviter. La deuxième méthode détaillée dans ce chapitre propose un asservissement basé capteurs utilisant l'estimation de l'orientation locale du sol en plus de l'information de distance mesurée au sol par chaque capteur. Les deux méthodes sont développées sur le simulateur de conduite de fauteuil et présentées au chapitre 3. Enfin, des simulations de conduite assistée par cette méthode dans un environnement virtuel sont présentées et discutées.

**Chapitre 6 :** Ce chapitre propose une méthode haptique d'aide à la navigation en fauteuil roulant. L'idée est d'aider les personnes en situation de handicap à percevoir une information de navigation qu'elles ne peuvent percevoir en raison de déficiences visuelles et/ou cognitives. L'expérience de conduite augmentée proposée est conçue pour apporter une couche supplémentaire aux méthodes d'aide à la navigation qui ont été proposées dans les chapitres 4 et 5 précédents. L'objectif est de calculer un retour haptique indiquant la correction de trajectoire qu'appliquerait le système d'assistance à la navigation présenté au chapitre 4 s'il était activé. La méthode proposée vise à accroître la perception de l'utilisateur de telle manière à ce qu'il ait un contrôle total tout en recevant une rétroaction haptique agissant comme un indice pour contrôler le fauteuil roulant en toute sécurité.

**Conclusion :** Enfin, nous présentons la conclusion de cette thèse et les perspectives pour les projets futurs basés sur ce travail de thèse.

# Chapter 1

## Introduction: Clinical and social motivations

### 1.1 Introduction

While using a wheelchair allows people with disability to compensate a loss of mobility, only 5 to 15 % of the 70 million people worldwide who require a wheelchair have access to this type of technical aid [O<sup>+</sup>15]. One of the reasons for this is that some people are either not allowed to drive a power wheelchair, or if they do, they cannot maneuver it safely by themselves. In such cases, they need to be accompanied and supervised. In particular, the ability to independently operate a mobility device safely can be altered by visual, visuo-spatial and/or cognitive impairments [CVM16]. The induced lack of independence and daily-life difficulties impact not only people with disability themselves but also caregivers as well as family members. Indeed, people with severe disabilities either live at home and must be accompanied by family carers or in specialized facilities with caregivers. On the one hand, living at home has also an impact on caregivers themselves as they can experience reduced social mobility. For example, a British report released in 2009 on Intellectual and Physical Disability, Social Mobility, Social Inclusion & Health [EMR<sup>+</sup>09] emphasized that family carers are more likely to experience reduced employment opportunities. In the other hand, it is also highlighted that the social disconnectedness experienced by people with disability is exacerbated by the use of "segregated" structures such as specialized schools or care facilities. Finally, it is generally observed that people with disability experience disadvantages in their social life including early childhood experiences, education, employment and labor market experiences, social and cultural life, health and well-being [EMR<sup>+</sup>09].

In this context where mobility limitations can effectively lead to a form of social exclusion because of reduced access to activities of social and professional life [CSU05], significant improvements have to be made for the mobility of people with disability. The question of environmental factors impacting mobility has first been investigated in terms of architectural barriers in the physical environment [SD97]. However, multiple factors such as physical, social, and political environments can also impact either positively

or negatively the ability of an individual to live independently and to fully participate in all aspects of daily life [WBM99]. In the case of powered mobility, an obvious way of lessening mobility issues is to reduce the physical environmental barriers: designing or modifying structures to alleviate barriers to powered mobility. However, addressing the modifications of the physical environment requires appropriate policies and major financial investments from local authorities but also from private building stakeholders. The difficulty of addressing the physical environment from such a macro-perspective stems from the breadth of disabilities and the limitations and disadvantages they imply. Indeed, the same environment can contain elements which are barriers to an individual mobility while being a facilitator to another individual.

In this context, mobility issues can also be addressed from an individual-perspective by deploying adapted assistive technologies in all types of environment. Mobility aids can be provided in the form of smart devices taking into account environmental constraints to assist the user mobility in daily life.

In that respect, many researchers work on the design of innovative solutions aiming to provide mobility assistance. When addressing powered mobility, several research laboratories develop "smart power wheelchairs" devices. Over the past 20 years, research has focused on various smart wheelchair projects that follow two major research axes: navigation assistance (autonomous or semi-autonomous) and alerts through adapted feedback interfaces. Despite such projects sometimes involving users in the development process by collaborating with rehabilitation structures, no smart power wheelchair system has been released on the market, nor used by therapists within rehabilitation centers or specialized structures.

Therefore, the aim here is to develop solutions which meet the needs and expectations of end users. This consists mainly of developing a cost-efficient and energy-efficient solution that can be easily plugged to any standard power wheelchair in order to facilitate market launch and affordability. This thesis work takes part in the quite unique collaboration between INSA Rennes and the rehabilitation center Pôle Saint Hélier combining robotic knowledge, therapists' expertise and users' advice. The solutions presented in this work are therefore developed using an end-user centered approach. Indeed, the proposed solutions development process involves from the beginning people with disability in short or long term care, neuropsychologists, occupational therapists, and neurologists.

## 1.2 Powered mobility clinical and social perspectives

According to recent figures from the World Health Organization (WHO), 110 to 190 million adults have significant difficulties in functioning and experience mobility difficulties [KOA<sup>+</sup>18]. In France, it has been estimated that 850 000 people face reduced mobility. The motivation for this work is then to design smart and adapted mobility assistance solutions aiming to improve the Quality of Life (QoL) of these people and to provide rehabilitation tools. In the following, an overview of mobility and disability challenges within clinical but also social perspectives will be presented. To do so, the

required skills involved in wheelchair driving will be detailed as well as impairments which may prevent safe operation of powered mobility devices. Finally, we will highlight the scientific findings on the positive outcomes from powered mobility access which have strongly motivated this thesis work.

### 1.2.1 Defining disability

*Disability* has been used to define different notions across the years. 40 years ago, the World Health Organization International Classification of Impairments, Disabilities, and Handicaps (ICIDH) first defined 3 terms namely *disability*, *handicap*, *impairment* to represent 3 notions which differ in terms of their level of impact on the individual daily life [O<sup>+</sup>80]. This way, the term *impairment* described any disorder at a body/organ level, *disability* described any disorder at an individual performance level, and the term *handicap* described the difficulties encountered by an individual while interacting with the environment *i.e.* the consequences of an impairment or disability. Nowadays, the term *handicap* still commonly used in French language, rather describes a social phenomenon involving specific social roles, the environment, barriers and expectations of individuals [O<sup>+</sup>93]. However, as emphasized in the ICIDH-2 revised version of the ICIDH report [WHOAG99], the pejorative connotations of the term *handicap* in English language led this term to be dropped to avoid stigmatizing and labeling. In the line of these guidelines, some essential definitions that will be used in this manuscript can be taken from the International Classification of Functioning, disability and health report (ICF report) [O<sup>+</sup>01]:

- **Impairment.** Impairment is defined as a loss or abnormality of a body part or body function (*e.g.* paralysis, blindness).
- **Participation.** Participation describes the involvement of an individual in a life situation and represents the societal perspective of the concepts covered by the term "functioning". **Participation restriction** defines the issues an individual may experience while getting involved in daily life situations (*e.g.* facing discrimination in transportation or in employment). The presence of a participation restriction is determined by making the comparison between participations for an individual with disability and what is expected for an individual without disability in a determined culture or society.
- **Activity.** Activity is the execution of a task or action by an individual. It represents the individual perspective of functioning. **Activity limitation** is the difficulty an individual may experience in executing an activity (*e.g.* walking, eating).
- **Barriers.** The notion of *barrier* covers environmental factors whose absence or presence limits functioning and can create disability. This includes physical environmental aspects but also the lack of relevant assistive technologies, negative attitudes of people towards disability, etc.

Finally, **disability** covers the difficulties encountered by an individual while interacting with the environment thus considering personal as well as environmental and social factors. Besides, *disability* is defined as a "umbrella term" for impairments, activity limitations, and participation restrictions [SO11].

## 1.2.2 Disability and mobility

Generally, mobility is affected by orthopaedic or neurological disabilities. Orthopaedic disabilities involve a deformity of the skeletal system either resulting from a congenital anomaly (*e.g.* clubfoot, spina bifida), a disease (*e.g.* muscular dystrophy, arthritis), or an accident (*e.g.* spinal cord injury). Neurological disabilities involve the nervous system affecting the ability to move, use or control some body parts. Such disabilities can either be the result of a disease (*e.g.* multiple sclerosis, Lyme disease), or a brain damage (*e.g.* cerebral palsy, brain injury, stroke). People with disability may experience impaired physical mobility in the form of a reduced muscle strength or limb mobility. A loss or decrease of mobility can also be associated with a progressive condition such as aging or degenerative disease (*e.g.* multiple sclerosis or Parkinson disease). In order to overcome the mobility limitations resulting from such disabilities, mobility aids such as power wheelchairs can be considered.

### 1.2.2.1 Power wheelchair mobility aids

Multiple devices can be used to assist mobility depending on the disability, mobility issues and individual's specific needs. The most common mobility aids include walking aids such as canes and crutches to transportation aids such as wheelchairs and stair lifts. Powered mobility devices can be prescribed for long-term use for people with severe or progressive disability or to address fatigue issues experienced while propelling a manual wheelchair.

In contrast to scooters, power wheelchairs allow seating configuration adaptation as well as upgrade as the user condition progresses. Indeed, the use of a power wheelchair is particularly crucial for people with severe or progressive disabilities as it allows to move while resting comfortably during the day with fewer transfers (*e.g.* to bed, to a chair). Indeed, some people can use their power wheelchair on a daily basis with an occupancy time of an average 12 hours a day [SS11].

Moreover, it has been reported that the transition from manual to power wheelchairs could enhance occupational performances, with increasing feeling of competence, adaptability, and self-esteem [BAS01]. Moreover, power wheelchair use has been associated with many psychological and physical benefits. Indeed, devices such as wheelchairs provide a better access to daily-life activities such that shopping, medical appointments, visiting relatives or attending social events [EFNDS07]. In addition, several systematic reviews covering multiple studies outcomes highlighted that power mobility can improve users' activity and participation and increases mobility (8 included studies) [SBS<sup>+</sup>09]. It also impacts positively independence, quality of life, mobility and engagement in adults (11 included studies) [FRMM13], but also overall development as well as inde-

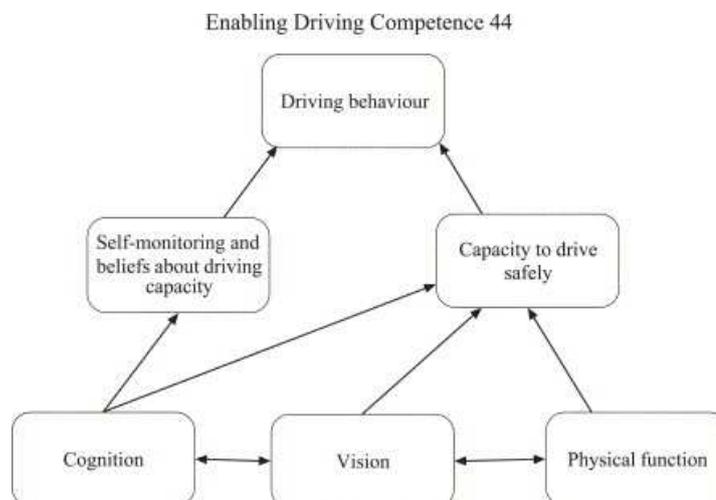


Figure 1.1 – Enabling power wheelchair driving [AWLW05].

pendent mobility in children and adolescents (29 included studies) [LF14]. In line with these findings, the World Health Organization (WHO) recommends designing assistive technologies to create equal opportunities for people with disabilities [OO<sup>+</sup>05].

However, disability can also impact visuo-spatial and/or cognitive functions. The presence of visual or cognitive impairments may compromise the ability of an individual to drive a power wheelchair safely. In the next section, we will provide an overview of these functions as well as how they may compromise safe wheelchair driving.

### 1.2.2.2 Visual and cognitive functions involved in wheelchair driving

Human vision is achieved by the functions of the eye, the muscles that move the eye, the optic pathway, as well as the visual cortex. Visual functions represent the sensory functions of the eye with respect to a physical stimuli.

People with disability may experience visual impairments reducing their ability to perceive their environment. For example, visual impairments consisting of a vision loss (*e.g.* loss of peripheral vision, blindness, hemianopia, reduced visual acuity) induce more difficulties while maneuvering a power wheelchair. Other visual impairments such as diplopia (double vision) or limited stereoscopic perception can induce a loss in perception of shapes and distances thus compromising the safe operation of a wheelchair.

While it appears obvious that physical and visual functions are solicited for driving tasks, cognitive functions also play a role in the ability to operate a vehicle safely (1.1). Cognitive functions are the ability to interact with the world around us. They include perception, attention, communication/language, memory, executive functions, gestuality/praxies. Cognitive impairments are generally the result of neurological lesions. The main required cognitive abilities for driving safely rely on memory, attention, executive functions and perception cognitive functions [AWLW05].

**Perception** The perception function concerns an individual ability to recognize, see and put meaning on something *i.e.* the ability of sensory recognition and identification (visual, auditory, tactile, gustatory, olfactory) as well as body self-perception in the environment (*e.g.* where I am, where are the parts of my body). In particular, visuo-spatial functions constitute the ability to understand visual representations as well as their spatial relationships (*e.g.* perceiving space, distances, and directions). In other words, visuo-spatial functions concern visual perception *i.e.* the mental organization and interpretation of the visual sensory information.

**Attention** Attention is highly solicited while driving a wheelchair. This cognitive function allows us to sort all the sensory information that reaches our brain in order to focus only on the most relevant information at the moment. Some neurodevelopmental disorders (such as Attention Deficit and Hyperactivity Disorder - ADHD), or neurodegenerative disorders (such as Parkinson's or Alzheimer's disease), or acute neurological injuries (*e.g.* following strokes) can induce severe and disabling deficits in this function. Several levels of attention required for power wheelchair driving can be distinguished:

- Intensity
  - **Alert.** This concerns the brain's ability to achieve and maintain a state of high sensitivity to incoming stimuli *i.e.* the ability of an individual to react to an event, for example, a short enough reaction time to stop when someone unexpectedly crosses in front of the vehicle. When such an event occurs, it disengages the individual from the current activity by capturing his attention. If the event is of no importance or priority, the individual may use inhibition mechanisms to neglect this event and re-engage in the driving task.
  - **Sustained attention** concerns at least vigilance and is typically involved while maintaining a safe route without being fully focused on the driving task itself.
- Selectivity
  - **Focused attention** is the brain's ability to concentrate its attention on a target stimulus for any period of time while inhibiting secondary stimuli to stay focused.
  - **Divided attention** corresponds to the highest attention level. It is the brain's ability to manage several stimuli at the same time while inhibiting other stimuli. Such a level of attention is necessary to drive a vehicle safely.

**Memory** Memory is composed of 5 categories: episodic memory, working memory, semantic memory, perceptual representations and procedural memory [EVD16]. Safe power wheelchair operation particularly requires good short time memory and adequate working memory (temporarily store information to be processed) so that relevant information may be held in mind during the decision making process [AWLW05].

**Executive functions** Executive functions are solicited in every daily life. They represent an individual's ability to use memory and attention functions but also concern inhibitory control processes, strategy, planning, decision making, reasoning, priority management or problem-solving aspects of daily life [Dia13]. All these cognitive processes are necessary to plan and coordinate sensorimotor and cognitive responses required to drive a vehicle [AWLW05].

### 1.2.2.3 Visual/and or cognitive impairments preventing safe power wheelchair driving

Power wheelchair use can have a positive impact on user autonomy and social inclusion [DSF03][EFNDS07]. However, driving such a vehicle is a challenging task which requires good visual, cognitive and visuo-spatial abilities.

Power wheelchair use can be jeopardized by technical factors (related to the wheelchair itself) [Eva00], environmental factors (*e.g.* physical barriers), social factors, or personal factors (*e.g.* cognitive and/or sensory impairments)[Har04]. Indeed, while safe driving requires physical, visual, and cognitive functions, people with disability may experience loss or impairment of some of these functions thus preventing them from operating safely any type of motorized vehicle. In this context, clinicians can decide to not prescribe a powered mobility aid for safety concerns (*e.g.* driving behavior is above a subjective risk level). [MCB13].

It is easily conceivable that visual impairments can lead to driving safety issues as they result in reduced/incomplete perception of visual information. However, visuo-spatial and cognitive impairments can hinder driving safety. These functions respectively define the ability to understand visual representations as well as their spatial relationships (*e.g.* perceiving space, distances, and directions) and the faculty for processing this information and to build understanding and initiate responses [CATT<sup>+</sup>09]. In particular, people having perception or attention disorders, or dysexecutive syndrome (*i.e.* executive functions impairments) are generally prevented from being prescribed a power wheelchair. For example, unilateral neglect, a syndrome of visuo-spatial neglect following unilateral brain injury makes it impossible to process a stimuli in half of the surrounding space thus significantly increasing the risk of injury and accident.

In addition, people who already drive a power wheelchair also experience safety and mobility issues while driving. For example, a study assessing environmental barriers perception by means of the CHIEF questionnaire [WHFM<sup>+</sup>04] completed by 100 wheelchair users has reported that 52% of wheelchair users are facing accessibility issues on a daily basis with 77% of them considering these issue as a major problem [DGR13]. Moreover, a semi-structured interview study including 12 power wheelchair users and 4 caregivers led in 2014 in Quebec has pointed out that the most commonly cited issues are narrow spaces (*i.e.* passing doorways, turn around maneuvers, lift maneuvers), navigating crowded places, and uneven/changing driving surfaces [KRA<sup>+</sup>14]. The findings of this study pointed out that smart wheelchair technologies may help users to overcome driving issues while emphasizing the necessity to include users in the development process of such smart assistive technologies.

### **1.2.3 Motivations for this work**

To sum up what has been shown previously, powered mobility is an important issue to be addressed. Indeed, if not operated safely because of severe disabilities, a powered mobility device can cause damage to property and/or represent a danger of injury for others or oneself [MMB<sup>+</sup>05]. Therefore, people with visual, visuo-spatial or cognitive impairments can be prevented from driving such a powered mobility aid device. Moreover, people with disability who already have a power wheelchair experience mobility issues because of the environment, social context, etc. In this context, some studies investigated the potential benefits of such assistive technology with users, caregivers or therapists. The general outcome of these studies is that smart power wheelchair technologies would be a relevant safe powered mobility benefiting regular users as well as training and rehabilitation within rehabilitation centers.

In addition, a study led in 2008 assessed that 61% to 91% of people with mobility restrictions could benefit from smart power wheelchair technologies by 2010 [SLC08]. This estimation included not only individuals with severe disabilities but also a larger portion of the population who could punctually benefit from such assistive technology. In addition, considering the aging population, the number of individuals with age-related impairments is estimated to grow by 2030, thus increasing the number of people who would potentially need a smart power wheelchair.

This work has then been strongly motivated by the clinical and social challenges that powered mobility represents. Smart power wheelchair technologies are eagerly expected by users, caregivers and therapists to assist people mobility within many aspects of their daily life. Their expectations constituted a strong motivation for me to take part in this research project. Indeed, I also believe that relevant technological solutions can be provided to these people. I believe that the combination of robotic knowledge with therapists' expertise and user advice is the winning formula to finally come up with an affordable powered mobility solution that can benefit the greatest number of people. The motivation for this work has been, and still is, that I believe such solutions would improve people's quality of life by providing not only independant mobility for those who already have a wheelchair, but also expand neurological rehabilitation possibilities.

## **1.3 Thesis outline**

In this chapter, the clinical and social motivations for this thesis were presented. The general objective is then the design of robotic solutions for assisted powered mobility in collaboration with users and therapists. The design of such innovative assisted powered mobility solutions represents an important robotic challenge. Indeed, as it aims to be used by the maximum of people who would need assistance in their daily-life or for rehabilitation purposes, it should meet challenging objectives. The solutions proposed in this work thus use innovative detection methods, provide shared-control methods taking into account user intention, and are compliant with industrial hardware integration requiring small, robust, low-cost, low-power hardware.

The remainder of this manuscript presents the different assistive solutions designed to meet these clinical, social and Robotics challenges in collaboration with end-users and clinicians. It is organized as follows.

**Chapter 2:** This chapter first presents an overview of the mechanical solutions which can improve the navigation of powered mobility devices within environments consisting of physical barriers. Then, an overview of wheelchair navigation assistance solutions is introduced. We then propose to summarize the technological requirements resulting from past projects. Finally, generic robotic tools and sensor-based control principles which have been applied to the proposed smart wheelchair solutions throughout this thesis work are presented.

**Chapter 3:** This chapter presents the design of an assisted powered mobility simulator. While virtual reality offers many advantages, we apply this technology to wheelchair driving simulation. In particular, the areas covered by the proposed simulator are ecological assessment of driving skills, use by clinicians for rehabilitation and learning, and rapid and collaborative design of new assistance solutions. Although some driving simulators are used in some research laboratories, even for clinical assessment purposes, no simulator incorporates assisted navigation methods nor the ability to easily develop new robotic solutions. The objective of this work is then to propose a standardized and easy-to-use simulator. On the one hand for research and development purposes, and on the other hand for driving skills assessment and learning as well as rehabilitation. Then, two studies conducted in collaboration with the Pôle Saint Hélier rehabilitation center with able-bodied people to evaluate the validity of the proposed simulator are presented.

**Chapter 4:** This chapter presents a solution for semi-autonomous navigation assistance in an indoor environment. A sensor-based shared control method applying smooth trajectory correction as the wheelchair approaches an obstacle is presented. Then, simulations demonstrate the properties of the proposed shared control solution and validate the mathematical framework. Finally, this chapter presents the validation of the proposed solution embedded on a standard power wheelchair is presented through a study conducted in collaboration with the clinicians of Pôle Saint Hélier. In this study, satisfaction and driving performance with and without activation of the assistance were assessed with 23 regular users.

**Chapter 5:** This chapter presents the work which has been achieved on shared control assisted navigation with respect to "negative" obstacles such as curbsides, steps, ramps. Two sensor-based servoing methods are proposed. Unlike the method presented in chapter 4, the detection of "negative" obstacles is based on the measurement of distance sensors facing the ground. The first proposed method is a direct application of the method introduced in chapter 4 for navigation in indoor environments. Indeed, it consists of using the definition of thresholds on the distance measured by each sensor

and to consider a significant difference of elevation as an obstacle to avoid. The second method detailed in this chapter proposes a sensor-based control using the estimation of the local orientation of the ground in addition to the distance to the floor measured by each sensor. Both methods were designed and tested on the wheelchair driving simulator presented in chapter 3. Finally, simulations of the proposed navigation assistance method are presented and discussed.

**Chapter 6:** This chapter proposes a haptic method for wheelchair navigation assistance. The idea is to assist people with disabilities in perceiving navigation information they cannot take from the environment because of visual and/or cognitive impairments. The proposed augmented driving experience is designed as an additional layer to the navigation assistance methods which have been proposed in previous chapters 4 and 5. The objective is to compute a haptic feedback indicating the trajectory correction which the navigation assistance system presented in chapter 4 would apply if it were activated. The proposed method aims to increase the user's perception so that he or she has full control while receiving haptic feedback that acts as a guide to safely control the wheelchair.

**Conclusion:** Finally we provide the conclusion of this dissertation and present perspectives for future projects based on this thesis work.

## Chapter 2

# Assisting power wheelchair navigation

This chapter presents works within the scope of smart wheelchair technologies. In the following sections, an overview of the methods involved in assisting power wheelchair navigation will be presented. Then, the generic modeling framework and robotics tools applied in this work to power wheelchair driving assistance will be presented.

Powered mobility aids such as power wheelchair devices are non-holonomic wheeled vehicles which have to navigate within complex environments. Safe navigation requires the wheelchair user to manage multiple challenges with respect to physical barriers, narrow environments, dynamical environments, crowds, etc. To alleviate the issues encountered by the users, solutions can be provided to make a wheelchair "smart" in a way that it is able to assist the user to manage these issues. Technological innovations are therefore investigated either to overcome physical barriers by means of specific mechanical designs or to ensure safer navigation by means of smart power wheelchair solutions.

In this chapter, a first overview of mechanical solutions will be provided. Then, a review of smart power wheelchair solutions will be introduced. After a review of the existing smart powered mobility solutions, we propose to summarize the technological requirements resulting from the past projects. Finally, a robotic "toolbox" is proposed to set out the sensor-based servoing principles which have been applied to the proposed smart wheelchair solutions all along this thesis.

### 2.1 Mechanical design solutions

As navigation issues experienced by power wheelchair users are often reported to be related to the wheelchair design itself as well as physical barriers in the environment [ROS15], power wheelchair navigation issues can be alleviated by improving the mechanical design itself so that the wheelchair can overcome the physical barriers (*i.e.* steps, curbs, uneven terrains) or be maneuvered more easily in specific situations. Within this scope, innovative wheelchair designs are investigated. For example, some wheelchair



Figure 2.1 – TopChair step climbing wheelchair.

designers propose holonomic designs allowing the power wheelchair to be maneuvered more easily in narrow environments without a series of difficult maneuvers. These types of design is usually used within indoor environment but present drawbacks while navigating outdoors. [KMLB17]. In addition, a systematic review describing step-climbing wheelchair designs (including leg-wheel hybrid systems, spider wheels, additional structures for lifting, and crawler tractors), claimed that many prototypes allowing single step or continuous steps climbing were under development [SWDC17]. However, only one of them, the TopChair (Figure 2.1), combining wheels and caterpillar track as available on the market. The TopChair was tested in France by 25 persons with Spinal Cord Injury (SCI) who have been able to successfully operate the TopChair indoors and outdoors [LGF<sup>+</sup>08]. However, the TopChair consists in a specific whole wheelchair design. Moreover, the TopChair is bulkier and heavier than other power wheelchairs because of its electromechanical property and caterpillar tracks. This type of solution therefore presents significant drawback for daily use by end-users.

## 2.2 Smart power wheelchair solutions

"Smart power wheelchair" is a denomination which can refer to 2 notions. Firstly, smart power wheelchair can refer to connected devices plugged onto a wheelchair. This type of smart device allows users to experience a better quality of daily life by making information accessible to everyone. Hence, users can get assistance from a community in the form of delivered information (for example about the accessibility of the route and services). Indeed, difficulties encountered while driving in a constantly changing city could typically be overcome by a smart connected wheelchair solution that provides a collaborative support for information exchange between power wheelchair users (*e.g.* for example to notify the presence of road works, accessible public toilet). In that regard, several solutions are designed to provide smart connected wheelchair suiting users needs.

Secondly, a smart power wheelchair can also refer to power wheelchairs instrumented with sensing devices, in other words robotic wheelchairs which can react to their environment. In the remainder of this work, "smart wheelchair" will always refer to this

type of devices. Smart wheelchair technologies therefore involve driving assistance in the way that wheelchair control support can be provided. Indeed, assistance can be provided on different levels in the same way as in the car industry *i.e.* from low-level assistance (*e.g.* parking assistance, automated emergency braking) to high-level assistance (*e.g.* collision avoidance, autonomous vehicles detecting road conditions, road signs and even pedestrians). While the former can be implemented to punctually assist power wheelchair regular users with respect to maneuvering difficulties in their daily experience, the latter can be considered for providing assistance to people with sensory and cognitive impairments that prevents them from driving a power wheelchair safely in all types of environment.

In this part, an overview of the robotics tools which have been investigated so far for designing smart power wheelchair solutions will be presented. This literature review will first cover sensing devices and techniques and then the control techniques designed to provide navigation support to wheelchair users.

### 2.2.1 Sensing

In order to react to its environment, a smart power wheelchair has to be equipped with exteroceptive sensors measuring the surrounding environment characteristics. In this part, the most commonly used sensors within smart power wheelchair research field will be presented. Then, the most relevant sensors for user-centered design of smart power wheelchair solutions will be discussed.

#### 2.2.1.1 Vision sensors

Vision sensors are widely used for robot navigation [MM14] [LXXZ18]. If common vision sensors used in mobile robotics are RGB-D cameras and omnidirectional cameras, some systems also use one or several low cost monocular cameras [FPRARM15]. Unlike other sensors, cameras can see color, thus allowing scene interpretation and features classification. Cameras are usually low-cost but necessitate high computational load and complex algorithms as they measure important amounts of data. Independently of the camera type, cameras have to be calibrated (manually off-line or automatically on-line). Calibration estimates intrinsic and extrinsic parameters. While the former depend on the geometry on the camera (focal length and principal point), the latter depend on the position of the camera in space (rotation and translation with respect to some coordinate system). A major drawback of camera use for mobile robot (and thus power wheelchair) navigation is the many factors that can impact the calibration of the camera. For example, environmental factors (*e.g.* humidity, temperature) can change the intrinsic camera information humidity or temperature. Moreover, a physical shock or damage to the wheelchair (*e.g.* while crossing a curb, hitting an object) can invalidate the previously acquired calibration. Monocular cameras have already been used within the scope of wheelchair assisted navigation [NPM<sup>+</sup>16] but showed important weaknesses. Indeed, the cameras attached to the wheelchair required autocalibration process in order to provide robust data. This autocalibration was not sufficient to

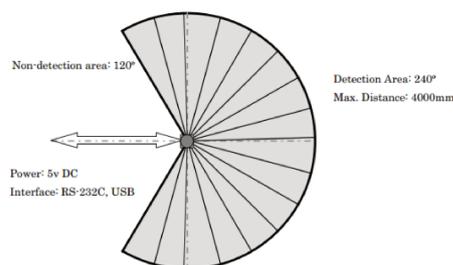
provide satisfying behavior while testing with regular power wheelchair users.

### 2.2.1.2 Laser rangefinders

Laser rangefinders are widely used in mobile robotics. This type of sensor uses a laser pulse to measure distances to objects. The most common types of laser rangefinders are based on the Time of Flight (ToF) principle which consists in measuring the absolute time that a laser pulse needs to travel from the emitter to the object and back to the receiver. The distance is then simply deduced from the travel time measurement and the known speed of the laser light. Thus laser rangefinders, also called LiDARs, incorporate a small rotating mirror shifting between each measurement allowing a scan of the environment which can be used to produce detailed maps of complex environments. For example, the Hokuyo URG-04-LX laser rangefinder has a detection area of 240 degrees wide and 6 cm to 4 m range (Figure 2.2).



(a) Hokuyo URG-04-LX sensor.



(b) Detection area.

Figure 2.2 – Laser range finder sensor example.

Laser rangefinders are used in many applications in robotics, in particular for navigation tasks such as localization or obstacle avoidance [FPRARM15]. They also have been widely used for power wheelchair navigation assistance research. However, they have shown significant drawbacks for smart wheelchair development. Particularly regarding their cost and fragility, as well as their limitation to only planar detection of a 3D world.

### 2.2.1.3 Ultrasonic sensors

Ultrasonic sensors are very popular in many robotics applications. These sensors have a lot of benefits as they are cheap, compact and low-power consuming.

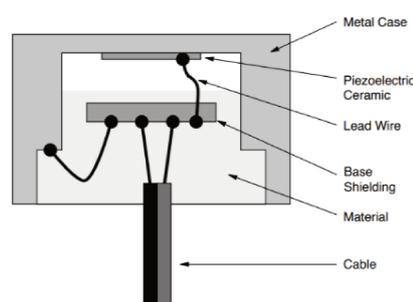
As shown in Figure 2.3b, a ultrasonic sensor is composed of a piezoelectric component attached to the top inside of a metal case. When a voltage is applied to this piezoelectric component, a mechanical distortion occurs. Therefore, it is possible to generate an ultrasonic wave by exciting this component with voltage pulses. The reverse is also true, the piezoelectric component generates electrical signals when receiving an ultrasonic wave. These sensors are then able to send ultrasonic waves and to receive the

echo produced by the reflection of the ultrasonic wave on an object. The echo is then converted into an electrical signal from which distance to the object can be deduced using the Time-of-Flight principle.

However, cross-talk and signal processing are still an issue limiting their use.



(a) Ultrasonic sensor and its electrical circuit board.



(b) Ultrasonic sensor composition.

Figure 2.3 – Ultrasonic sensor.

#### 2.2.1.4 Infrared sensors

Infrared sensors have been used a lot in applications requiring accurate distance measurement. However, they have not been popular in the mobile robotics field in particular to perform navigation tasks. Indeed, the first generation of infrared sensors (Figure 2.4a) simply measured the amount of light received by the detector. The resulting restricted detection range as well as the cost were prohibitive to consider the use of such sensors to perform robot navigation tasks. Therefore, the use of infrared sensor was for a long time restricted to proximity detection only. However, a new infrared sensor technology, FlightSense, has been recently developed and patented by ST Microelectronics. This new generation of sensors is based on the Time-of-Flight (ToF) technology. Moreover, the detection range which was restricted to less than 1 meter with the previous generation is greatly increased and can reach 4 meters. The most recent sensor VL53L1 from STMicroelectronics (Figure 2.4b) also allows multi-zone detection. Moreover, this type of sensor is about 5 times cheaper than the first generation of infrared sensors.

#### 2.2.1.5 Which sensor(s) for a smart power wheelchair ?

Within the scope of navigation assistance, the most relevant sensors are those measuring distances from a robot to a target in order to reach or at the contrary avoid an object. Although sensors such as LIDARs are widely used in robotics as they provide accurate distance detection, they are, because of their cost and fragility, less likely to be incorporated into industrial low-cost accessible solutions.

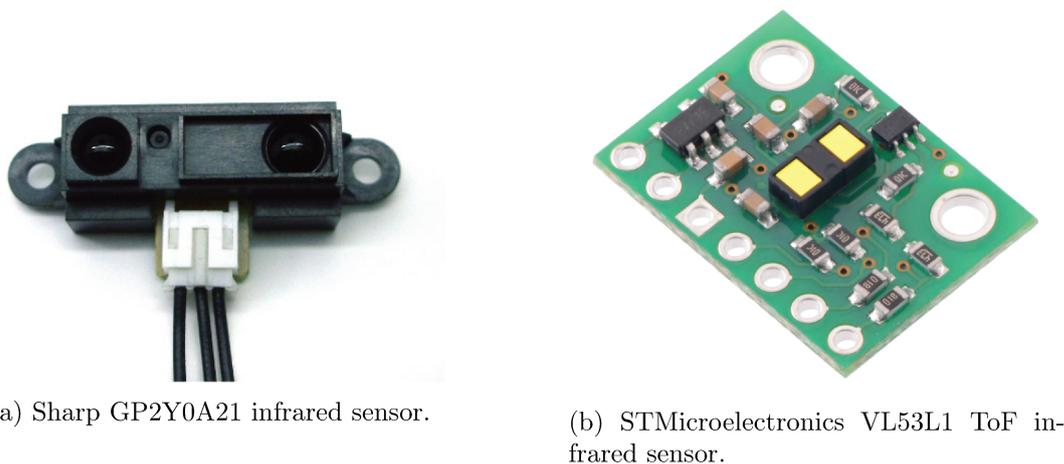


Figure 2.4 – Infrared sensors.

As Simpson highlighted in his review on smart power wheelchair technologies [Sim05], an ideal sensor for power wheelchair navigation assistance would be a low-cost and low-power consumption sensor that can detect obstacles as well as drop-offs over a wide range of operating conditions and surface materials. Although sensing technologies have largely been improved since 2005, there still exists no such sensor available on the market. Hence, there is a trade-off between high-performance but also expensive and fragile sensors such as LiDARS or stereoscopic cameras and low-cost more robust sensors such as infrared and ultrasonic sensor.

## 2.2.2 Control

When a power wheelchair has been instrumented with sensors gathering information from the environment, navigation assistance solutions can be designed in the form of semi-autonomous or autonomous wheelchair control techniques.

Although the term "smart wheelchair" appeared in the literature in the early 1980s [Jaf82], few actual wheelchair navigation assistive solution have ever been used by people with disability. Since that time, many research teams have focused on the development of power wheelchair navigation assistance solutions.

In this section, we present the most commonly used navigation assistance techniques investigated within the smart power wheelchair research field, namely autonomous methods and semi-autonomous control methods.

### 2.2.2.1 Autonomous navigation assistance

Autonomous navigation assistance solutions can be designed to assist people with severe motor disabilities (*e.g.* amyotrophic lateral sclerosis, locked-in syndrom) or executive functions impairments preventing theme to plan or execute a task [DJF02]. Autonomous solutions require the user to indicate the task to perform (maneuvering backwards,

passing a door, etc.) or the destination to reach. Instructions to the wheelchair can be given by speech control [SL02], gaze-based interfaces [MIO01], with a tactile screen device [MDBM10] and even by Brain-Computer Interfaces (BCI) [CM13].

**Localization and mapping** A popular approach to perform navigation tasks safely is path planning. This technique usually requires localization in the environment (*i.e.* in an already known environment, from a starting point, by means of environment instrumentation, with respect to a reconstructed local map of the environment around the robot). Localization consists in determining the pose of a robot relatively to a given representation of the environment in the form of global localization (robot position is estimated without taking account its initial position) or position tracking (estimation of current position by keeping track of motion from initial position). The main localization methods for robot localization are beacon-based localization, dead reckoning localization, and map-based localization.

The beacon-based localization method requires environment instrumentation with elements which the robot will detect to localize itself. These elements, called beacons, are detected by using exteroceptive sensors. Active and passive beacons can be distinguished. Active beacons send a signal which is received by the robot (*e.g.* GPS for outdoor navigation, WiFi for indoor navigation [BV10] [TACA09]) whereas passive beacons emit no power and can be detected by passive exteroceptive sensors such as cameras (*e.g.* 2D bar codes, street signs). The main drawback of this method is that it usually requires the knowledge of the environment or at least an instrumentation of the environment for indoor navigation. However, smart power wheelchair solutions aim to provide assistance while driving a wheelchair in an environment consisting of environmental physical barriers as well as dynamic obstacles such as other vehicles or pedestrians. Therefore, such a method relying on the instrumentation of the environment does not meet the smart wheelchair requirements.

Another typical approach to achieve robot localization is dead reckoning [HBBC96]. Dead reckoning consists of estimating the robot position by calculating its expected positions in the environment given a known starting position. This is achieved by robot's proprioception measurements such as acceleration, heading, wheel rotation. Measuring only the rotation of each actuated wheel using sensors such as encoders is called odometry. One major drawback of this localization technique is that its limited long-term use due to error accumulation: the integration of the sensor data as well as wheel slippage cause inaccurate wheel rotation measurements [BF95]. Some errors are closely related to the design of the robot; these errors can then be reduced by adapting the mechanical design of a robot [CK97]. In addition, wheel slippage issues are common to a majority of mobile robot, power wheelchairs are then also subject to variations of load shifts inducing variations in wheel diameter. This adds errors in the estimation of lateral position [BBL<sup>+</sup>94]. Therefore, the development of solutions on commercialized power wheelchairs which were not designed to minimize dead reckoning errors is particularly not compatible with accurate localization required for a robust control framework.

Finally, autonomous wheelchair navigation is usually achieved by means of map-based navigation [MDBM10] [MHV05] [SSMS17]. In this case, the robotic wheelchair

uses a map of the environment to locate itself using exteroceptive sensors (usually LiDARs) measurements. Some smart power wheelchairs are based on the well-known SLAM technique [CLS<sup>+</sup>10] [CBF<sup>+</sup>14]. This approach consists of mapping the local environment while simultaneously localizing the wheelchair relative to the built map. The benefit of using such a method is that it provides localization without using odometry methods. However, the drawback of these methods is their high computational cost as well as issues while dealing with dynamical environments. Other techniques such as probabilistic map-based discretized occupancy grids can be used to represent the position of obstacles in the environment and compute a safe trajectory within the computed local map [RMSL11]. The trajectory of the wheelchair is often computed using autonomous planners such as the Potential Field Approach. This technique consists in generating collision-free trajectories while relying on a local map of the environment. A commonly used path planning technique is the potential field method [Kha86] [TDG<sup>+</sup>10] which is inspired from the concept of electrical charges. This method consists in considering the robot as an electrically-charged particle that is influenced by charged fields in the environment that can be the goal position to reach (towards which the robot is attracted) and the obstacles to avoid (by which the robot is repelled).

To sum up, a lot of works have been conducted on autonomous wheelchair navigation using path planning, localization, map-based techniques. However, these techniques require the use of expensive sensors (*e.g.* LiDARS, RGB-D cameras). Moreover, the computation of the local map around the wheelchair generally requires high computational capacities which are not compatible with low-cost and low-power consumption embedded computing units.

**Autonomous servoing** Specific driving tasks such as door-passing or navigating safely within a corridor can also be achieved by visual servoing techniques [PNBC16] [NPM<sup>+</sup>16] [PBS13]. The visual servoing approach allows autonomous wheelchair control without relying on a map of the environment or odometry measurement. Moreover, visual servoing techniques provide low-cost and efficient solutions which can be easily embedded on standard power wheelchairs. However, the need for autocalibration prevents the use of cameras in assistive solutions because of robustness issues.

### 2.2.2.2 Semi-autonomous navigation assistance

Navigation support can also be provided in the form of semi-autonomous assistance. Semi-autonomous navigation assistance methods consist in sharing control with the user *i.e.* to allow the wheelchair to progressively take over the control while user input is unsafe. In the literature, three different strategies have been identified [Coo95] [UPFC<sup>+</sup>10]. The first one is based on a goal prediction framework, and requires odometry and usually expensive sensors such as LiDARs. The second one is called behavior-based shared control and switches alternatively between different modes of navigation leading to potentially unwanted discontinuities in the control law. The third solution, denoted as continuous shared control approach, regulates the assistance in a progressive manner while fusing the user control with a collision avoidance framework.

As for autonomous methods, some semi-autonomous methods can rely on local maps of the environment representing the position of the obstacles to avoid [HABC12] [ETD<sup>+</sup>17] [LPN13] [BAK<sup>+</sup>13]. The resulting shared control between the system and the driver is usually achieved by blending techniques or activation of the assistance while needed.

Various semi-autonomous wheelchair project have been designed over the past 25 years such as the Wheelesley [BCM<sup>+</sup>07] or NavChair [LBJ<sup>+</sup>99] projects. However, they usually remained on the stage of laboratory research and no technological transfer was achieved.

## 2.3 Smart power wheelchairs requirements

While with the design of smart automotive solutions, the difficulty in smart power wheelchair development relies on the design, which has to take into account disability specific requirements. Indeed, assistive navigation solutions aim to be used by two end-user categories. While the first concerns people who already have a wheelchair and experience driving difficulties in their daily-life, the second concerns people with severe or degenerative disabilities who cannot drive a power wheelchair safely because their sensory and/or cognitive impairments.

Although Smart Power Wheelchairs have been a research topic since the 1990s, there is still no device available on the market. This lack of technological transfer may be explained by the lack of involvement of end users and clinicians in the development process. And if some research teams had the opportunity to test their smart power wheelchair prototype within rehabilitation centers or care facilities with end users and clinicians, it was typically at the end of the development process. Although user and clinician feedback on the final prototype is very useful, it has been highlighted that they should take part from the beginning in the design and development process. In Rennes, the collaboration between INSA Rennes and Pôle Saint Hélier in which this thesis has taken part is quite unique and made possible the sharing of knowledge and expertise of robotics researchers, neurologists, therapists, and healthcare network. As a result, the proposed Smart Wheelchair solutions are developed using an end-user centered approach. Indeed, the development process involves people in short and long term care, neuropsychologists, occupational therapists, neurologists specialized in physical and rehabilitation medicine.

Moreover, while inexpensive sensors such as infrared or ultrasonic ones are used to detect distances in educational robots, industrial robots still mainly use expensive technologies such as laser rangefinders to detect distances as the measurement are highly accurate and reliable. However, industrial robots do not face the many constraints that embedded robots have to meet, especially robotized wheelchairs.

In 2005, the literature review made by Simpson [Sim05] covering 46 projects worldwide gave an overview of the existing smart power wheelchairs as well as perspectives and guidelines for future smart wheelchair designs in order to achieve widely use. This review highlights the need for low-cost, plug-and-play, easy to learn solutions.

A more recent review on smart power wheelchair technologies defines the best smart wheelchair as a device utilizing at the same time a multi-modal interface that combines computer vision, touch, voice, and brain control; 3D map-based autonomous navigation; cloud computing applications streaming and analyzing sensory data in real-time [LL17]. While such a wheelchair could be useful for people with physical impairments, it would not suit the needs of clinicians and people with severe disability in the context of rehabilitation. Indeed, lessons learned from past projects as well as the collaboration with end-users and clinicians rather recommend simple and easy to learn interfaces and devices, in particular for people with visuo-spatial and cognitive impairments.

The objective of this work is then to provide simple, cost-effective, smart powered mobility solutions. As all these solutions have to be available to end-users, the proposed smart power wheelchairs solutions have to face the following constraints:

- **Power efficiency:** A power wheelchair is generally equipped with a pair of 12V batteries generating 24V. These batteries allow the user to drive for a distance of 30 km range per battery charge. The devices embedded on the power wheelchair (e.g. distance sensors, computing unit) are powered by these batteries. Therefore, the use of low-power consumption devices is mandatory to have a minimum impact on battery usage.
- **Low-cost.** Smart power wheelchairs solutions are intended to provide navigation assistance to people with disability. The provided assistance can take place in the daily life of a person who has a power wheelchair but also in long term care facilities with the aim to maintain autonomy or be used as a training or rehabilitating tool by occupational therapists in rehabilitation centers. Therefore, smart power wheelchair solutions are intended to be low-cost solutions affordable and available for widespread usage.
- **Plug and play solution immediately compliant with any model of commercialized wheelchair:** Depending on the lifestyle, impairments and other factors related to the person who needs a power wheelchair, there are many different power wheelchair types and models available on the market. Therefore, it is important to provide navigation assistance for every model and for all budgets. Moreover, a plug-and-play system can be purchased once and be adapted to multiple chairs over its lifetime. It also provides flexibility in terms of sensor configuration and input controller devices thus matching more easily each individual needs [Sim05].
- **Form factor.** Plug-and-play assistive devices must not modify the size or shape of the wheelchair. Indeed, it is mandatory to maintain the wheelchair's ability to pass doorways and navigate within narrow spaces. Moreover, unchanged size and shape are crucial for the transfers at home or within specialized centers (from the wheelchair to a bed, from a chair to the wheelchair).
- **Low computational cost algorithms:** Embedded computing units such as micro-controllers or Raspberry Pi computers fit the requirements in terms of low-power

consumption, cost, and form factor. However, they offer less processing capabilities. Therefore, smart power wheelchair solutions will have to run with a low-computational cost.

Based on these requirements, smart power wheelchair solutions design is a challenge on innovative detection methods, shared-control methods taking into account user intention but also hardware integration requiring small, robust, low-cost, low-power consumption hardware. In the following, we propose to use sensor-based servoing techniques to design smart powered mobility solutions applied to power wheelchair navigation.

## 2.4 Robotics tools for smart power wheelchair design

### 2.4.1 Power wheelchair modeling

The power wheelchair is modeled as a rigid body composed of 2 actuated wheels; each of which being actuated by independent motors mounted on a common axis. These motors can turn clockwise or anti-clockwise, enabling the wheelchair to achieve linear motion as well as turn motion. As therapists usually recommend 6 wheel wheelchairs to people with driving difficulties, the modeled wheelchair is a 6 wheel wheelchair consisting of 4 passive caster wheels of which 2 are at the front and 2 are at the rear ensure wheelchair support and stability. The classical design of a 6 wheels power wheelchair is represented in Figure 2.5.



Figure 2.5 – Standard 6 wheels power wheelchair (Quickie Salsa M<sup>2</sup>).

This differential drive system induces a non-holonomic constraint on the motion of the wheelchair which is then kinematically equivalent to a unicycle type robot from the class of type (2, 0) robots as defined in [dWSB12]. In the following, let  $\mathcal{F}_R(R, \vec{X}_R, \vec{Y}_R, \vec{Z}_R)$  be the frame attached to the robotic wheelchair (Figure 2.6a).

The control input  $\mathbf{u}$  for such a 2-DoF system is given by

$$\mathbf{u} = \begin{bmatrix} v \\ \omega \end{bmatrix}, \quad (2.1)$$

where the 2 variables  $v$  and  $\omega$  respectively denote the translational velocity along  $\vec{X}_R$  and the rotational velocity around  $\vec{Z}_R$  (Figure 2.6b).

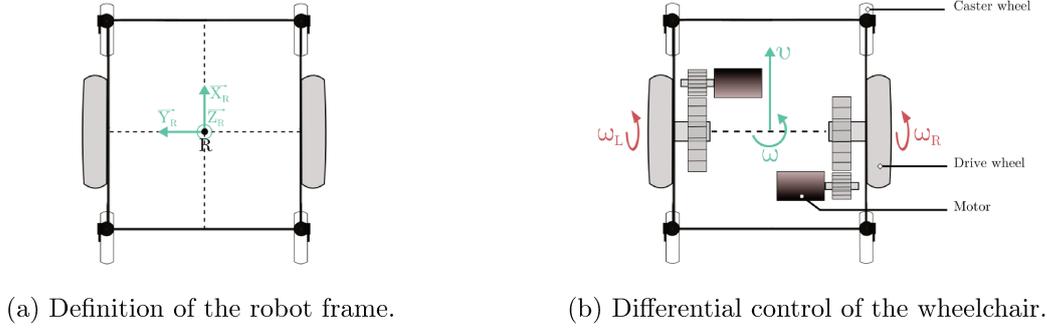


Figure 2.6 – Modeling of the robotic wheelchair.

### 2.4.2 Sensor-based modeling

Let  $\mathbf{x}$  be the a set of data of dimension  $m$  provided by a sensor  $s$ . The sensor jacobian  $\mathbf{J}_s$  links the control input  $\mathbf{u}$  to the sensor signal variation  $\dot{\mathbf{x}}$  so that

$$\dot{\mathbf{x}} = \mathbf{J}_s \mathbf{u}. \quad (2.2)$$

Sensor-based control uses the sensor position with respect to the robot. Let  $\mathbf{v}_s$  be the velocity of the sensor. The sensor motion can then be characterized by its instantaneous velocity

$$\mathbf{v}_s = \begin{bmatrix} \mathbf{v}_s \\ \boldsymbol{\omega}_s \end{bmatrix}, \quad (2.3)$$

where the translational velocity and rotational velocities are respectively given by  $\mathbf{v}_s = [v_x \ v_y \ v_z]$  and  $\boldsymbol{\omega}_s = [\omega_x \ \omega_y \ \omega_z]$ . The sensor motion  $\mathbf{v}_s$  is related to the robot motion  $\mathbf{v}_r$  by

$$\mathbf{v}_s = {}^s\mathbf{W}_r \mathbf{v}_r, \quad (2.4)$$

where  ${}^s\mathbf{W}_r$  is the velocity screw transformation matrix from the sensor frame  $\mathcal{F}_s$  to the robot frame  $\mathcal{F}_R$ . This matrix is given by [Pau81]

$${}^s\mathbf{W}_r = \begin{bmatrix} {}^s\mathbf{R}_r & [{}^s\mathbf{t}_r]_{\times} {}^s\mathbf{R}_r \\ \mathbf{0}_{3 \times 3} & {}^s\mathbf{R}_r \end{bmatrix}, \quad (2.5)$$

where  ${}^s\mathbf{R}_r$  is the rotation matrix and  ${}^s\mathbf{t}_r$  is the translation vector between  $\mathcal{F}_R$  and  $\mathcal{F}_s$ , and  $[{}^s\mathbf{t}_r]_{\times}$  is the  $3 \times 3$  skew-symmetric matrix related to  ${}^s\mathbf{t}_r$ .

The robot velocity is also expressed as

$$\mathbf{v}_r = {}^r\mathbf{J}_r \mathbf{u}, \quad (2.6)$$

where  ${}^r\mathbf{J}_r$  is the robot jacobian expressed in the robot frame such that

$${}^r\mathbf{J}_r = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}. \quad (2.7)$$

Combining 2.4 and 2.6, we can highlight the link between sensor velocity  $\mathbf{v}_s$  and the control input  $\mathbf{u}$  by

$$\mathbf{v}_s = {}^s\mathbf{W}_r {}^r\mathbf{J}_r \mathbf{u}. \quad (2.8)$$

In addition, the variation of the sensor features  $\dot{\mathbf{x}}$  can also be expressed by

$$\dot{\mathbf{x}} = \mathbf{L}_s \mathbf{v}_s, \quad (2.9)$$

where  $\mathbf{L}_s$  is the sensor interaction matrix defined in [SEB91] and [ECR92].

Finally, the sensor jacobian defined in 2.2 is obtained from 2.9 and 2.8, hence

$$\mathbf{J}_s = \mathbf{L}_s {}^s\mathbf{W}_r {}^r\mathbf{J}_r. \quad (2.10)$$

### 2.4.3 Sensor-based control

In case of mobile robotics, while planning techniques require a priori models of the environment, sensor-based control only requires knowledge about the interaction matrix as well as the sensor location with respect to the robot frame. Moreover, this method allows to achieve low-computational cost thus meeting the embedded systems requirements. In addition, it is possible to achieve flexible and reactive control while at the same achieving satisfying precision and speed performances.

The goal of a sensor-based task is to control the system by regulating the error  $\mathbf{e} = \mathbf{x} - \mathbf{x}^*$  defined as the difference between the set of data  $\mathbf{x}$  of dimension  $m$  provided by a sensor mounted on a robot and its desired value  $\mathbf{x}^*$  to zero. The motion task is expressed in the sensor space, there is no pose estimation nor motion planning. Therefore, no a priori knowledge of the environment is needed leading to better robustness against unpredictable events (*e.g.* dynamic obstacles).

Based on the sensor-based modeling presented in Section 2.4.2, we can then determine the control law ensuring at best an exponential decrease of the error  $\mathbf{e}$  as

$$\dot{\mathbf{e}} = -\lambda \mathbf{e}. \quad (2.11)$$

Combining 2.9 and 2.11, we obtain the following control law:

$$\mathbf{u} = -\lambda \mathbf{J}_s^+ (\mathbf{x} - \mathbf{x}^*) \quad (2.12)$$

where  $\lambda > 0$  is a gain and  $\mathbf{J}_s^+$  is the Moore-Penrose pseudo-inverse of the sensor jacobian  $\mathbf{J}_s$ .

## 2.5 Towards user-centered smart powered mobility design

This chapter has presented an overview of existing works on assistive solutions for powered mobility. From the review of these works outcomes and conclusions, technological requirements for new designs have been deduced. This thesis aims to take into account the feedback from all these past projects experiences and conclusions to develop adapted, relevant navigation assistance solutions. To do so, this thesis also relied on

the close collaboration with users and therapists to better define the expectations as well as limitations related to the output of this work. In the next chapters, we will present the tools and solutions for powered mobility which arise from this thesis. We first present a powered mobility simulator enabling rapid design of proof-of-concept as well as a promising tool for learning and rehabilitation purposes. The navigation assistance methods developed in this work rely on the sensor-based modeling and techniques presented in section 2.4.

## Chapter 3

# An assisted powered mobility simulator

This chapter presents the design of an assisted powered mobility simulator. We present here the clinical and technological motivations for this work. Then, we present the proposed powered mobility simulator framework. Finally, we present validity assessments of the proposed assisted powered mobility simulator. The content of this chapter has been presented at the IEEE International Conference on Rehabilitation Robotics (ICORR) in 2017 [C.1].

### 3.1 Why design a powered mobility driving simulator ?

#### 3.1.1 Virtual reality benefits

**A tool for ecological assessment** Virtual Reality (VR) is a promising tool to be directly used by therapists and patients. Indeed, it has been shown to be easy to use, safe, and to contribute to high patient satisfaction within a clinical context [DRI<sup>+</sup>17] while also impacting positively on user's motivation [BBB<sup>+</sup>06][How17]. Real-world scenarios can be simulated within flexible, and repeatable Virtual Environments (VE). Moreover, simulated scenarios are risk-free and therefore require less supervision from therapists as they provide a safe environment without any risk of collision or physical injury. VR allows the therapists to achieve abilities assessment by simulating more ecological situations [OASL18] by placing patients in simulated daily-life scenarios which can hardly be set up within classical evaluation because of time, cost, space or risk considerations.

**A tool for rehabilitation** VR can also play a positive role within rehabilitation purposes. Indeed, some VR systems have already been investigated to help people with disability develop new communication skills [Str97], and improve their ability to achieve tasks of the daily-life situations simulations within outdoor environments [DMC<sup>+</sup>12][KKS<sup>+</sup>13]. Moreover, as VR allows full control over the simulated environ-

ment, it also enables control of events and thus the amount of distractions and tasks to achieve is controllable. Therefore, a simulated virtual environment can contain more or less distractors or tasks to achieve and thus adapt the cognitive load for patients. Hence, it is possible to challenge participants execution functions during grocery shopping simulation [KKS<sup>+</sup>12] or attention functions street crossing [NLN<sup>+</sup>13] or to train specific tasks such as driving a wheelchair [IL95].

**A tool for prototyping** These last decades, simulators have played a critical role in robotics research as they provide the possibility of quick and efficient testing of new concepts, strategies, and algorithms. Indeed, Virtual Prototyping (VP) uses virtual rendering to design a system and evaluate its performances while eliminating the need for designing physical prototypes. In addition, VP allows quick developments thus reducing the time involved in design and performance evaluation of complex systems as well as their development costs [RHT16]. Besides, VP also allows multiple persons to design and test different prototypes [CFS17] without requiring multiple physical platforms to be available. This makes VP a powerful tool for within robotics research and development processes.

### 3.1.2 Powered mobility simulation: related work

Powered mobility simulation started in 1992 with the very first power wheelchair driving simulator [LW92]. However, almost 30 yrs later, powered mobility simulation is still a research topic with few on-going projects and no industrial solution available on the market, in particular for clinical use by therapists.

Several powered mobility simulator have been designed for power wheelchair navigation. In France, a research team elaborated the ViEW simulator to identify driving difficulties by performing driving analyzes but also training sessions aiming to improve driving performances in the real world [MBC<sup>+</sup>18]. This simulator allows to easily and quickly perform driving sessions while recording driving-related data without instrumenting a wheelchair or the environment. It is displayed on a single computer screen and has been already used within rehabilitation center with children having Cerebral Palsy (CP) (Figure 3.1) as well as people with multiple sclerosis [MFR<sup>+</sup>14]. The positive results of a recent study tend to show that, in terms of training, a powered mobility simulator can be a valuable decision-making tool for evaluation of driving abilities by therapists [MBC<sup>+</sup>18].

Another simulator has been developed in Quebec, the miWe simulator. This powered mobility simulator also aims to assist therapists in assessing and training power wheelchair driving skills. It is also displayed on a single computer screen (Figure 3.2).

While a majority of simulators use a single screen display, some simulators use 3 or 4 screens to give a wider view of the virtual environment as well as increase user sense of immersion. The simulator proposed in [MDCD13] uses 3 computer screens to perform wheelchair driving performances assessment and training [MDCD13]. An other design combines the use of 4 computer screens display with the use of a 6 axes stewart platform to increase user sense of immersion [ISIK09]. However, this type of design does



Figure 3.1 – Scene from the view simulator [MBC<sup>+</sup>18].

not seem safe enough to be accepted nor used by clinicians and people with disability. Some other simulators use more immersive display devices: Head Mounted Displays (HMD) [Gon14][RPM<sup>+</sup>15][HDP<sup>+</sup>15][NGSK17]. Although greatly improving the sense of immersion within the simulation, HMDs require user embodiment representation in the virtual world. This can be achieved by accurate motion capture of the whole body thus requiring the use of specific additional sensors or even markers displayed on the user body. However, solutions requiring instrumentation of the body as well as wearing a mask can cause user acceptability issues.

The majority of powered mobility simulation devices are displayed on screens and thus poorly immersive. Nevertheless, several research teams have developed driving simulators and VR applications including power wheelchair navigation scenarios [ACR09], [Rod15], [ARO17]. Most of the driving simulators in the literature are displayed on a computer screen or with a Head Mounted Device (HMD). In such configuration, the virtual simulation generally includes the representation of a self-avatar as it increases the sense of immersion and improves size and distance judgments [Sch10]. The presented work can be considered as a first step in the simulator development process. As user embodiment is complex to be transcribed because it requires motion capture of the all user body parts (feet, legs, hands, etc.), we rather use an immersive 3D life-size scale platform allowing the user's real body to be immersed within the virtual environment.

Finally, the powered mobility simulator must ideally be validated in terms of similarities with real world experiences to ensure proper use and benefits within clinical assessment and rehabilitation contexts. In the literature, 4 levels of simulator validity have been identified, namely physical, experiential, ethological, and psychological validity [MF01]. Physical validity refers to the similarity of sensory perception between real and virtual environments (*i.e.* accelerations, contrasts, spatial sound). Experiential



Figure 3.2 – Scene from the miWe simulator [ACS<sup>+</sup>11].

validity is the similarity between sensations experienced in real and virtual situations. Ethological validity concerns the similarity between the behaviors adopted on the simulators and in real situation. Finally, psychological validity deals with the underlying processes which lead to a the adopted behavior.

In the field of car driving, a long-term study has shown positive transfer of driving skills from the virtual situation to real world situations [HB16]. As for wheelchair driving, some studies have started to investigate simulator validity assessment. For example, a study on the miWe simulator comparing wheelchair driving performances between 2 groups in real and simulated environments showed similar driving performances between driving in virtual situation and in real life [ATC<sup>+</sup>12]. Another older study has also shown compared wheelchair driving performance with 2 joysticks inputs both in virtual and real environments [CSJ<sup>+</sup>02] showed similar wheelchair driving performances in the real and virtual conditions. They also emphasized the fact that virtual wheelchair driving training may provide greater practice to users while not requiring more clinician time than clinical evaluation and training currently carried out in real environments.

Although driving simulators are used in some research laboratories even within clinical assessment contexts, no simulator incorporates assistive navigation methods nor the possibility to easily develop robotic solutions. The purpose of this work is then to propose such a standardized, easy to use simulator for research and development but also driving skills assessment, learning, and rehabilitation.

## 3.2 An assisted powered mobility simulator

This section details the proposed simulator for assisted powered mobility.

### 3.2.1 Generic driving simulator framework

The idea is to propose a simulation framework in which a virtual wheelchair can be actuated with any type of input controller (e.g. wheelchair standard joystick, game controller, chin control device). The resulting 3D Virtual Environment (VE) aims to be displayed on multiple virtual devices (e.g. computer screen, on an HMD, or on an immersive VR room). In order to provide a realistic behavior, the dimensions and the behavior of the virtual wheelchair have to be rigorously similar to those of a chosen real wheelchair model. The virtual wheelchair designed for this simulator has been modelled from the Luca power wheelchair from the Sunrise company (Figure 3.3a). This wheelchair has previously been used as a first prototype of smart wheelchair solutions [BPG<sup>+</sup>15]. The virtual and real wheelchairs are presented in Figure 3.3.

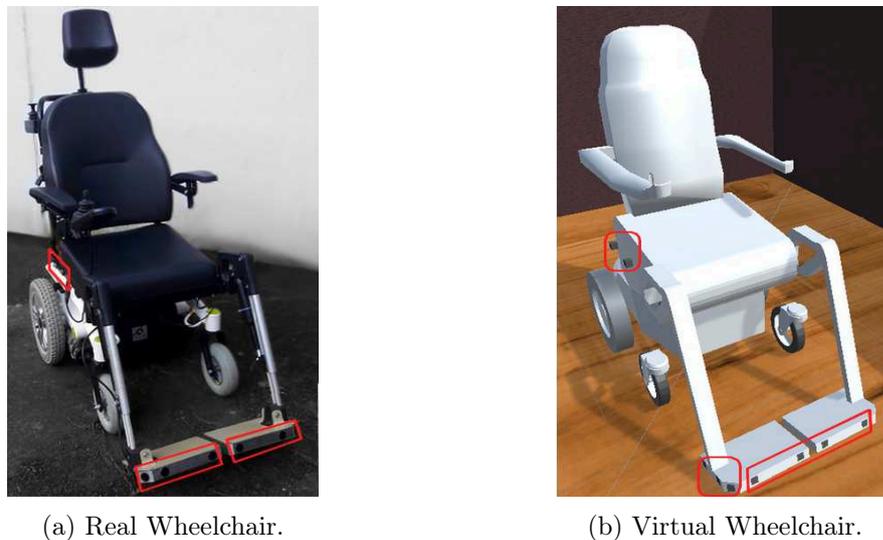


Figure 3.3 – Real and virtual wheelchairs. Red frames indicate sensor positions.

### 3.2.2 Wheelchair driving simulation

The proposed framework was developed in collaboration with the Irisa/Inria Hybrid team using the Unity 3D/MiddleVR game development platform especially to be easily interfaced with the 4 screen Immersia Virtual Reality platform located in Rennes (Figure 3.4). Unity 3D is a widely used cross-platform game creation system developed by Unity Technologies. It includes a game engine and an integrated development environment. MiddleVR is a generic immersive VR plugin compatible with Unity. The communication

between 3D world and VE is achieved by means of a generic framework developed with the middleware ROS .



Figure 3.4 – Immersia is one of the largest VR research platforms in the world. It is composed of 4 large screens on which images are projected for a total volume of approximately  $90m^3$ . The 3D rendering is achieved by using active stereoscopic method associated with shutter glasses. 16 infrared cameras track the moving objects on the platform.

As a first step, the virtual power wheelchair actuation is implemented using the framework represented in Figure 3.5. The proposed framework is composed of the following 3 ROS nodes, namely:

- Display ROS node. This node manages VE display *i.e.* the display of virtual components within the scene. It also deals with the physical engine computations allowing wheelchair realistic behavior in terms of navigation and interaction with the VE. Moreover, this ROS node manages automated data collection from the VE. Finally, the Display ROS node also manages virtual wheelchair control, here torques applied to each motor wheel.
- Controller ROS node. This ROS node manages input controller data collection, here the standard wheelchair joystick commands.
- Control ROS node. This node manages the computation of the velocity control input to be applied to the wheelchair.

At this stage, the proposed framework allows wheelchair control within the VE (Display node) using a velocity control input (Control node) computed from the controller information (Controller node).

### 3.2.3 Assisted navigation within the virtual environment

In addition to power wheelchair driving simulation, the proposed simulator also consists of an assisted navigation functionality. The simulator is thus provided with a robotized virtual wheelchair equipped with virtual sensors able to detect environmental features.

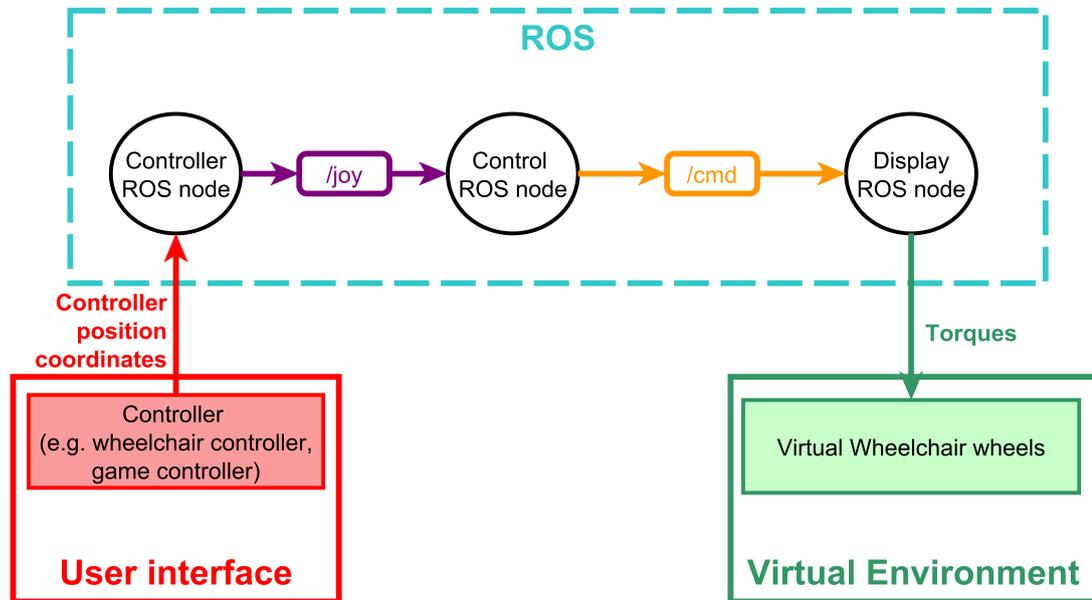


Figure 3.5 – Input commands are collected using the Controller ROS node and used by the Control ROS node to compute the commands to apply to the virtual wheelchair. The Display node handles the display of the VE as well as the commands to the virtual wheelchair actuators.

As multiple assisted navigation solutions aim to be designed within this simulator, the proposed framework has to be versatile and flexible in order to easily add new functionalities and switch between the different solutions. The resulting generic framework (Figure 3.6) is an extension of the framework presented in section 3.2.1.

In this framework, the virtual wheelchair is controlled by means of torques applied on its wheels (Display node) which are computed from the velocity control input (Control node) calculated from input controller information (Controller node). Virtual sensor information (represented in blue dashed line) is used to compute a control law (Control node). The resulting velocity control input can be used to modify the virtual wheelchair trajectory within the VE or to send additional information to the user through a haptic a feedback interface (black dashed line).

### 3.3 Simulator validity assessment

#### 3.3.1 Study design

The proposed simulator was assessed in terms of quality of experience and satisfaction with able-bodied participants. This experiment consisted in navigating in the VE while sitting on a real power wheelchair placed on the immersive platform (Figure 3.7). The proposed study was designed and conducted in collaboration with the clinical staff of the Rehabilitation Center Pôle Saint Hélier.

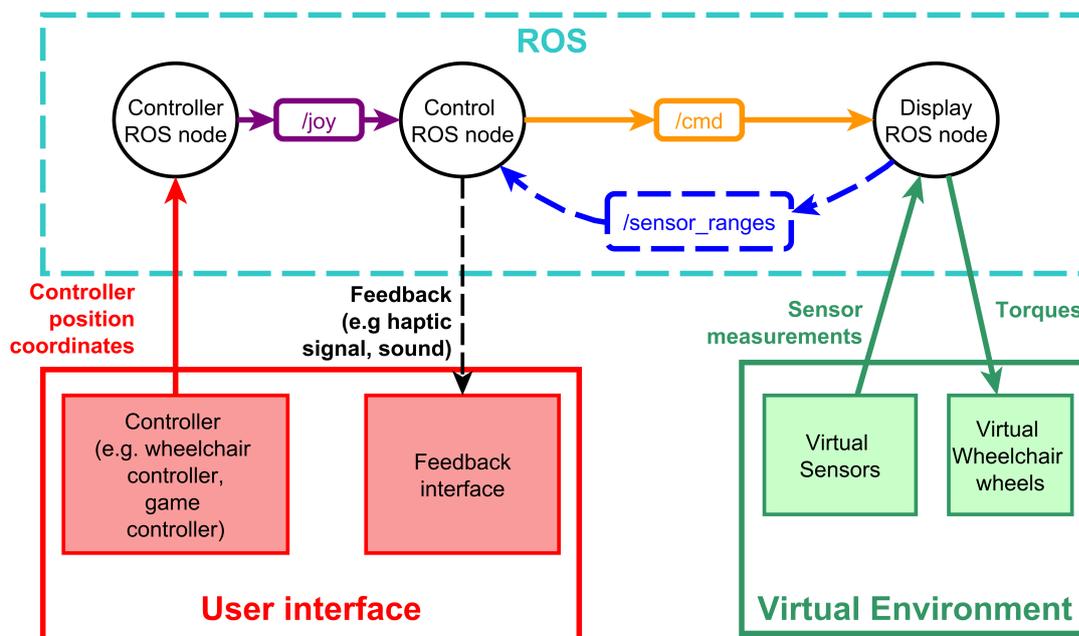


Figure 3.6 – Power wheelchair assisted navigation simulator framework.



Figure 3.7 – User sitting on a real power wheelchair placed on the immersive platform.

The VE used in this study was composed of two obstacle courses:

- Obstacle course A (Figure 3.8): This obstacle course is taken from [HWM13]. It is composed of maneuvers such as right/left turns, discrete maneuverability obstacles, straight line path and a turnaround.
- Obstacle course B (Figure 3.9): The second obstacle course was designed for the experiment. The user starts at the beginning of a corridor of decreasing width, turns right and follows a 1 m wide corridor with a 0.9 m wide open door on his right. At the end of the corridor the user passes through a narrower passage and traverses a space with obstacles.

Participants were first asked to perform a set of individual driving tasks derived from the widely used standardized Wheelchair Skill Test ([KDM<sup>+</sup>04]) such as rolling forwards,

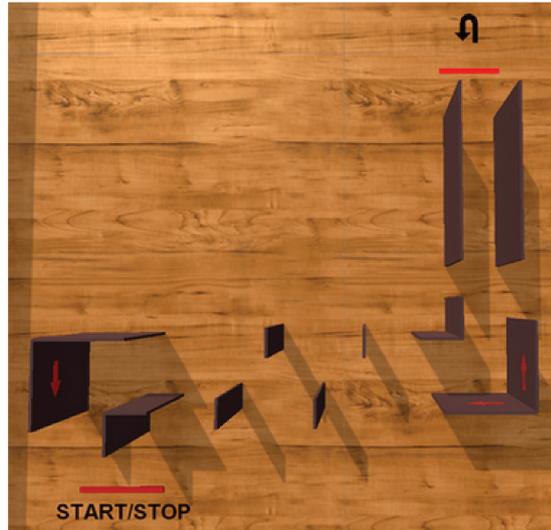


Figure 3.8 – Obstacle course taken from [HWM13] in the VE.

turning  $90^\circ$  while moving forward, turning in place. This preliminary training session was done in order to ensure that participants were able to manipulate the wheelchair in the VE before accomplishing other tasks in the VE.

After this short training, participants were asked to drive the wheelchair on the two obstacle courses with and without driving assistance in single-blind so that the participants were not aware of the state of activation of the assistance. Trials were randomized by switching the order of the driving assistance state of activation. Moreover, the order of passage was alternated for the 2 obstacle courses to avoid a possible learning effect. Instructions were given before the trial. Signs were added to indicate the user the direction to follow in the virtual environment in order to minimize the experimenter’s intervention while the participant was on the platform because preliminary tests showed that it was strongly uncomfortable and disturbing for a participant to have someone giving instructions while navigating in the virtual environment. The overall test took about 20 minutes per participant.

### 3.3.2 Data collection

Automated data collection using ROS was used to record the following data

- commands from the wheelchair joystick,
- commands sent to the virtual wheelchair,
- wheelchair position and velocity with respect to the global world,
- collision coordinates in the virtual environment,
- virtual sensors data,

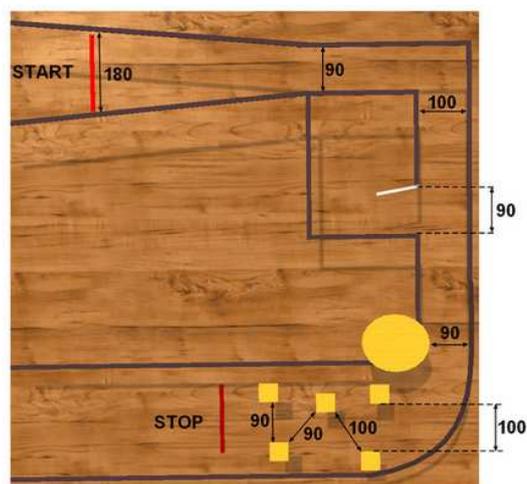


Figure 3.9 – Obstacle course designed for the experiment.

- time completion.

After completing the obstacle courses on the simulator, participants were asked to complete a set of questionnaires. The first one is the I-Group Presence Questionnaire (IPQ [Sch03]). This test consists of 14 items divided into 4 categories namely Spatial Presence (SP), Experienced Realism (REAL), Involvement (INV), and General Impression (G) evaluated using a 7-point Likert scale. The workload imposed by the simulator was also assessed using the widely used NASA Task Load Index questionnaire (TLX [Har06]). It is composed of six questions related to the following workload factors: Mental Demand (M), Physical Demand (PD), Temporal Demand (T), Performance (P), Effort (E), and Frustration (F).

The following 7-point Likert questions were added to the participants questionnaire sheets

- Rate your experience with power wheelchair.
- Did you experience sickness on the simulator?
- Did you experience headache on the simulator?
- How often do you play video games?
- How often do you use virtual reality devices?

in order to better understand the answers of the participants.

### 3.3.3 Results

9 able-bodied participants aged from 11 to 38 years old have volunteered to participate in this study. Most of the participants were novice with power wheelchair driving, only

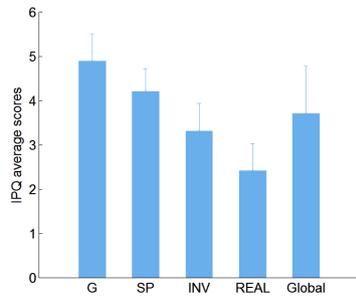


Figure 3.10 – Average IPQ score for each category. Global represents the global score. Error bars indicate standard deviation.

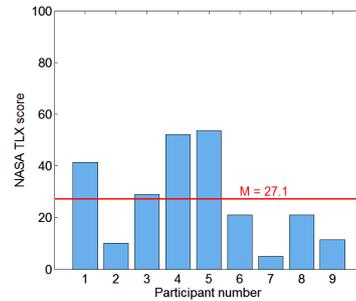


Figure 3.11 – NASA-TLX scores M represents the mean value over the 9 participants.

one of them rated his experience with power wheelchair driving as 5 out of 6 on a 7-point Likert-type scale.

### 3.3.3.1 Presence

Presence was measured using the IPQ Questionnaire [Sch03]. Means and standard deviation for all categories are displayed in Figure 3.10. Scores were on average above 3 for Involvement (INV) and above 4 for General Impression (G) and Spatial Presence (SP). Experienced Realism score (REAL) was on average below 3.

### 3.3.3.2 Perceived Workload

Perceived workload was assessed using the NASA-TLX Questionnaire [Har06]. The user rates each workload factor on a scale from 0 to 100. The total workload score is calculated by a weighted sum of the six scores. NASA-TLX scores are displayed on Figure 3.11. The results show scores on average below 50 and with a mean of 27.2 +/- 18.2 (Mean +/- Standard Deviation) over the 9 participants.

### 3.3.3.3 Simulator sickness

6 participants reported having felt sick during and/or after the experiment and 4 of them also suffered from headache. The intensity of these effects was moderate and did not prevent the users from completing the experiment.

### 3.3.3.4 Driving assistance

7 participants out of 9 noticed the activation of the driving assistance. Figure 3.12 shows the number of collisions that occurred with no assistance activated during the experiments. Participants collided a total number of 25 times. With assistance activated, only 1 participant hit an obstacle.

The completion time values are summarized in Figure 3.13 and show that trials with assistance last more time than trials without assistance.

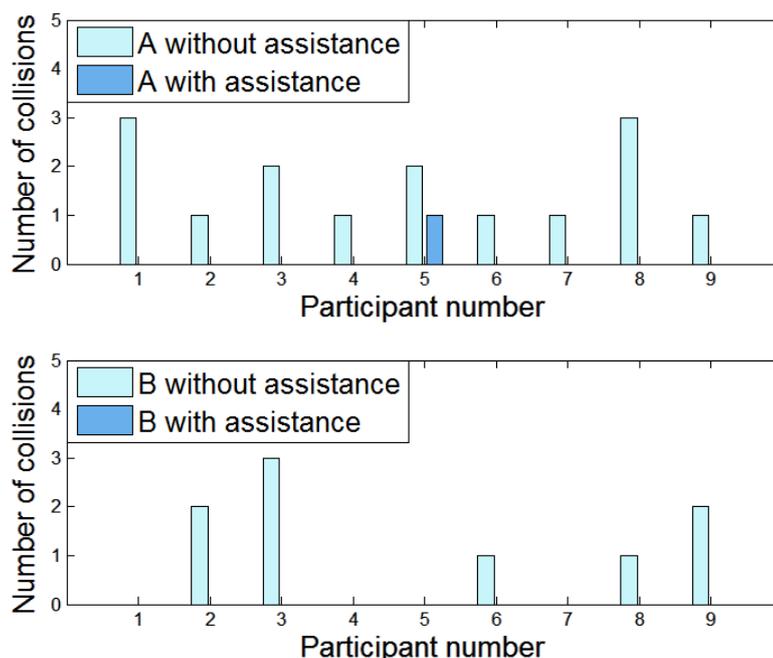


Figure 3.12 – Number of collisions for each participant on both obstacle courses with and without driving assistance activated.

### 3.3.4 Discussion

Based on the IPQ questionnaire results, the proposed simulator seemed to generate a rather good sense of presence. The only low IPQ questionnaire score is related to Experienced Realism (on average below 3), indicating that participants did not interpret the simulated environment as a real one, which is not surprising as the design of the VE was poorly realistic. NASA TLX questionnaire suggests that the use of the simulator requires moderate cognitive load. As for the driving assistance, 7 out of 9 participants noticed its activation. It is to be noted that most of them were aware of the nature of our research work probably leading to a bias in their perception of driving assistance activation. One of the two other participants who did not notice the activation of the assistance is used to drive a power wheelchair: this tends to show that the behavior of the virtual wheelchair in the simulator is not altered by the application of the driving assistance algorithm.

Most of the participants reported having felt moderately sick during the navigation tasks. This issue could be partly due to the fact that driving in the VE generates quick movements for which the refresh rate of the virtual reality platform (60 images per second) could be insufficient. For another part, this is due to the fact that the wheelchair

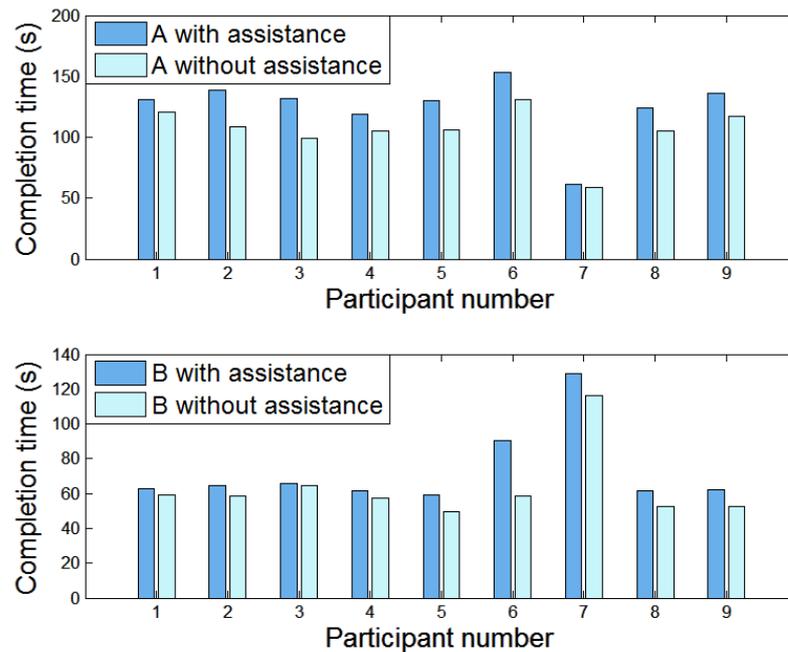


Figure 3.13 – Completion time for each participant on both obstacle courses with and without driving assistance activated.

is not moving while moving images are displayed on the screens. This probably leads to an alteration of the perceived self-motion. To address this issue some improvements of the simulator can be made. First, as it is indicated in [RVSP09], adding auditory cues can increase the perceived self-motion. Future works will then address this problem by adding sounds to our simulator, especially wheelchair brake sounds. Future work will also focus on increase navigation realism and perceived self-motion by adding tactile sensory cues using a mechanical force feedback platform [RPM<sup>+</sup>15].

Results of the experiments show that participants collided a total of 25 times with no driving assistance whereas only one participant collided once with an obstacle while the assistance was activated. Collisions happened more often on the obstacle course A, particularly on the part with moveable obstacles. Here, performing navigational tasks on obstacle courses allowed us to validate the use of virtual sensors to perform driving assistance. The collision recorded while the assistance was activated happened on a difficult maneuver where obstacles are discrete and quite thin. Therefore, this collision was most probably due to the fact that the rays sent by virtual sensors did not detect the thin obstacle. One solution to this could be to improve virtual sensor measurement by using cone-shaped virtual objects instead of raycasting method.

However, while this study showed simulator validity in terms of able-bodied user quality of experience within VE only, such a powered mobility simulator has to ensure behavioral and experiential realism. While the former concerns wheelchair dynamical

behavior such as speed, acceleration and driving sensations, the latter concerns the correspondence between virtual and real environments. In particular, standardized environments and scenarios are expected to enable benchmarking between different smart power wheelchair solutions. Within the scope of training or rehabilitation, experiential validity is highly required, particularly to ease skills transfer and behaviors acquired during the wheelchair driving sessions.

## 3.4 Simulator experiential validity assessment

The objective of the proposed study is to assess experiential validity of the proposed powered mobility simulator. The idea is to carry out driving tests within virtual and real identical environments on identical virtual and real driving circuits.

### 3.4.1 Assessment protocol

#### 3.4.1.1 Objectives

The first objective is to compare user wheelchair driving performance on the same driving task between real and virtual conditions. Moreover, this study aims to evaluate the simulator experiential validity *i.e.* the similarity of feeling between the real environment and its virtual equivalent. In other words it is the degree of subjective credibility given to the simulated situation. In this case, the objective is to compare the wheelchair driving experience between real and virtual conditions.

#### 3.4.1.2 Assessed criteria

In this study, the following criteria are assessed:

- navigation task completion time,
- number of collisions,
- sense of immersion (IPQ questionnaire [Sch03]),
- cognitive load on the wheelchair driving task in real and virtual conditions (NASA-TLX Questionnaire [Har06]),
- participant sickness level (only in virtual condition) with a single 10 points Likert scale,
- participant satisfaction (USE Questionnaire [Lun01]).

#### 3.4.1.3 Population

10 able-bodied participants aged from 18 to 28 years old without prior wheelchair driving experience participated in this study.

#### 3.4.1.4 Driving task

Participants were asked to drive on a driving course which has been designed within the scope of the Interreg ADAPT project (<https://adapt-project.com>). This course, depicted on Figure 3.14, consists of the following steps

- wheelchair starting before the starting line,
- go to the end,
- turn around,
- continue back to the start line,
- cross the start line,
- turn around a plastic cone positioned 1 meter from the start line,
- cross the start line again,
- go forward for 3 meters, stop,
- go backward until the start line and stop.

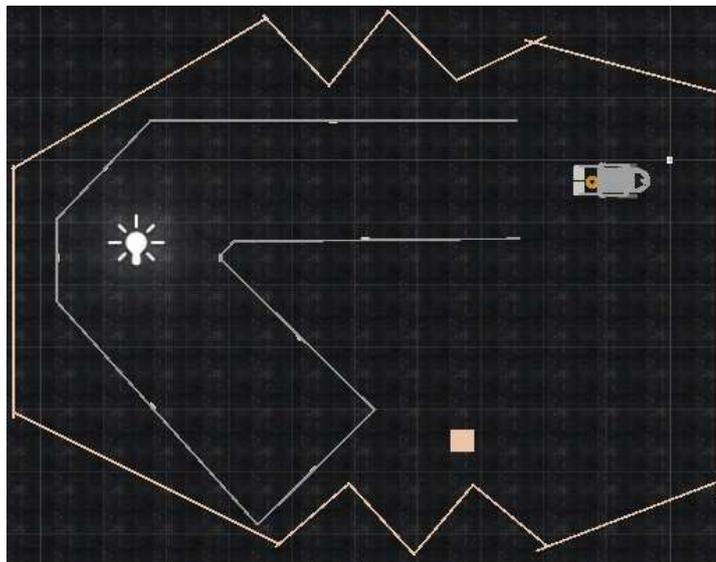


Figure 3.14 – Circuit designed for this study.

#### 3.4.1.5 Procedure

Tests were performed on two days. Participants performed the wheelchair driving test in the real condition on the first day and the virtual wheelchair driving tests in the

virtual condition on the second day. The instruction given to the participants for the 2 conditions were to drive the fastest they can without colliding. Wheelchair parameters (acceleration, deceleration, speed) were the same for all the participants.

**Day 1: Real condition** Before performing the driving task, participants were given 3 minutes off the circuit to take the power wheelchair in hand by performing basic maneuvers. Then, participants were asked to perform the driving task 6 times in a row. At the end of the 6 times performing this driving circuit, participants were asked to fill all the questionnaire and evaluation scales. Circuit setup is shown on Figure 3.15.



Figure 3.15 – Driving circuit setup in the real condition.

**Day 2: Virtual condition** Tests in the virtual condition were conducted on the VR platform Immersia (Figure 3.4). The user's head position is tracked in order to move the virtual scene viewpoint accordingly to user movements.

The circuit used in virtual condition is the same circuit, with the same exact dimensions reproduced within the virtual environment. Circuit setup is shown on Figure 3.16.



Figure 3.16 – Driving circuit setup in the virtual condition.

The virtual wheelchair is configured with the same speed as in the real condition. In this framework, the user is sitting on a real standard power wheelchair placed on a VR

platform at the same position as the virtual wheelchair in the VR platform's frame. The participant sitting on the real power wheelchair operates a standard joystick from Penny & Giles attached to the wheelchair to control the virtual wheelchair (Figure 3.17).



Figure 3.17 – Participant driving the virtual wheelchair in the VE while seating on a real wheelchair.

Before performing the driving task, participants were given 3 minutes off the circuit to take the control of the power wheelchair in virtual reality and perform basic maneuvers in the virtual environment.

Then, participants were asked to perform the driving task 6 times in a row.

At the end of the 6 times performing this driving circuit, participants were asked to fill all the questionnaire and evaluation scales.

### 3.4.2 Results

We here present the results of the experiential validity simulator assessment.

### 3.4.3 Discussion

Participants generally took less time to perform each trial of the course in the virtual condition. While there was no gap between numbers of collisions in real and virtual conditions (Table 3.5), the difference between time completion (Table 3.4) results can be explained by the lack of caster wheels dynamical effects on the trajectory of the virtual wheelchair. This study has been conducted with a version of the proposed simulator which relies on the Unity physics engine and thus cannot take the caster wheel effect

PN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	MS
1	2	5	5	3	4	5	5	5	6	5	6	2	3	2	4,14
2	5	2	7	6	4	5	5	6	6	5	4	2	2	6	4,64
3	4	3	2	3	2	6	1	6	6	6	2	1	4	7	3,79
4	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
5	3	5	5	5	3	6	2	6	3	5	5	2	3	5	4,14
6	5	3	7	4	4	5	5	5	5	5	5	2	4	6	4,64
7	3	2	7	6	4	5	3	6	6	6	5	2	2	5	4,43
8	4	4	6	3	4	5	5	5	5	5	2	2	3	3	4,00
9	5	5	6	7	6	4	3	6	6	5	6	1	5	3	4,86
10	2	6	5	4	4	6	3	5	4	5	2	3	4	4	4,07
11	3	3	5	5	4	5	5	5	6	5	5	1	6	5	4,50
MS	3,6	3,8	5,5	4,6	3,9	5,2	3,7	5,5	5,3	5,2	4,2	1,8	3,6	4,6	4,3

Table 3.1 – IPQ questionnaire detailed scores. MS = Mean Score. PN = Participant Number. \* = participant withdrawal.

	Mean score
General	3,6
Spatial presence	4,6
Involvement	4,9
Experienced realism	3,6
Global	4,3

Table 3.2 – IPQ questionnaire mean scores.

into account. This issue could be alleviated by implementing a full power wheelchair physical engine allowing identical behavior to real navigation. This work is currently undergoing within the Interreg ADAPT project.

In terms of immersion in our simulator, we can notice better global results than in the previous study presented in section ???. This was mainly due to the fact that participants recognized the reconstituted real environment in which they performed the first part of the trial on the day before. Indeed, IPQ Questionnaire results 3.1 were rather satisfying, with better scores than the previous study. Moreover, NASA-TLX scores are higher in virtual reality but still rather low (Table 3.6). This suggests that the

Participant	1	2	3	4	5	6	7	8	9	10	11	Mean Score
Sickness level	10	9	3	*	2	8	4	*	7	7	8	6,44

Table 3.3 – Participant sickness level scores. \* = Participant withdrawal.

	Real condition	Virtual condition
Mean	86,21	79,94
SD	1,555	0,980

Table 3.4 – Time of completion mean scores (s). SD = Standard Deviation.

	Real condition	Virtual condition
Mean	0,08	0,11
SD	0,106	0,088

Table 3.5 – Number of collisions. SD = Standard Deviation.

	Real condition	Virtual condition
Mean	2,98	3,60
SD	1,229	1,091

Table 3.6 – Task load. NASA-TLX questionnaire mean scores (Likert 7-point scale). SD = Standard Deviation.

	Ease of use	satisfaction	ease of learn
Real condition	5,96	6,59	5,24
Virtual condition	5,53	6,27	4,80

Table 3.7 – User satisfaction results. USE Questionnaire mean scores (Likert 7-point scale)

simulator is simple enough to learn and use. Moreover, results of the USE Questionnaire show user rather equal satisfaction with both conditions (Table 3.7).

In addition to experiential validity, behavioral validity will also be assessed before considering clinical use of the simulator for assessment and rehabilitation purpose. Indeed, such a simulator has to provide behavioral validity *i.e.* corresponding behavior between real and virtual environment. This is mandatory to properly assess either one individual's performances or transferring skills acquired in virtual reality to the real world. To do so, future works will aim to investigate user behavior analyzes within real and virtual conditions. Additional data can then be recorded, for example, the deviation from an ideal trajectory [MSD<sup>+</sup>11] or user interventions on the controller input [ACS<sup>+</sup>11][MBC<sup>+</sup>18].

Moreover, future works will aim to define multiple scenarios including different difficulty levels from basic maneuvers within indoor environments without distractions to complex maneuvers within complex highly distractive environments.

In terms of physical validity, existing systems including the proposed simulator, are not technically able to produce physical validity [MF01]. Therefore, technical solutions can be used to produce illusions relying on human sensory and visual perception limitations. Although the results on immersion and satisfaction seem to be satisfying, the feeling of nausea, headache or even sickness are still felt by the participants (Table 3.3). While one of the participants has withdrawn from the experiment during the tests on the virtual platform, on other has withdrawn during the filling of the scales at the end of the trial. Apart from these 2 participants who felt very sick, sickness levels are rather disparate from 2 to 10 with a mean score of 6,44 on all the participants. This shows that physical validity is not achieved yet. To alleviate this issue, the physical validity of the proposed simulator aims to be significantly improved by future use of a dedicated mechanical platform (Figure 3.18) rendering driving sensations. This platform comes with a Salsa M2 wheelchair seat. This physical rendering platform aims to reproduce physical sensations such as acceleration or damping. Hence, it will replace the standard wheelchair currently used to control the virtual wheelchair within the virtual environment. This work is on going within the Interreg ADAPT project.

### 3.5 Conclusion

As discussed in section 3.1, VR is a relevant tool for assisted navigation solutions prototyping and driving skills assessment and rehabilitation. The powered mobility simulator proposed in this work first aims to allow rapid design of proof-of-concepts and feasibility tests of assisted navigation solutions within a realistic simulated environment to reproduce real-life situations.

As it provides risk-free environments for power wheelchair navigation with automated data collection, such a simulator could also further be extended to the evaluation and training of inexperienced power wheelchair users if validated through future tests with occupational therapists and people with disability. Since it has been designed in such a way that it is multi-platform, it could easily be displayed on an HMD or be



Figure 3.18 – Mechanical platform for enhanced virtual experience.

reproduced in a smaller and low-cost VR platform in a rehabilitation center. Then, the idea is to extend the use of such a tool to clinical assessment and rehabilitation use, for example to perform relevant driving skills learning in particular situations such as crossing the road or navigating on a curb. Moreover, as this tool aims to ease assisted navigation solutions development, driving assistance solutions also aim to be available within this simulation to assist the therapist within rehabilitation scenarios.

With a powerful tool such as Virtual Reality more ecological situations should be designed. People with disability could greatly benefit from virtual training within daily life situations encountered by wheelchair users. The training could consist of learning how to maneuver a wheelchair in large spaces but also challenging driving abilities with more difficult tasks such as navigation in a narrow corridor or with obstacles on the way. Future works will aim to improve the simulator with new Virtual Environments and the introduction of more sensory cues to increase the sense of immersion. In addition, this simulator is now used as a development tool to go further in the design and evaluation of new driving assistance solutions within the Rainbow team laboratory. Indeed, this simulator has the advantage of providing quick and easy setting as well as requiring significantly less time and material resources.

Finally, the proposed simulator is flexible and provides interchangeability of the navigation assistance algorithms and virtual sensor types in order to foster collaborative work. The resulting powered mobility simulator also aims to provide a standardized comparative and benchmarking tool for assisted navigation solutions. Indeed, it is still extremely difficult to compare different solutions because of the multiple changing parameters involved in the evaluation process (*e.g.* evaluation environment configuration, power wheelchair model and dynamical parameters).



## Chapter 4

# Indoor power wheelchair navigation assistance

This chapter details a wheelchair navigation assistance method in indoor environments. The idea is to define a velocity controller using a sensor-based servoing method which aims to semi-autonomously provide control input regulation while driving a power wheelchair. This semi-autonomous driving assistance consists in providing progressive wheelchair velocity adaptation ensuring a safe collision-free wheelchair trajectory. Practically, this shared control paradigm consists in using distances measured from sensors to "positive" or vertical obstacles (*i.e.* which level is higher than floor level) to compute a wheelchair control input which respects the user input as much as possible (*i.e.* intention) while avoiding collisions with obstacles.

The content of this chapter has been published in the IEEE International Conference on Robots and Systems (IROS) proceedings in 2016 [C.2].

## 4.1 Generic shared control approach

Designing a trajectory correction process requires shared control frameworks. The resulting semi-autonomous navigation system fuses manual control and robotic control, leading to a man-in-the-loop robotics application. To increase the Quality of Experience of such an assisted navigation, the proposed solution should integrate the user intention. To this aim, we here propose a generic shared control approach that takes into account the user velocity instruction, the manual control coming from a traditional joystick and a set of constraints deduced from the sensors. Similarly to the Dynamic Window Approach, this shared control solution is based on the definition of two distinct areas (allowed/forbidden areas) in the wheelchair velocity domain. The proposed method uses a sensor-based servoing approach to provide a low complexity algorithm and to simplify the geometry of the areas.

### 4.1.1 Objective

As presented in section 2.4.3, the purpose of sensor-based controls is to regulate the error  $\mathbf{e} = \mathbf{s} - \mathbf{s}^*$  represented by the difference between the measured  $\mathbf{s}$  and desired  $\mathbf{s}^*$  value of a set of features.

Sensor-based control is widely used in visual servoing processes where visual features, extracted from vision sensors such as cameras, are used to control robot motion in a closed loop system. *Visual servoing* or *visual servo control* [CH06] can be categorized within 2 main approaches:

- Position based Visual Servoing (PBVS). This approach consists of a 3D localization problem in which the pose of the camera with respect to some reference coordinate frame is used to define the set  $\mathbf{s}$ . To do so from an image, it is necessary to know the camera intrinsic parameters as well as the 3-D model of the object observed by the camera.
- Image based Visual Servoing (IBVS). This approach consists in using a set  $\mathbf{s}$  of visual information directly available in the image data to control the robot motion. Within this paradigm, the motion task is expressed in the sensor space and there is no robot pose estimation nor planning.

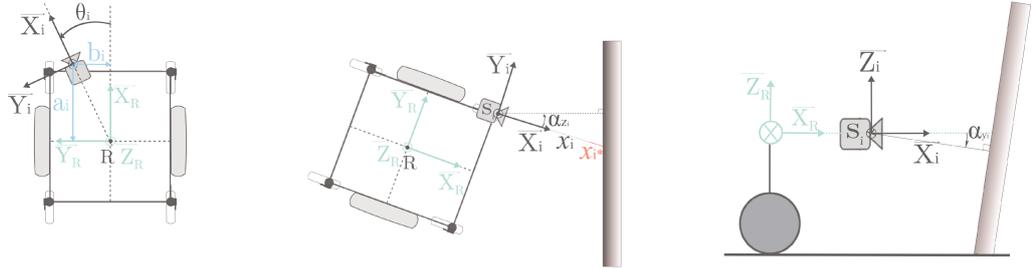
In this work, we will apply the IBVS approach to our robotic wheelchair with distance sensors instead of vision sensors. For each distance sensor attached to the wheelchair, we will extract a set of features  $\mathbf{s}$  which will directly be used to compute wheelchair velocity regulation with the aim to avoid hazardous situations such as collisions with obstacles.

### 4.1.2 Modeling

As shown on Figure 4.1,

- let  $\mathcal{F}_R(R, \vec{X}_R, \vec{Y}_R, \vec{Z}_R)$  be the frame attached to the robotic wheelchair,

- let  $\mathcal{F}_{s_i}(S_i, \vec{X}_i, \vec{Y}_i, \vec{Z}_i)$  be the frame attached to the sensor  $s_i$ ,
- let  $\mathbf{u} = (v, \omega)$  be the 2-DoF control input of the wheelchair,
- let  $\mathbf{v}_{s_i}$  be the velocity of the sensor  $s_i$ ,
- let  $x_i$  be the distance from the sensor  $s_i$  to the obstacle,
- let  $x_i^*$  be a minimum allowed distance from the sensor  $s_i$  to the obstacle,
- let  $\theta_i$  be the orientation of the sensor  $s_i$  with respect to the robot frame  $z$ -axis,
- let  $\alpha_{z_i}$  be the angle formed by the sensor  $s_i$   $x$ -axis and the normal of the detected obstacle in the  $xOy$  plane,
- let  $\alpha_{y_i}$  be the angle formed by the sensor  $s_i$   $x$ -axis and the normal of the detected obstacle in the  $xOz$  plane.



(a) Definition of robot and sensor frames in the horizontal plane. (b) Definition of frames in the vertical plane.

Figure 4.1 – Definition of the robot and sensor frames.

Each sensor  $s_i$  is rigidly fixed to the robot frame so that the translation vector  ${}^r\mathbf{t}_{s_i}$  between  $\mathcal{F}_{s_i}$  and  $\mathcal{F}_R$  is such that

$${}^r\mathbf{t}_{s_i} = \begin{bmatrix} a_i \\ b_i \\ 0 \end{bmatrix}, \quad (4.1)$$

with  $a_i$  and  $b_i$  depicted on Figure 4.1.

The rotation matrix  ${}^{s_i}\mathbf{R}_r$  relative to sensor  $s_i$  frame  $\mathcal{F}_{s_i}$  with respect to the robot frame  $\mathcal{F}_R$  is given by

$${}^{s_i}\mathbf{R}_r = \begin{bmatrix} \cos \theta_i & \sin \theta_i & 0 \\ -\sin \theta_i & \cos \theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (4.2)$$

The translation  ${}^{s_i}\mathbf{t}_r$  between the robot  $\mathcal{F}_R$  frame and the sensor  $s_i$  frame  $\mathcal{F}_{s_i}$  is then obtained from  ${}^{s_i}\mathbf{R}_r$  with

$${}^{s_i}\mathbf{t}_r = {}^{s_i}\mathbf{R}_r {}^r\mathbf{t}_{s_i}. \quad (4.3)$$

From  ${}^{s_i}\mathbf{R}_r$  and  ${}^{s_i}\mathbf{t}_r$ , the velocity screw transformation matrix defined in equation 2.5 is given by

$${}^{s_i}\mathbf{W}_r = \begin{bmatrix} {}^{s_i}\mathbf{R}_r & [{}^{s_i}\mathbf{t}_r]_{\times} {}^{s_i}\mathbf{R}_r \\ \mathbf{0}_{3 \times 3} & {}^{s_i}\mathbf{R}_r \end{bmatrix}. \quad (4.4)$$

with  $[\ ]_{\times}$  the skew matrix expression.

The velocity  $\mathbf{v}_{s_i}$  of the sensor  $s_i$  in the sensor frame  $\mathcal{F}_{s_i}$  is derived from the robot 2-DoF control input  $\mathbf{u}$  in the robot frame using

$$\mathbf{v}_{s_i} = {}^{s_i}\mathbf{T}_r \mathbf{u}, \quad (4.5)$$

with

$${}^{s_i}\mathbf{T}_r = {}^{s_i}\mathbf{W}_r {}^r\mathbf{J}_r, \quad (4.6)$$

where  ${}^r\mathbf{J}_r$  is the robot jacobian defined in equation 2.7.

#### 4.1.2.1 Interaction matrix computation

For each sensor  $s_i$ , the interaction matrix  $\mathbf{L}_{x_i}$  links the velocity  $v_{s_i}$  of the sensor  $s_i$  to the measured distance variation  $\dot{x}_i$  such that

$$\dot{x}_i = \mathbf{L}_{x_i} \mathbf{v}_{s_i} \quad (4.7)$$

with  $\mathbf{L}_{x_i} \in \mathbb{R}^{1 \times 6}$ .

All the sensors are rigidly attached to the robot frame and the rotation around  $x$ -axis does not induce distance measurement variation. Therefore, the interaction matrix  $\mathbf{L}_{x_i}$  for each sensor  $s_i$  is such that

$$\mathbf{L}_{x_i} = \begin{bmatrix} -1 & \tan(\alpha_{z_i}) & \tan(\alpha_{y_i}) & 0 & x_i \tan(\alpha_{y_i}) & x_i \tan(\alpha_{z_i}) \end{bmatrix}, \quad (4.8)$$

where  $\alpha_{z_i}$  is the angle formed by the sensor  $s_i$  x-axis and the perpendicular to the detected obstacle (Figure 4.1).

#### 4.1.2.2 Practical consideration

In this work, we propose to use ultrasonic sensors to measure distances to obstacles. This choice was made on a thorough examination of the smart power wheelchair solution requirements which came out of previous works on this topic (part 2.3). Due to the physical properties of the ultrasonic wave propagation, the distance measured by an ultrasonic sensor corresponds to the shortest path taken by the emitted ultrasonic wave to reach the obstacle and echo back to the sensor receptor within its field of view.

#### 4.1.2.3 Case of frontal and lateral sensors, $\theta_i \in \{0, \frac{\pi}{2}, \pi, -\pi, -\frac{\pi}{2}\}$

As discussed above, the physical properties of ultrasonic sensors allow us to apply the principle of the shortest path, *i.e.* we assume that the obstacle is exactly located at the minimum distance given by the sensor, and oriented perpendicular to the sensor  $s_i$   $x$ -axis. Then, an obstacle detected by a sensor  $s_i$  is considered perpendicular to its  $x$ -axis. Therefore, for each obstacle detected by an ultrasonic sensor, we consider the angle  $\alpha_{z_i}$  formed by the sensor  $s_i$   $x$ -axis and the detected obstacle (Figure 4.1) is such that  $\alpha_{z_i} \simeq 0$  (Figure 4.2).

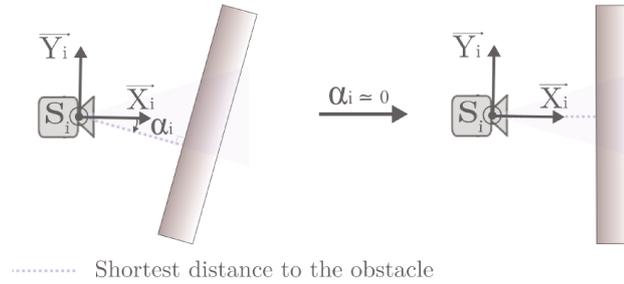


Figure 4.2 – Case of frontal and lateral sensors:  $\alpha_{z_i} \simeq 0$ .

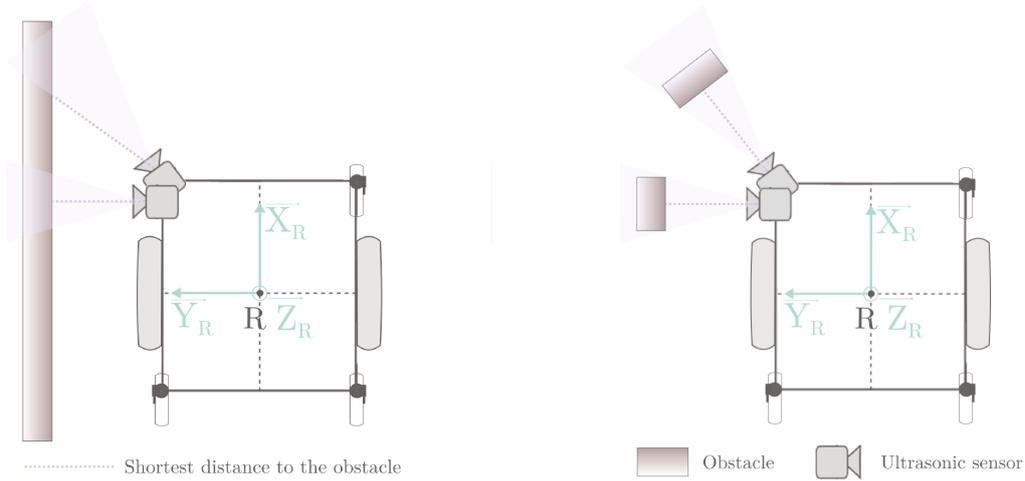
This approximation is applicable to all the sensors attached on the wheelchair, except for corner sensors which will require an estimation of the orientation of the detected obstacle by additional computations in order to provide a consistent behavior of the wheelchair.

#### 4.1.2.4 Particular case of corner sensors, $\theta_i \notin \{0, \frac{\pi}{2}, \pi, -\pi, -\frac{\pi}{2}\}$

As discussed in part 4.1.2.2, it is not possible to determine the orientation of a detected object with the measurement of a single ultrasonic sensor. Indeed, the only information available from such a sensor is a distance measurement. As previously shown for lateral and frontal sensors, it is possible to consider the obstacle perpendicular to the sensor  $s_i$   $x$ -axis by approximating  $\alpha_{z_i} \simeq 0$ . However, this approximation would lead to detection limitations in the case of corner sensors. This limitation can be easily illustrated by taking the example of navigation along a wall. In this situation, lateral sensors and corner sensors can detect distances to the wall (Figure 4.3a). However, as the assumed information measured by each sensor is the shortest path to the obstacle, the theoretical detection is different from the actual obstacle configuration (Figure 4.3b).

In order to overcome this issue, it is possible to estimate the orientation  $\alpha_{z_i}$  of an obstacle detected by a corner sensor  $s_i$ . To do so, each corner of the wheelchair is equipped with 3 sensors arranged such as shown on Figure 4.4.

The sensor  $s_i$  is oriented with an angle  $\theta_i$  with respect to the robot frame  $z$ -axis. The sensors  $s_{i+1}$  and  $s_{i-1}$  are respectively oriented with angles  $\sigma_{i+1}$  and  $\sigma_{i-1}$  with respect to the sensor  $s_i$   $z$ -axis with  $|\sigma_{i-1}| = |\sigma_{i+1}| = \frac{\pi}{4}$ . The orientation of an obstacle detected by a corner sensor  $s_i$  can be estimated from the information measured by the sensor  $s_i$



(a) Actual obstacle configuration while navigating with a wheelchair along a wall.

(b) Obstacle configuration theoretically deduced from corner distance measurements.

Figure 4.3 – Examples of corner sensor detection while navigating along a wall. Purple cones represent sensors field of view.

adjacent sensors  $s_{i-1}$  and  $s_{i+1}$ .

As shown on Figure 4.5

- let  $\beta_{i-1} = \arctan\left(\frac{x_{i+1}}{x_{i-1}}\right)$  and  $\beta_{i+1} = \arctan\left(\frac{x_{i-1}}{x_{i+1}}\right)$ ,
- let  $\vec{n}$  be the normal to the detected obstacle.

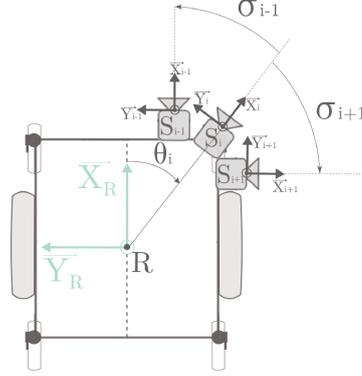
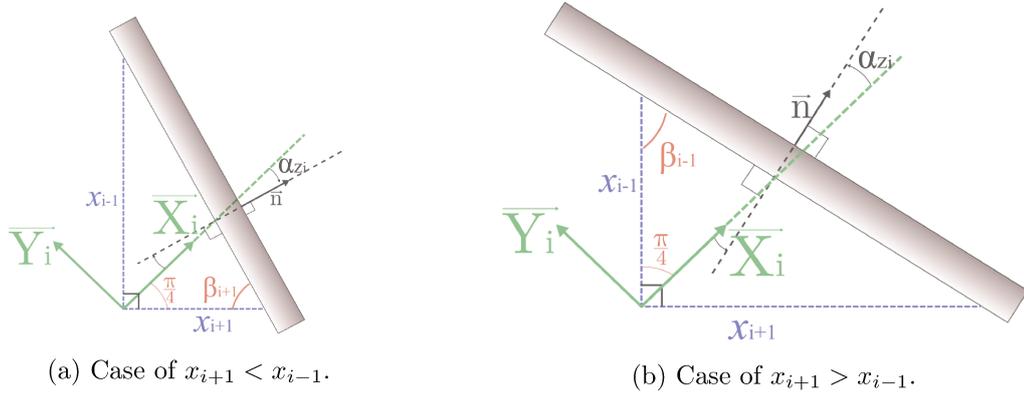
The computation of the estimation  $\hat{\alpha}_{z_i}$  of  $\alpha_{z_i}$  can be divided into 3 cases:

$$\begin{cases} \hat{\alpha}_{z_i} = \beta_{i+1} - \frac{\pi}{4}, & \text{if } x_{i-1} > x_{i+1}, \\ \hat{\alpha}_{z_i} = \beta_{i-1} - \frac{\pi}{4}, & \text{if } x_{i+1} > x_{i-1}, \\ \hat{\alpha}_{z_i} = 0, & \text{else.} \end{cases} \quad (4.9)$$

Thanks to this estimation  $\hat{\alpha}_{z_i}$  of the detected obstacle orientation  $\alpha_{z_i}$ , the detection method can be improved by 2 methods:

**Method 1:** Referring to section 4.1.2.1, the first and straightforward way to incorporate the estimation of the obstacle orientation  $\hat{\alpha}_{z_i}$  into the calculations would intuitively be to use this estimation into the interaction matrix calculation. Therefore, we would have

$$\mathbf{L}_{x_i} = [-1 \quad \tan(\alpha_{z_i}) \quad \tan(\alpha_{y_i}) \quad 0 \quad x_i \tan(\alpha_{y_i}) \quad x_i \tan(\alpha_{z_i})] \quad (4.10)$$


 Figure 4.4 – Corner sensor  $s_i$  arrangement.

 Figure 4.5 – Calculation of  $\alpha_{z_i}$  with  $\theta_i = \frac{\pi}{4}$ .

In addition, considering detected obstacles are vertical, the interaction matrix expression can be simplified by using the approximation that  $\alpha_{y_i} \simeq 0$ . Therefore, we have

$$\mathbf{L}_{x_i} \simeq [-1 \quad \tan(\alpha_{z_i}) \quad 0 \quad 0 \quad 0 \quad x_i \tan(\alpha_{z_i})] \quad (4.11)$$

with

$$\begin{cases} \alpha_{z_i} = \hat{\alpha}_{z_i}, & \text{if } s_i \text{ is a corner sensor,} \\ \alpha_{z_i} = 0, & \text{elsewhere.} \end{cases} \quad (4.12)$$

With this method, the interaction matrix linking the velocity  $v_{s_i}$  of the sensor  $s_i$  to the measured distance variation  $\dot{x}_i$  takes different values depending on  $s_i$  being a corner sensor or not.

**Method 2:** In order to take benefit from the intrinsic physical properties of ultrasound waves by considering the measured distance being the shortest path taken by the ultrasonic sensor signal to reach the obstacle and echo back, an other way to use the estimation  $\hat{\alpha}_{z_i}$  of the obstacle orientation detected by a corner sensor  $s_i$  is to virtually

modify the orientation of the sensor  $s_i$  to make its  $x$ -axis perpendicular to the obstacle. This is done by defining a matrix  ${}^{s_i}\mathbf{T}'_r$  taking  $\hat{\alpha}_{z_i}$  into account if  $s_i$  is a corner sensor.

In this case, for all sensors, the interaction matrix  $\mathbf{L}_{x_i}$  is such that

$$\mathbf{L}_{x_i} = [-1 \ 0 \ 0 \ 0 \ 0 \ 0], \quad (4.13)$$

and equation (4.5) can be rewritten as

$$\begin{cases} \mathbf{v}_{s_i} = {}^{s_i}\mathbf{T}'_r \mathbf{u}, & \text{if } s_i \text{ is a corner sensor,} \\ \mathbf{v}_{s_i} = {}^{s_i}\mathbf{T}_r \mathbf{u}, & \text{otherwise,} \end{cases} \quad (4.14)$$

with  ${}^{s_i}\mathbf{T}'_r$  such that

$${}^{s_i}\mathbf{T}'_r = {}^{s_i}\mathbf{W}'_r {}^r \mathbf{J}_r, \quad (4.15)$$

with

$${}^{s_i}\mathbf{W}'_r = \begin{bmatrix} {}^{s_i}\mathbf{R}'_r & [{}^{s_i}\mathbf{t}_r]_{\times} {}^{s_i}\mathbf{R}'_r \\ \mathbf{0}_{3 \times 3} & {}^{s_i}\mathbf{R}'_r \end{bmatrix}, \quad (4.16)$$

where  ${}^{s_i}\mathbf{R}'_r$  is such that

$${}^{s_i}\mathbf{R}'_r = \begin{bmatrix} \cos(\theta_i + \hat{\alpha}_{z_i}) & \sin(\theta_i + \hat{\alpha}_{z_i}) & 0 \\ -\sin(\theta_i + \hat{\alpha}_{z_i}) & \cos(\theta_i + \hat{\alpha}_{z_i}) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (4.17)$$

## 4.2 Autonomous robotic wheelchair control

The objective of sensor-based autonomous servoing is to control the robot to ensure at best an exponential decrease of the error  $\mathbf{e} = \mathbf{s} - \mathbf{s}^*$  (part 2.4.3). Within the framework of smart power wheelchair navigation, a distance sensor  $s_i$  attached to the robot frame  $\mathcal{F}_R$  can be used to measure a distance  $x_i$  to a detected obstacle. Then, the error  $e_{s_i}$  is such that  $e_{s_i} = x_i - x_i^*$  where  $x_i \in \mathbb{R}^+$  and  $x_i^* \in \mathbb{R}^+$  being respectively the distance measured by a sensor  $s_i$  to an obstacle and the minimum allowed distance between the robot and the obstacle.

### 4.2.1 Autonomous control framework

The dedicated control law ensuring exponential decrease of  $e_{s_i}$  is such that

$$\dot{e}_{s_i} = -\lambda e_{s_i} \quad (4.18)$$

where  $\lambda \in \mathbb{R}^{+*}$  is a gain.

As the minimum allowed distance to the obstacle  $x_i^*$  is a constant value,  $\dot{e}_{s_i} = \dot{x}_i$ . This leads to have

$$\dot{x}_i = -\lambda e_{s_i}. \quad (4.19)$$

Considering that  $\dot{x}_i = \mathbf{L}_{x_i} \mathbf{v}_{s_i}$  (4.7) and  $\mathbf{v}_{s_i} = {}^{s_i}\mathbf{T}_r \mathbf{u}$  (2.8), leading to

$$\dot{x}_i = \mathbf{L}_{x_i} {}^{s_i}\mathbf{T}_r \mathbf{u}, \quad (4.20)$$

the control law introduced in equation (4.19) can be rewritten as

$$\mathbf{L}_{x_i}^{s_i} \mathbf{T}_r \mathbf{u} = -\lambda e_{s_i}. \quad (4.21)$$

The error  $e_{s_i}$  is defined such that  $e_{s_i} = x_i - x_i^*$ , therefore we get

$$\mathbf{L}_{x_i}^{s_i} \mathbf{T}_r \mathbf{u} = -\lambda(x_i - x_i^*), \quad (4.22)$$

leading to

$$\mathbf{J}_{s_i} \mathbf{u} = -\lambda(x_i - x_i^*) \quad (4.23)$$

with  $\mathbf{J}_{s_i} = \mathbf{L}_{x_i}^{s_i} \mathbf{T}_r$  being the sensor  $s_i$  Jacobian introduced in equation (2.10).

Finally, the 2 DoF control input  $\mathbf{u}$  of the robot is then controllable with the following control law

$$\mathbf{u} = -\lambda \mathbf{J}_{s_i}^+(x_i - x_i^*) \quad (4.24)$$

with  $\mathbf{J}_{s_i}^+ \in \mathbb{R}^{2 \times 1}$  the Moore-Penrose pseudo-inverse of the sensor jacobian  $\mathbf{J}_{s_i}$ .

#### 4.2.1.1 Simulation

In Figure 4.6, we report a simulated case meant to illustrate the convergence of the control law. The simulation aims to demonstrate the properties of the autonomous control law introduced in equation (4.24) for 4 different robot configurations with respect to an obstacle.

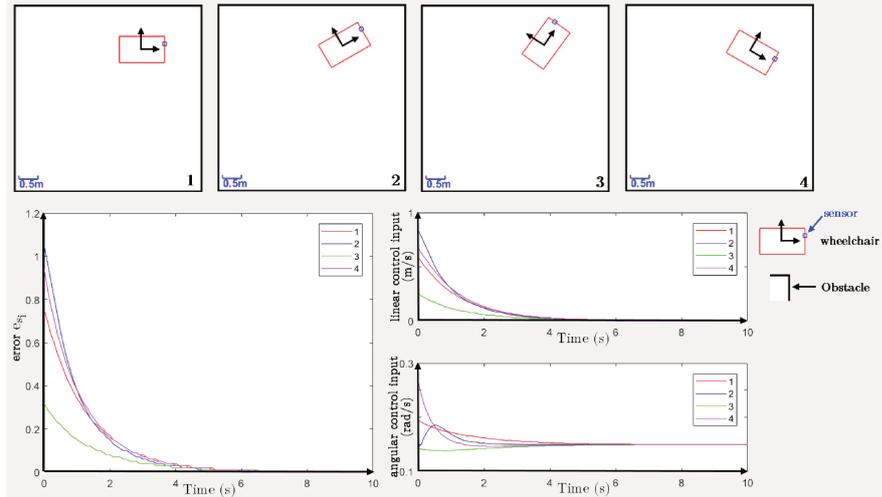


Figure 4.6 – Evolution of  $e_{s_i}$ ,  $v$  and  $\omega$  in simulation.

The simulation results show the exponential decrease of the error  $e_{s_i}$  associated with a decrease of linear and rotational robot control inputs to zero as the error  $e_{s_i}$  decreases. In other words, wheelchair velocity control inputs progressively decrease as the wheelchair approaches the obstacle until it reaches the minimum allowed distance  $x_i^*$ . As a result of this autonomous sensor-based control, the robotic wheelchair smoothly

reduces its velocity while approaching a detected obstacle and gently stops when the measured distance  $x_i$  equals the virtual safety margin  $x_i^*$  *i.e.*  $e_{s_i} = 0$ . Based on these results, it can be concluded that the proposed control input regulation method using distance sensor-based information allows the robot to approach a detected obstacle until reaching a minimum allowed distance to the obstacle.

However, despite the ability of this method to approach a detected obstacle until reaching the minimum allowed detected distance, it does not take the user input *i.e.* user intention into account. This lack of consideration for the user input within the control loop does not allow consistent wheelchair navigation behavior and therefore does not meet smart power wheelchair navigation assistance requirements.

### 4.3 Sensor-based servoing for semi-autonomous navigation

In this part, we will present a sensor-based semi-autonomous wheelchair velocity regulation method. Such a navigation assistance method aims to avoid collisions with obstacles by smoothly correcting the wheelchair trajectory while respecting as much as possible user intention.

Control methods involving user input within the control loop can be denoted as semi-autonomous control methods or "shared-control" methods. In this framework, the wheelchair velocity control is shared between the user and the navigation assistance algorithm. The purpose of such a system is for the system to be able to take over the control of the wheelchair while there is a danger for the user. In this type of situation, the user progressively loses control to the system which modifies the wheelchair control input in order to ensure a safe local trajectory correction.

Therefore, such a sensor-based control system could meet safety navigation expectations as it decreases speed and, if necessary, stops the wheelchair while approaching an obstacle. However, such a system is also expected to be adapted to people with disability needs for navigation assistance. To meet this requirement, the system will have to be able to involve the user into the control loop to provide a wheelchair behavior consistent with the user intention. This is achievable by means of sharing control between the user and the navigation assistance system.

#### 4.3.1 Semi-autonomous control framework

Sensor-based servoing for semi-autonomous navigation consists in regulating the velocity control input of the wheelchair in order to avoid a detected obstacle while still allowing full control to the user when there is no danger of collision. This can be achieved by the formulation

$$\dot{\mathbf{e}} \geq -\lambda \mathbf{e} \quad (4.25)$$

where  $\mathbf{e} = \mathbf{s} - \mathbf{s}^*$  is defined as the difference between the set of data  $\mathbf{s}$  and its desired value  $\mathbf{s}^*$ .  $\lambda \in \mathbb{R}^{+*}$  is a gain.

Within the framework of smart power wheelchair navigation assistance, a wheelchair can be equipped with distance sensors measuring distances to the obstacles around the

wheelchair. For each sensor  $s_i$ , the error  $e_{s_i}$  is such that  $e_{s_i} = x_i - x_i^*$  where  $x_i, x_i^* \in \mathbb{R}^+$  respectively the distance measured by a sensor  $s_i$  to an obstacle and the minimum allowed distance between the robot and the obstacle.

- Let  $\mathbf{u}_{op} = (v_{op}, \omega_{op})$  be the user desired control input,
- let  $\mathbf{u}_{cmd} = (v_{cmd}, \omega_{cmd})$  be the robot control input,
- let  $x_i^*$  be a minimum allowed distance from the sensor  $s_i$  to the obstacle,
- let  $e_{s_i} = x_i - x_i^*$  be the error between  $x_i$  and  $x_i^*$ .

**Case of a single sensor:** Considering that the minimum allowed distance to the obstacle  $x_i^*$  is a constant value, involving  $\dot{e}_{s_i} = \dot{x}_i$ , in equation (4.25) gives

$$\dot{x}_i \geq -\lambda e_{s_i}, \quad (4.26)$$

where we constrain  $\dot{x}_i$  by a minimum value  $-\lambda e_{s_i}$  leading to the design of a proportional velocity limitation around obstacles.

Considering that  $\dot{x}_i = \mathbf{L}_{x_i}^{s_i} \mathbf{T}_r \mathbf{u}$  (equation (4.20)), inequality (4.26) can be written

$$\mathbf{L}_{x_i}^{s_i} \mathbf{T}_r \mathbf{u} \geq -\lambda e_{s_i} \quad (4.27)$$

*i.e.*

$$\mathbf{J}_{s_i} \mathbf{u} \geq -\lambda e_{s_i}. \quad (4.28)$$

where  $\mathbf{J}_{s_i} = \mathbf{L}_{x_i}^{s_i} \mathbf{T}_r$  stands for the sensor  $s_i$  Jacobian introduced in equation (2.10).

The system (4.28) is thus a linear inequality system. As opposed to the system (4.23) for which a unique solution can be calculated, this system which can admit an infinite number of solutions and forms a 2D half-plane in the wheelchair velocity domain. This half-plane, defined by inequality 4.28, can be rewritten as

$$a_{s_i} v + b_{s_i} \omega \geq -\lambda e_{s_i} \quad (4.29)$$

with  $a_{s_i} \in \mathbb{R}$  and  $b_{s_i} \in \mathbb{R}$  such that  $\mathbf{J}_{s_i} = [a_{s_i} \ b_{s_i}]$ . The graphical representation of this half-plane in the wheelchair domain is illustrated on Figure 4.7.

Defining  $\mathbf{A}_i = \mathbf{J}_{s_i}$  and  $B_i = -\lambda e_{s_i}$ , inequality (4.29) can also be written

$$\mathbf{A}_i \mathbf{u} \geq B_i. \quad (4.30)$$

**Case of  $N$  sensors:** When considering  $N$  sensors, we can rewrite inequality (4.30)

$$\mathbf{A} \mathbf{u} \geq \mathbf{B} \quad (4.31)$$

using

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_0 \\ \vdots \\ \mathbf{A}_{N-1} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{s_0} \\ \mathbf{J}_{s_1} \\ \dots \\ \mathbf{J}_{s_{N-1}} \end{bmatrix} \text{ and } \mathbf{B} = \begin{bmatrix} B_0 \\ \vdots \\ B_{N-1} \end{bmatrix} = \begin{bmatrix} -\lambda e_{s_0} \\ -\lambda e_{s_1} \\ \dots \\ -\lambda e_{s_{N-1}} \end{bmatrix}.$$

which defines a convex polygon in the wheelchair velocity domain as shown on Figure 4.8.

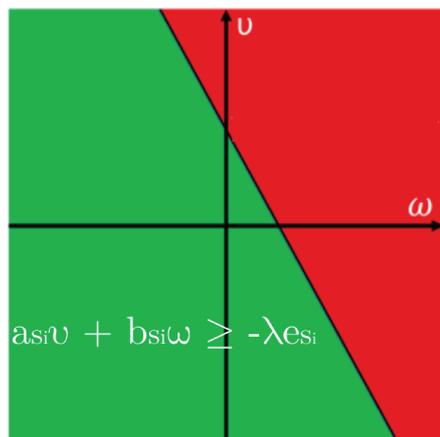


Figure 4.7 – Half plane in the velocity domain

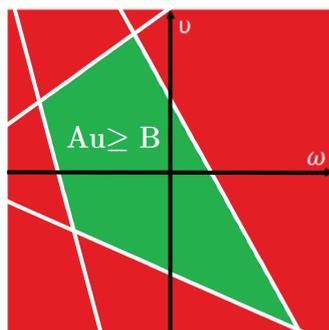


Figure 4.8 – Convex polygon in the wheelchair velocity domain

#### 4.3.1.1 Computing shared control values

Shared control is achieved by providing assistance to the user while performing the navigation task by blending user input and a computed virtual input. In this case, the desired velocity  $\mathbf{u}_{cmd}$  is computed from user velocity input  $\mathbf{u}_{op}$ .

The computation of the virtual desired velocity input  $\mathbf{u}_{cmd}$  consists of the following optimization problem

$$\begin{cases} \mathbf{u}_{cmd} = \min_{\mathbf{u}} f(\mathbf{u}_{op}, \mathbf{u}) \\ \mathbf{A} \mathbf{u} \geq \mathbf{B} \end{cases} \quad (4.32)$$

which consists of the minimization of a cost function  $f$  under the inequality constraints (4.31).

Shared control aims first to respect as much as possible user intention by allowing full control while there is no danger of collision and by providing smooth velocity adaptation in the case where the wheelchair gets close to an obstacle. To do that, a safe control input  $\mathbf{u}$  can be computed from sensors measurements constraints. The shared control results in a trade-off between the input  $\mathbf{u}$  and the user input  $\mathbf{u}_{op}$ . This trade-off is obtained by

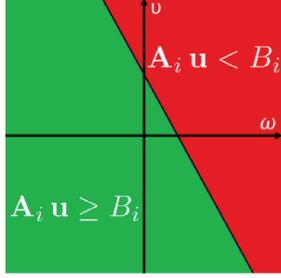
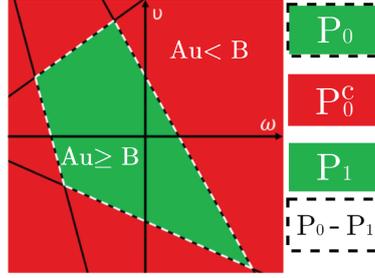
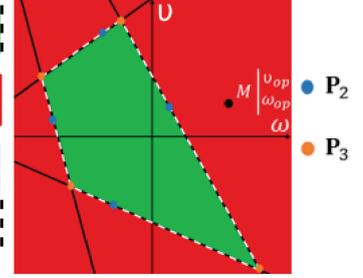


Figure 4.9 – Half plane in the velocity domain

Figure 4.10 – Definition of  $\mathbf{P}_0$  and  $\mathbf{P}_1$ Figure 4.11 – Definition of  $\mathbf{P}_2$  and  $\mathbf{P}_3$ 

choosing  $f$  as a weighted euclidean norm that corresponds to the minimization of the euclidean distance between the input  $\mathbf{u}$  and the user input  $\mathbf{u}_{op}$ .  $f$  is defined as

$$f(\mathbf{u}_{op}, \mathbf{u}) = \alpha(v - v_{op})^2 + \beta(\omega - \omega_{op})^2 \quad (4.33)$$

where  $\alpha \geq 0$  and  $\beta \geq 0$ .

Shared control also determines how the user intention is taken into account. A human-in-the-loop control scheme provides a control value  $\mathbf{u}_{cmd}$  which respects as much as possible the main direction given by the user. To do so, the weighting parameters  $\alpha$  and  $\beta$  can be set so that they model intention of the user. This way,  $\alpha$  and  $\beta$  are set to the following values

$$\begin{cases} \alpha = |v_{op}| \\ \beta = |\omega_{op}|. \end{cases} \quad (4.34)$$

The problem can then be written as a classical quadratic optimization problem using

$$\begin{cases} \mathbf{u}_{cmd} = \min_{\mathbf{u}} \mathbf{g}^T \mathbf{u} + \frac{1}{2} \mathbf{u}^T \mathbf{H} \mathbf{u} \\ \mathbf{A} \mathbf{u} \geq \mathbf{B} \end{cases} \quad (4.35)$$

with  $\mathbf{g} = \mathbf{u}_{op} \begin{bmatrix} -\alpha & 0 \\ 0 & -\beta \end{bmatrix}$  and  $\mathbf{H} = \begin{bmatrix} \alpha & 0 \\ 0 & \beta \end{bmatrix}$ .

Wheelchair control is computed from user velocity input in the wheelchair velocity domain with respect to constraints deduced from sensors measurements.

First, we define two sets  $\mathbf{P}_0$  and  $\mathbf{P}_1$  as shown on Figure 4.10, such that

$$\begin{aligned} \mathbf{P}_0 &= \{\mathbf{u} | \mathbf{A} \mathbf{u} \geq \mathbf{B}\} \\ \mathbf{P}_1 &= \{\mathbf{u} | \mathbf{A} \mathbf{u} > \mathbf{B}\} \end{aligned} \quad (4.36)$$

Hence, the problem (4.35) can be resolved only if  $\mathbf{P}_0 \neq \emptyset$ . To alleviate this issue, the set  $\mathbf{P}_0 = \emptyset$ , the minimum allowed distance from a sensor  $s_i$  to the obstacle  $x_i^*$  can be dynamically decreased to expand the size of  $\mathbf{P}_0$  thus solving the problem.

The area defined by  $\mathbf{P}_0$  can be defined as an "allowed" input area for which user input is considered as safe. By opposition, the area defined by  $\mathbf{P}_0^c$  (Figure 4.10) can be defined as a "forbidden" area for which user input is considered unsafe *i.e.* with a risk of collision. Therefore, when considering user input  $u_{op}$ , 2 different cases can be distinguished:

**Case 1:** if  $\mathbf{u}_{op} \in \mathbf{P}_0$ , user input is within the virtual "allowed" area, meaning that no collision can occur. Then, the resulting wheelchair control is such that  $\mathbf{u}_{cmd} = \mathbf{u}_{op}$ ,

**Case 2:** otherwise, if  $\mathbf{u}_{op} \in \mathbf{P}_0^c$ , user input is within the "forbidden" area and is considered as unsafe. As the cost function is convex, its minimum is reached when  $\mathbf{u} = \mathbf{u}_{op}$ ,  $\mathbf{u}_{cmd} \in \mathbf{P}_0 - \mathbf{P}_1$ . The problem can then be solved as there exists at least one  $i$  such that  $\mathbf{A}_i \mathbf{u} = B_i$ .

Under Case 2, as all the constraints are linear, only two different sub-cases are possible:

**Case 2.1:** there exists one and only one  $i$  such that  $\mathbf{A}_i \mathbf{u} = B_i$ . Then, for each sensor  $s_i$ , the system

$$\begin{cases} \hat{\mathbf{u}} = \min_{\mathbf{u}} \mathbf{g}^T \mathbf{u} + \frac{1}{2} \mathbf{u}^T \mathbf{H} \mathbf{u} \\ \mathbf{A}_i \mathbf{u} = B_i \end{cases} \quad (4.37)$$

has to be solved. We then look for a set  $\mathbf{P}_2 = \{\hat{\mathbf{u}} | \hat{\mathbf{u}} \in \mathbf{P}_0\}$  of possible solutions (Figure 4.11). In fact, the system (4.37) corresponds to a cost function minimization along a line and is easily solved. As all the constraints are linear, we get  $card(\mathbf{P}_2) \leq N$  *i.e.* a maximum of  $N$  computations of the cost function. This case corresponds to the minimum being located on a segment of the polygon described by  $\mathbf{P}_0 - \mathbf{P}_1$ ,

**Case 2.2:** there exists one and only one couple  $\{i, j\}$  such that for each couple of sensors  $\{s_i, s_j\}$ , the system

$$\begin{cases} \mathbf{A}_i \hat{\mathbf{u}} = B_i \\ \mathbf{A}_j \hat{\mathbf{u}} = B_j \end{cases} \quad (4.38)$$

is solved. We then look for a set  $\mathbf{P}_3 = \{\hat{\mathbf{u}} | \hat{\mathbf{u}} \in \mathbf{P}_0\}$  of possible solutions (Figure 4.11). The system (4.38) corresponds to a linear system and is once again easily solved. As all the constraints are linear, we also get  $card(\mathbf{P}_3) \leq N$  *i.e.* a maximum of  $N$  computations of the cost function. In this case, the minimum is achieved on a corner of the polygon described by  $\mathbf{P}_0$ .

Finally, the optimization problem (4.35) can be written as

$$\begin{cases} \mathbf{u}_{cmd} = \min_{\mathbf{u} \in \mathbf{P}_2 \cup \mathbf{P}_3} \mathbf{g}^T \mathbf{u} + \frac{1}{2} \mathbf{u}^T \mathbf{H} \mathbf{u} \end{cases} \quad (4.39)$$

An exhaustive search on  $\mathbf{P}_2 \cup \mathbf{P}_3$  leads to at most  $2N$  computations of the cost function and provides the solution of the problem (4.35).

To sum up, the user velocity input is considered as a coordinate within the wheelchair velocity domain. This velocity domain is split into 2 areas deduced from the constraints computed from sensors measurements:

- an "allowed" area within which user input is unchanged,
- a "forbidden" area within which the user velocity input is considered unsafe.

The proposed shared control solution allows progressive control of the wheelchair while respecting as much as possible user input. This shared control allows the user full control when the wheelchair is operated without risk of collision (*i.e.* user velocity input is within the "allowed" area). If there is a danger of collision (*i.e.* user velocity input is within the "forbidden" area), user velocity input is progressively blended with its projection value within the "allowed area" thus smoothly regulating the wheelchair velocity to avoid the collision while keeping moving and respecting as much as possible user velocity input. The formulation of the problem leads to solving a simple quadratic system under constraints.

## 4.4 Simulations

This section presents the results of a simulation to better demonstrate the properties of the proposed shared control law with a virtual wheelchair .

As shown on Figure 4.13a, the virtual environment corresponds to a 2 meter wide and 10 meter long corridor with 4 obstacles. The virtual wheelchair starts from the beginning of the corridor facing the top wall with an angle of  $60^\circ$ . The user input is constant and equal to 100% of the maximum speed of the wheelchair. The wheelchair is equipped with 9 virtual sensors with a refresh rate of  $50Hz$ . This number of sensors has been chosen as a worst case scenario to test the collision avoidance all around the wheelchair. The dynamics of the wheelchair are simulated using values corresponding to the average parametrization of a real-user wheelchair by occupational therapists:

- a maximum forward speed of  $0.9 m.s^{-1}$ ,
- a maximum forward acceleration of  $2 m.s^{-2}$ ,
- a maximum rotational speed of  $1 rad.s^{-1}$ ,
- a maximum rotational acceleration of  $3 rad.s^{-2}$ .

In order to reduce the computation cost of the algorithm, the estimation  $\hat{\alpha}_{z_i}$  of  $\alpha_{z_i}$  defined in equation (4.9) is obtained by computing the product of the mean value weighted by the inverse of the measured distances so that

$$\hat{\alpha}_{z_i} = \frac{\sum_{j=i-1}^{i+1} \frac{\theta_j - \theta_i}{x_j}}{\sum_{j=i-1}^{i+1} \frac{1}{x_j}}. \quad (4.40)$$

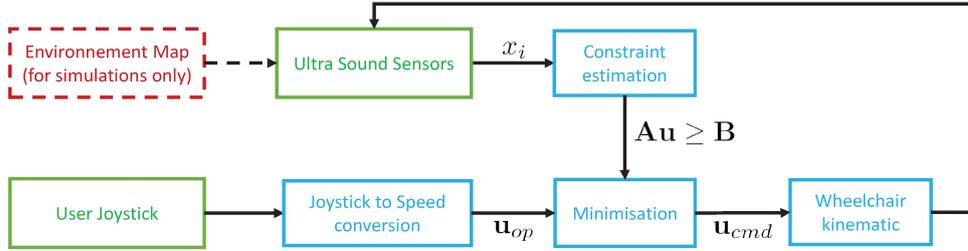


Figure 4.12 – Simulated algorithm

Figure 4.12 shows the whole algorithm used for simulation purposes. Distances to virtual obstacles  $x_i$  are computed from the map of the virtual environment and the pose of the virtual wheelchair. Constraints are estimated using the inequality (4.31). From the user joystick position, the user control input  $\mathbf{u}_{op}$  of the wheelchair is estimated. From  $\mathbf{u}_{op}$  using equation (4.39), the quadratic minimization is performed leading to the velocity  $\mathbf{u}_{cmd}$  which is then applied to the wheelchair, *i.e.*

Note that the map and the pose are used for simulation visualization purposes only.

Figure 4.13a shows the trajectory of the wheelchair during the simulation. Without any map of the environment and without any correction from the user (only a constant forward velocity is applied), the wheelchair moves smoothly around the obstacles and follows the corridor.

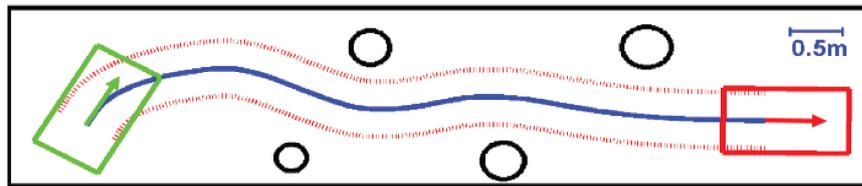
As the simulated user joystick is set to input a constant forward velocity, the cost function expressed by equation (4.33) used in the simulation tries to maximize the forward velocity. Therefore, as shown on Figure 4.14, the chosen couple of forward and rotational velocities is the one that maximizes the forward velocity and not the one that is the closest in the sense of the Euclidean norm to the user input. As shown on Figure 4.13b, when getting closer to an obstacle, the wheelchair slows down to provide a comfortable and safe motion.

With a constant forward velocity input, the rotational velocity is also servoed to avoid obstacles (Figure 4.13c). As the user only asks to move forward, the direction chosen by the control law depends on the orientation of the wheelchair with regards to the corridor and the obstacles.

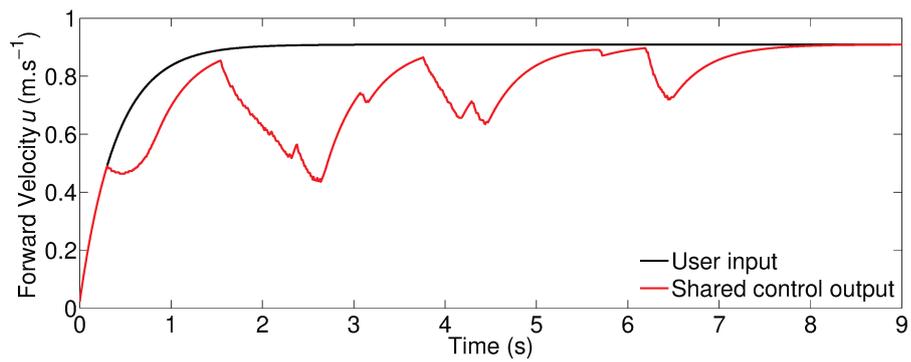
We have then demonstrated the ability of the system to provide a smooth trajectory correction while avoiding obstacles. In particular, the simulations validate the case when the user input is kept constant.

## 4.5 Evaluation and validation with regular power wheelchair users

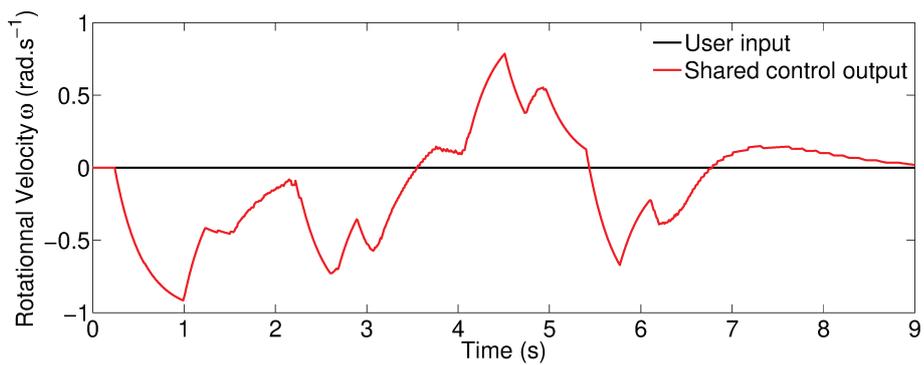
As part of the Handiviz collaborative project, the semi-autonomous power wheelchair driving assistance solution presented above was assessed during clinical trials within the rehabilitation center Pôle Saint Hélier. Until this study, this system has never been



(a) Simulated trajectory for the wheelchair.



(b) Forward velocity applied to the wheelchair.



(c) Rotational velocity applied to the wheelchair.

Figure 4.13 – Simulation results: (4.13b) and (4.13c) represent the corrected forward velocity and rotational velocity with respect to the timeline of the obstacle avoidance represented in (4.13a).

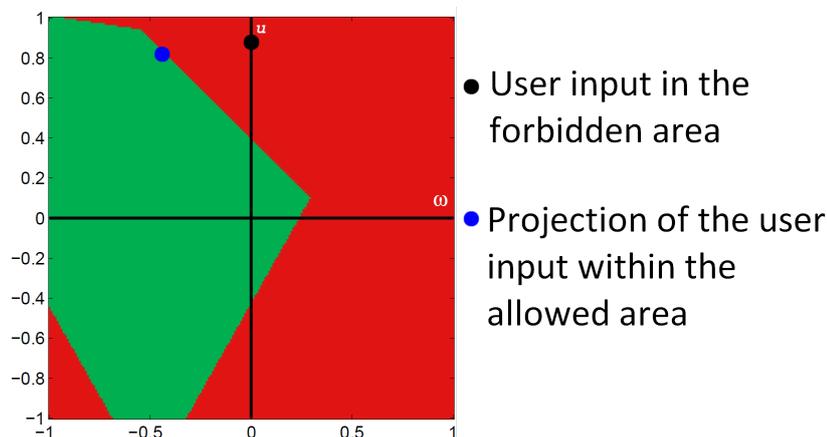


Figure 4.14 – Example of allowed/forbidden areas during the simulation

assessed by regular wheelchair users.

One of the major challenges is that the driving assistance can preserve navigation comfort for a good driving experience. The purpose of this study was the validation of the proposed power wheelchair driving assistance system in terms of ease of use, safety, and efficiency as well as driving comfort from the user point of view. In this section, we present the study conducted within the Pôle Saint Héliier with 23 regular wheelchair users who were asked to drive the proposed smart wheelchair solution on two driving circuits with and without assistance.

#### 4.5.1 Study design

##### 4.5.1.1 Primary objective

To compare regular wheelchair users' driving performances on ecological vs obstacle course between two conditions: driving assistance activated/deactivated.

##### 4.5.1.2 Main assessed criteria

Circuit completion time and number of collisions on the circuits. A collision was defined during the obstacle course by a displacement of a piece of cardboard, and as an impact during the ecological course. Collisions were recorded by direct observation and circuit completion time was manually measured.

##### 4.5.1.3 Secondary objective

Assessing the regular users satisfaction with the proposed driving assistance system.

##### 4.5.1.4 Secondary assessed criteria

User satisfaction was assessed through the 2.0 version of the ESAT (Évaluation de la Satisfaction envers une Aide Technique) questionnaire. ESAT 2.0 is a french translation

Age (years)	50.4 +/- 14
Sex ratio (F/M)	12/11
Height (cm)	165 +/- 12
Weight (cm)	73.9 +/-20

Table 4.1 – Participants characteristics (Mean +/- Standard Deviation).

of the 2.0 version of the QUEST (Quebec User Evaluation of Satisfaction with assistive Technology) questionnaire, a validated outcome measure of user satisfaction with an assistive device. This questionnaire is composed of 12 satisfaction items split into 2 parts: 8 items assessing user satisfaction with the device and 4 items assessing user satisfaction with the related services [DWLS00][DWLS02]. The ESAT questionnaire is quick to complete and can then be used in research studies that require rapid acquisition of satisfaction data. For the purpose of this study we used only the 8 items related to the device with a specific analysis for each item.

#### 4.5.1.5 Participants

The experimental study was approved by the local ethical committee of Rennes University Hospital (CHU Pontchaillou, Rennes). A total of 23 people volunteered to participate to the assessment of the proposed power wheelchair driving assistance system (participants characteristics are given in Table 4.1). Before being included in the study, they were clearly informed about the purpose of the driving tests and gave their written consent. Participants were older than 18 years old and regularly use a power wheelchair. The trials were conducted with regular users in order to assess the technical reliability of the proposed wheelchair driving assistance system.

### 4.5.2 Study conduct

Users were asked to drive our power wheelchair equipped with the proposed driving assistance system on two circuits. Before performing the test on each circuit, users transferred from their wheelchair to the smart power wheelchair and were then given 5 minutes to maneuver the wheelchair and get familiar with it.

#### 4.5.2.1 Procedure

Two circuits have been defined for the trials.

**Circuit 1: ecological circuit.** An ecological circuit has been designed within the corridors of the Rehabilitation Center Pôle Saint Héli r. This circuit consists of static and dynamic obstacles together with maneuvers in narrow spaces (turning around, backward maneuvers) in order to approach situations that are typically encountered at home (Figure 4.15).

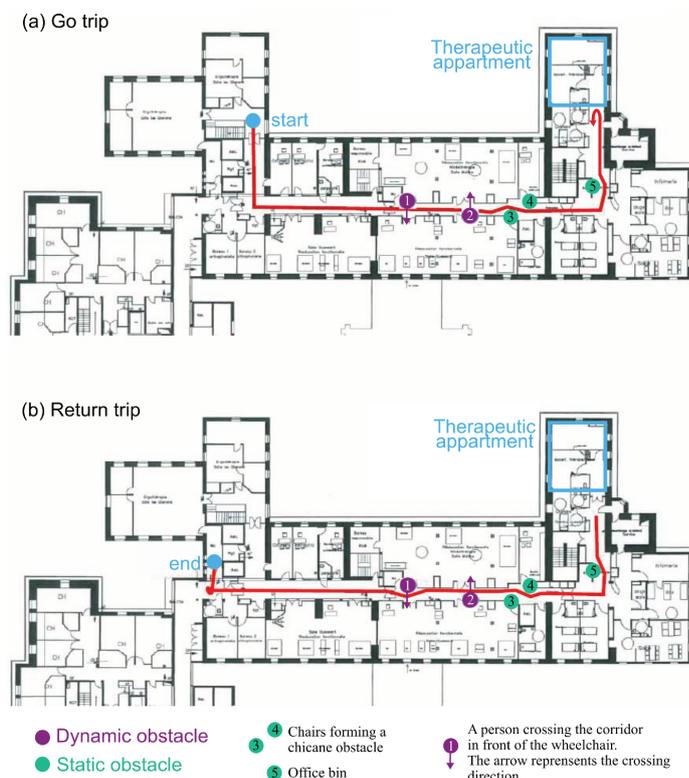


Figure 4.15 – Ecological circuit.

**Circuit 2: driving circuit.** An obstacle course made up of cardboard boxes has been designed for this study (Figure 4.16).

**Conditions** All the participants performed the tests on the ecological circuit and then on the obstacle course. This order allowed us to ensure that the participants were able to drive the power wheelchair on an ecological situation before asking them to drive the power wheelchair on the obstacle course which was much narrower and composed of more difficult maneuvers.

All assessments were performed with and without the assistance activated. This was conducted in single blind *i.e.* only experimenters were aware of the state of activation of the power wheelchair driving assistance module. This single-blind method is necessary to avoid a behavior bias for the participants. Indeed participants could be influenced by knowing when the assistance is activated.

**Instructions given to the participants** For the driving circuit, participants were given the following instruction: "perform the course as quickly as possible without colliding with obstacles". Users received no further instructions except for global indications concerning the course, the trajectory was not imposed. In both cases, the course

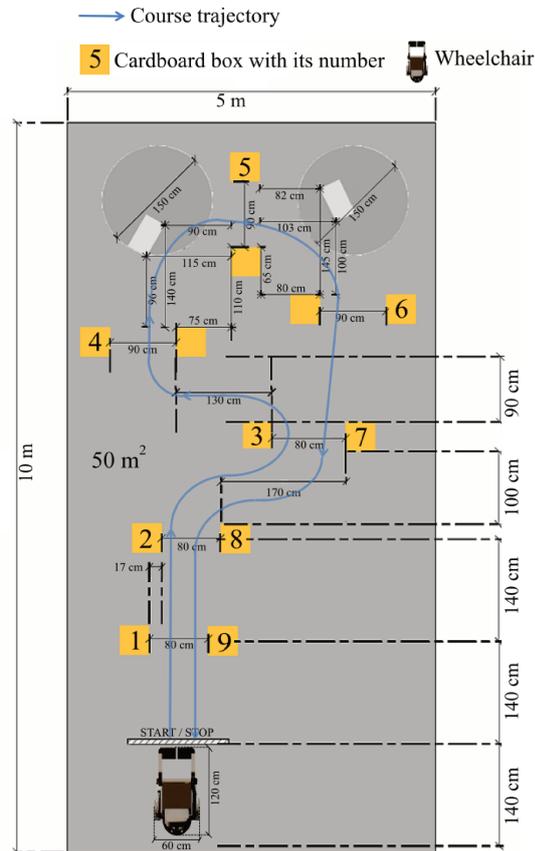


Figure 4.16 – Driving circuit.

was first demonstrated to the participants before starting the actual trial.

In order to prevent learning effect, the order of turn was counterbalanced (50% of the participants have started with assistance activated and 50% have started without assistance) for each circuit.

#### 4.5.2.2 Practical setup

Our smart wheelchair prototype was based on a standard Luca power wheelchair from the Sunrise company, equipped with its standard joystick from Penny & Giles company. This wheelchair has been robotized with

- 9 HC-SR04 low-cost ultrasonic sensors (Figure 4.17) give measurement with a refresh rate of 50 Hz. The 9-sensors arrangement corresponds to the one used during simulations (section 4.4) and to the minimum configuration to cover the area around the wheelchair except for the back of the wheelchair where a single sensor is clearly not sufficient enough to cover the area behind the wheelchair and thus prevent from all collisions risks while maneuvering backwards,. Indeed, the HC-SR04 ultrasonic sensor used in practice has a total field of view of  $30^\circ$ ,

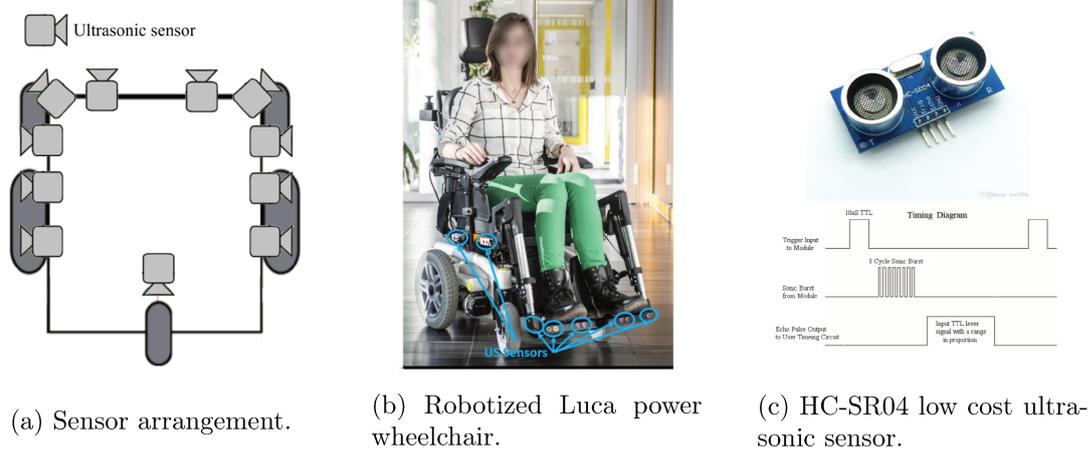


Figure 4.17 – Ultrasonic sensors on the power wheelchair.

- a dedicated interface for clinicians (Figure 4.18). The activation of the algorithm and experimental data recording were realized by means of an interface designed in consultation with clinicians. This interface allows them to start/stop the trial and to activate/deactivate the driving assistance module. As this interface is positioned behind the wheelchair, the users are neither aware of the activation nor the deactivation of the power wheelchair driving assistance system,

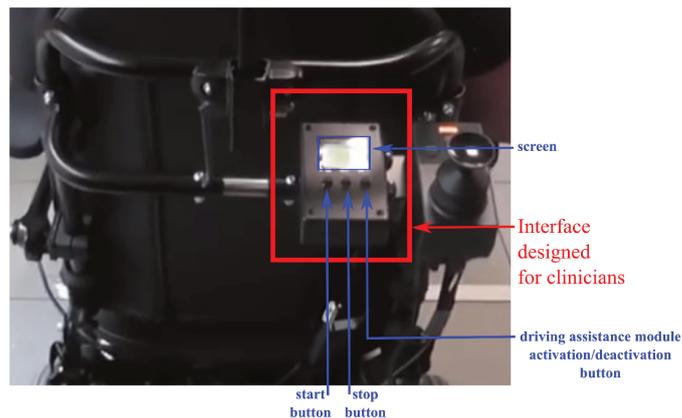


Figure 4.18 – Dedicated interface for clinicians.

- an embedded Raspberry Pi 3 computer used to communicate with the sensor as well as computing the assisted wheelchair control on-board.

As the algorithm is low complexity, all calculations can be performed during one cycle of the CAN bus leading to a latency of 10ms or less. This amount of latency has been shown to be undetectable by users.

	Completion time (s)	Nb of collisions
No assistance	72,9 +/- 30.8	2.35 +/- 2.50
Assistance	84.2 +/- 32.7	2.6 +/- 2.1
First trial	98.3 +/- 54.4	2.5 +/- 2.1
Second trial	85.2 +/- 41.1	2 +/- 2.2

Table 4.2 – Obstacle course results (Mean +/- Standard Deviation).

For both circuits, wheelchair speed was set and locked a maximum speed of 0.6 m/s. The wheelchair velocity was deliberately limited to provide a single configuration ensuring participants were performing the tests in the same conditions. Accelerations, decelerations as well as driving assistance algorithm parameters were also the same for all the participants for the same reasons. The activation rate of the wheelchair velocity correction was also calculated for each course.

### 4.5.3 Results

Descriptive statistics are shown as mean +/- standard deviation (M +/- SD) for continuous variables and frequencies and percentages for categorical variables. Comparisons between quantitative data are obtained using the classically used non parametric Wilcoxon test.  $p < 0.05$  is considered statistically significant.

#### 4.5.3.1 Driving circuit condition

No difference was observed between the two conditions, with even a slightly higher number of collisions with the assistance system activated on the obstacle course (Table 4.2). On both courses, users needed more time to complete the course when the assistance was activated but it was not statistically significant.

The assessment of the learning effect on the circuit obtained by comparing the first and second trials, without considering the activation of assistance did not find any statistically significant difference, although a decreasing trend in the number of collisions was noticed as well as a decrease of the circuit completion time between the first and the second trial.

#### 4.5.3.2 Ecological circuit condition

The results found no statistically significant difference between trials with and without assistance but with a trend towards a decrease of collisions with the assistance activated (Table 4.3). Even if the number of collisions decreased by 50% between trials without the assistance activated and trials with the assistance activated, this was not significant because of a very small number of collisions.

	Completion time (s)	Nb of collisions
No assistance	72,9 +/- 30.8	2.35 +/- 2.50
Assistance	84.2 +/- 32.7      p = 0.0813	2.6 +/- 2.1      p = 0.5344
First trial	98.3 +/- 54.4	2.5 +/- 2.1
Second trial	85.2 +/- 41.1      p = 0.2419	2 +/- 2.2      p = 0.1727

Table 4.3 – Ecological circuit results (Mean +/- Standard Deviation).

	Without assistance	With assistance
Esat 1 Dimensions	3.87 +/- 1.10	3.900 +/- 1.12      p = 0.5640
Esat 2 Weight	4.26 +/- 0.86	4.260 +/- 0.81      p > 0.9990
Esat 3 Adjustments	4.26 +/- 0.75	4.300 +/- 0.76      p = 0.3282
Esat 4 Safety	4.00 +/- 0.95	4.300 +/- 0.70      p = 0.0845
Esat 5 Durability	4.22 +/- 0.6	4.350 +/- 0.65      p = 0.0833
Esat 6 Ease of use	4.39 +/- 0.66	4.260 +/- 0.92      p = 0.1797
Esat 7 Comfort	4.00 +/- 1.13	4.040 +/- 1.15      p = 0.3282
Esat 8 Effectiveness	4.17 +/- 0.98	4.130 +/- 0.92      p = 0.6547
Esat total	33.17 +/- 3.35	33.56 +/- 3.49      p = 0.3091

Table 4.4 – ESAT results (Mean +/- Standard Deviation).

#### 4.5.3.3 Subjective assessment

The results on the ESAT scale showed no statistically significant difference, whether on the overall score or on sub scores (Table 4.4). However, safety item score seems to improve with the activation of the power wheelchair driving assistance but results are not statistically significant.

#### 4.5.4 Discussion

The purpose of this study was the assessment of regular users' driving performances on two types of circuits with and without the driving assistance. At the same time, it allowed us to assess the proposed smart wheelchair solution prototype's ease of use with regular users. This step was essential before considering tests with people who unsafely drive a power wheelchair. Simpson emphasizes the importance of the assessment of assistive devices by regular users, making the connection between their lack of involvement in the evaluation process and the limited commercial availability of such systems [SL02][Sim05]. Indeed, no driving assistance device for power wheelchair is currently available on the European consumer market. The rare commercialization attempts were not successful enough [CTC<sup>+</sup>02] [HWM13]. The assessment of the system was performed with driving tests on an ecological course as well as on a rather difficult obstacle course, more complex than the ecological course, but it did not turn out to be

discriminant enough.

For ethical reasons, participants in this first study were regular wheelchair users who are not a priori the targets for a power wheelchair driving assistance system. This could explain, the rather high rate of collisions on the obstacle course because some users wanted to perform the best time, and on the other hand, the low rate of collisions for the ecological course because users are accustomed to this type of situation. On the ecological course, results show a slight trend towards a decreasing number of collisions between trials without assistance and with the assistance activated. However, even though the number of collisions decreased by 50% with the assistance activated, this remains statistically not significant probably due to a small number of collisions. On the obstacle course, there was no decrease of the number of collisions between trials without assistance and trials with assistance as we would have expected. Most of the collisions happened with participants' feet or elbows.

Collisions which occurred will allow us to improve the proposed power wheelchair driving assistance system in terms of obstacle detection. The trials on the obstacle course put our system to the test. In particular, collisions which occurred with assistance have shown some shortcomings of the sensors coverage. Hence, the results obtained during these tests highlighted the need of a better sensor positioning on power wheelchairs. Achieving this will improve the system efficiency in difficult maneuvers and narrow spaces.

As for the power wheelchair driving assistance system reliability, no failure was noticed during the tests on the two courses. One of the major concerns was particularly whether the assistance system could disrupt the driving by inducing stops and speed reductions due to the sinuosity of the course causing an alteration of the power wheelchair ease of use. It seems that the power wheelchair driving assistance system activation did not alter the driving comfort of the participants with no statistically significant difference on the ESAT results. Thus, these regular wheelchair users were equally satisfied with the driving experience they had with and without the power wheelchair driving assistance system activated.

This study also leads us to consider creating an obstacle course which will contain more difficult maneuvers in order to provide a more discriminant reliability assessment for the power wheelchair driving assistance system. As the system did not show failure except for sensor coverage, once sensor positioning will be improved, we will be able to consider performing similar assessments with people who experience difficulties to drive a power wheelchair safely i.e. without risk of injury for them or others. Such a study will have the purpose to assess the impact of the proposed power wheelchair driving assistance system on their ability to navigate with a power wheelchair. From a methodological point of view the learning effect on the courses must also be taken into account, although there was no statistically significant difference, the results tend to improve at the second attempt. This must be underlined for future driving assistance systems assessment studies.

Finally, these tests have emphasized the importance of the involvement of end-users in the assessment process of a driving assistance system. Indeed, by including users into the process, we will be able to reach the next level after laboratory assessment and

therefore to ease the technological transfer [Sim05]. This requires close collaboration between research laboratories and medical teams specialized in Physical and Rehabilitation Medicine.

## 4.6 Conclusion

The proposed shared control navigation assistance solution consists of a sensor-based method relying on no map and providing reactive obstacle avoidance. The proposed solution was validated in terms of reliability, safety and ease of use with regular wheelchair users. This system provides adaptive assistance in the form of trajectory correction while encountering hazardous situations with a power wheelchair. The driving tests performed with and without assistance on an ecological course as well as on an obstacle course showed that the provided trajectory correction solution is smooth and intuitive enough so that regular users perception is not altered. No driving disruption has been observed even when users made high driving assistance demands because of their hazardous wheelchair steering. The ESAT scores show a high level of satisfaction with the use of the system. Although there was no significant decrease of the number of collisions, we noticed an increase of the ESAT safety item score. Concerning the design of the power wheelchair driving assistance system, sensor positioning can be improved in order to cover a wider area around the wheelchair for more efficient obstacle detection.

Testing the proposed navigation assistance method with regular users was very helpful to get feedback on the technical solution itself. Trials with regular users brought very positive and encouraging feedback about the driving assistance itself. However, many participants criticized the solution as not being able to provide assistance while driving in urban environment. Indeed, many participants asked for assistance with respect to curbsides or steps, emphasizing that these obstacles were particularly dangerous and that assistance was much needed to avoid wheelchair tipping and falling. In the following chapter, we then present the part of this thesis work addressing navigation assistance with respect to "negative" obstacles in order to provide more autonomy and thus more independence while navigating outdoor.

## Chapter 5

# Navigation assistance for outdoor power wheelchair

This chapter proposes a framework for wheelchair navigation assistance in outdoor environments. Two velocity controller designs based on sensor-based servoing methods are proposed. In both methods, assistance is semi-autonomously provided to the user while driving a power wheelchair. The proposed driving assistance methods consist of applying progressive wheelchair velocity adaptation while avoiding "negative" obstacles (*i.e.* which level is lower than the floor level). Indeed, accidents involving tipping or falling situations can occur while negotiating high curbsides, highly inclined slope, step, etc. Practically, this shared control paradigm consists in using distances measured from sensors oriented towards the floor to compute a wheelchair control input which respects as much as possible user input (*i.e.* intention) while correcting trajectory.

The first part of the content of this chapter has been presented at the HANDICAP Conference [C.7] and published in the AMSE Journal in 2018 [J.1]. More recent works presented in the second part of this chapter has been submitted to ICRA 2019 and is under review [DPBC19].

## 5.1 Introduction

### 5.1.1 Context and motivations

Driving a power wheelchair safely is a daily challenge particularly in urban environments while navigating on sidewalks, negotiating curbs or dealing with uneven grounds. Differences of elevation are part of the most challenging environmental barriers to negotiate when driving a wheelchair [Sal11][EM10][AKAMP13]. Tipping and falling constitute the most common power wheelchair accidents. Indeed, a case-control study including 95 wheelchair users assessing accident mechanisms and consequences over a 3-year period identified that among the 3 categories of wheelchair-related accidents, 87.7% were tips and falls [CJW<sup>+</sup>11]. In particular, many of the accidents occur outdoors or on ramps [KASB<sup>+</sup>94].

When interviewing regular users, one of the most frequently cited accident risk factors is uneven or sloping terrain [ROS15]. In some cases, it has been highlighted that such accidents can have serious consequences including traumatic brain injury or spinal cord injury [OGR09].

In addition, the risk of accidents due to differences of elevation is strongly increased when the wheelchair user has cognitive and/or visual impairment. The risk of injury for such an individual having difficulty to safely operate a power wheelchair is generally a sufficient reason to prohibit its prescription and use.

Yet, recent studies highlight the benefits of power mobility in the case of outdoor activities [LPIB12] [SW14]. It is reported that power mobility can improve the user self-esteem and sense of independence as it allows them to go outdoors more easily and to have the opportunity to socialize and enjoy daily activities such as shopping.

### 5.1.2 How to lessen power mobility issues, especially outdoors ?

Mobility issues experienced by people with disability involve interaction issues with the external environment. One way to lessen these mobility issues is to directly apply modifications to the external environment. These modifications can consist of providing additional assistive devices or physical structures alterations [CG97]. One intuitive way to improve the Quality of Experience (QoE) of people with disabilities experiencing difficulties to navigate safely is to modify and adapt the physical environment lessening accessibility issues, especially at home or within specialized care facilities [Git15]. In the case of wheelchair navigation, environmental modifications by means of the reduction of physical barriers can also greatly help wheelchair users to benefit from a more secure driving experience [Eva09]. However, such environmental modifications can show limits at an individual level as several individuals experience different navigation issues in the same environment. In other words, some elements considered as barriers for some people will not impact other ones or will be considered as facilitators for some others. For example, curb cuts without textured paving are considered as facilitators by power wheelchair users but are considered as a barrier by blind people [OO<sup>+</sup>05]. In France, the accessibility issue was addressed with the 1975 handicap law establishing the obligation of accessibility of all new built housing. Then, the "handicap" law voted

in 2005 aimed to apply this law by creating standards and requiring public places and public transports to be accessible to people with disability by the 1st of January 2015. However, only 30% of establishments out of 1 million were accessible by this deadline. Therefore, the law of 5th August 2015 introduced new deadlines: from 3 years (for establishments that can accommodate up to 200 people such as convenience stores or medical practices) to 6 years, or even 9 years for larger establishments or rail transport. More recently, the ELAN law voted in June 2018 the reduction from 100% to 10% of new housing that must comply with accessibility standards.

The case of France is an example of the difficulty of applying such environmental changes at the national level. The main reason given for the failure of policies to implement such standards everywhere is budgetary consideration (e.g. the cost of adaptation or construction or the higher selling price for the same built surface). In this context, the emergence of a completely "barrier-free" environment is impossible in France and that an environment with reduced barriers may still take several years to emerge.

It is then our challenge to design assistive solutions for power wheelchair navigation in all types of environments, allowing users to drive safely even if the environment is not barrier-free. Such a navigation assistance system is expected to detect both "positive" and "negative" obstacles in order to provide respectively collision avoidance and assistance while negotiating differences of elevation.

### 5.1.3 Related works

While lots of works have been accomplished in the last 20 years on smart power wheelchairs navigation assistance in an environment with "positive" obstacles, significantly less research has been conducted on detecting "negative" obstacles and developing navigation assistance on non-planar surfaces.

In the early 2000's, a prototype has been developed within the Smart Wheelchair Component System project (SWCS) using infrared sensors to stop the wheelchair when detecting a drop-off under the wheelchair footrests [HLS<sup>+</sup>03][SLH<sup>+</sup>04]. Although these results were published 15 years ago, there is, to the best of our knowledge, still no system available on the market with this technology.

As part of the UT Intelligent Wheelchair Project taking place within the University of Texas at Austin, a robotic power wheelchair equipped with a stereo vision-based system reconstituting a model of the wheelchair 3D local surround has been prototyped to provide assistance while driving with respect to "positive" as well as "negative" obstacles [MK09]. Although this prototype handles non-planar situations, it achieves only autonomous navigation by means of motion planning and requires sensors such as LIDARs and/or stereoscopic cameras. However, these devices have been shown to not meet smart power wheelchair requirements (section 2.3). Moreover, the plug-and-play and form-factor requirements are not taken into consideration as the prototype is a non-commercially 5-wheeled mobile base with a wheelchair seat attached to its frame. To the best of our knowledge, no development has continued beyond this study. Finally, no technological transfer from the laboratory to the industry has been made.

In 2007, a detection algorithm relying on depth information using stereo vision able

to find obstacle edges has been published [CS07]. However, while some efforts have been made in order to detect drop-offs using a robotized power wheelchair, no control law is given in order to assist the user while driving.

More recently, a research team initially working on feedback canes systems for people with Cerebral Palsy (CP) decided to investigate smart wheelchair solutions. The emerging system is a semi-autonomous power wheelchair taking into account "positive" obstacles in the environment as well as "negative" obstacles such as steps [FJJ<sup>+</sup>18]. The implemented method uses a self made multibeam laser telemetry sensor attached to the wheelchair armrest and oriented toward the floor. When this sensor detects an ascending or descending stair, the wheelchair speed progressively decreases until the wheelchair stops and stays stationary. Although the used sensor is able to perform more robust detection than cheap ultrasonic sensors or classical infrared sensors, there is no shared control law allowing the user to continue navigating nor feedback to the user, the wheelchair only stops while detecting is a step.

To sum up, there still exists no assistive solution allowing safe trajectories in an environment consisting of negative obstacles. Particularly there exists no semi-autonomous solution taking user intention into account. Indeed, existing solutions ensure at best that the wheelchair stops when detecting such an obstacle.

#### 5.1.4 Objective

When testing the solution for driving assistance within indoor environment presented in chapter 4, many participants were asking for assistance with respect to curbsides or steps, emphasizing that these obstacles were particularly dangerous and that assistance was much needed to avoid wheelchair tipping and falling.

In this work, the proposed solution consists of a similar shared-control approach to the one presented in section 4.1. Here, instead of avoiding walls and obstacles, the proposed solutions aim to assist the user while navigating in an environment with "negative" obstacles. To this end, the same mathematical method is used for wheelchair velocity regulation but with a different obstacle detection method. Thanks to this innovative detection method, the proposed solutions not only corrects the wheelchair trajectory while approaching a drop-off but also provides assistance on progressive differences of elevation such as accessible slopes. Indeed, while the former is a barrier representing a danger of tipping or falling, the latter is a facilitator helping wheelchair user to get on or get off a different floor elevation. Thus, in order to be compliant with end-user daily needs in terms of navigation, such an assistance system preventing tipping or falling while approaching drop-offs must also facilitate maneuvers on slopes.

To provide such an assistance, the detection of differences of elevation is here achieved by means of distance sensors mounted all around the wheelchair. Hence, floor orientations from local areas covered by distance sensors are selected as features. In this framework, the velocity regulation applied to the wheelchair depends on the steepness of the detected slope.

As in section 4.1, this sensor-based control approach takes into account the human-in-the loop factor through a shared control framework that fuses the velocity commands

of the control law and the user input.

## 5.2 Methods

The outdoor navigation assistance solution presented in this section mainly differs from the indoor navigation assistance method presented in section 4.1 in how the relevant information is detected. While the indoor navigation assistance required detection of obstacles in a 2D horizontal space parallel to the motion of the wheelchair, the proposed outdoor navigation assistance method needs "negative" obstacle detection.

### 5.2.1 How to detect relevant information ?

Information about surrounding floor elevations can be detected by using different exteroceptive sensors such as stereovision cameras laser rangefinders, etc. While expecting a reactive behavior of the power wheelchair with respect to such obstacles, changes of elevation can be measured by simple distance detection around the wheelchair. Referring to smart wheelchair solutions development requirements (section 2.3), the used distance sensors are expected to be cost efficient and with small dimensions and low-power consumption. In section 4.1, ultrasonic sensors were used to detect distances to the obstacles as such sensors fit all these requirements. While the proposed shared control method was validated using this type of sensor, the physical properties of ultrasound reflection on plane surfaces makes this type of sensor unsuitable for reliable elevation detection. Indeed, such sensors would have to be positioned with an incidence angle on the wheelchair and would not receive enough echoes to correctly detect the negative obstacles. Another low-cost, low-power and small dimension constraint distance sensor is the infrared sensor. Up to now, infrared sensor have been restricted to short distances detection thus restricting their use for assisted navigation. However, the recent new generation of infrared sensors detection characteristics (*e.g.* multi-zone detection, Time-of-Flight technology) brings new perspectives in the robotics field (section 2.2.1).

### 5.2.2 Modeling

In this chapter, we will present 2 methods which have been developed to provide reactive shared-control wheelchair navigation assistance in an environment consisting of negative obstacles. For both methods, distance sensors are attached to the wheelchair with the configuration shown on Figure 5.1a. As shown on this figure,

- let  $\mathcal{F}_R(R, \vec{X}_R, \vec{Y}_R, \vec{Z}_R)$  be the frame attached to the robotic wheelchair,
- let  $\mathcal{F}_{s_i}(S_i, \vec{X}_i, \vec{Y}_i, \vec{Z}_i)$  be the frame attached to the sensor  $s_i$ ,
- let  $a_i$  and  $b_i$  be the distances from the robot frame to the sensor frame respectively along the robot  $X_r$ -axis and  $Y_r$ -axis.
- let  $\theta_i$  be the orientation of the sensor  $s_i$  around the robot frame  $Z_r$ -axis,

- let  $\phi_i$  be the orientation of the sensor  $s_i$  with respect to the robot  $X_r Y_r$  plane,
- let  $d_i$  be the distance measured by the sensor  $s_i$ ,
- let  $\mathbf{u} = (v, \omega)$  be the 2-DoF control input of the wheelchair,
- let  $\mathbf{v}_{s_i}$  be the velocity of the sensor  $s_i$ ,

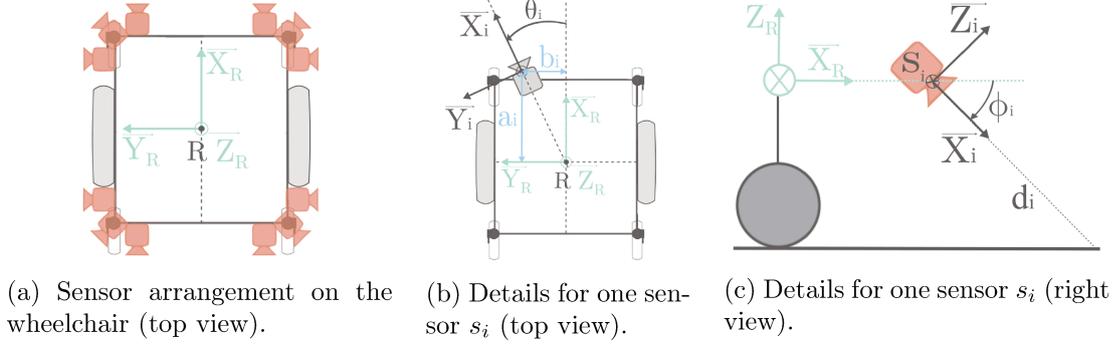


Figure 5.1 – Wheelchair modeling and sensor arrangement.

For both methods 12 sensors are attached to the power wheelchair frame with an orientation of an angle  $\phi_i$  (Figure 5.1c) with respect to the robot  $X_r Y_r$  plane. This way, distance sensors are oriented towards the floor.

Each sensor  $s_i$  is rigidly fixed to the robot frame so that the translation vector  ${}^r \mathbf{t}_{s_i}$  between  $\mathcal{F}_{s_i}$  and  $\mathcal{F}_R$  is such that

$${}^r \mathbf{t}_{s_i} = \begin{bmatrix} a_i \\ b_i \\ 0 \end{bmatrix}. \quad (5.1)$$

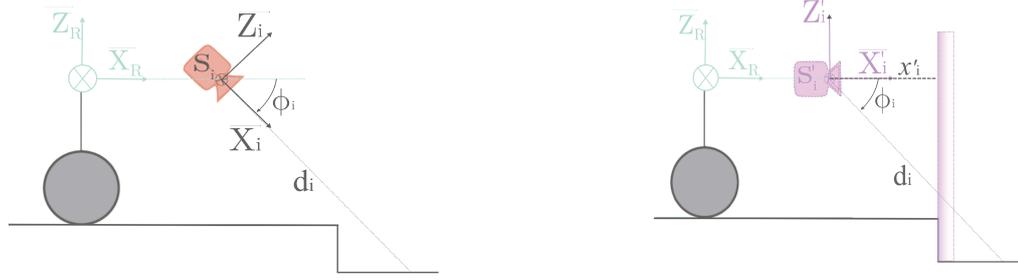
## 5.3 Curbside avoidance method

This section present a first outdoor assisted navigation method. The proposed method has been designed and tested on a real wheelchair in order to provide a proof-of-concept.

### 5.3.1 Method

The purpose of this first proof-of-concept is to deduce a distance from the sensor  $s_i$  to a detected "negative" obstacle in the horizontal plane. To do so, we propose to use a virtual sensor  $s'_i$  located at the same location as  $s_i$  with  $a'_i = a_i$ ,  $b'_i = b_i$ ,  $\theta'_i = \theta_i$ , and  $\phi_i = 0$ . The distance  $d_i$  measured to the floor by each sensor  $s_i$  is used to estimate a distance  $x'_i$  from a virtual sensor  $s'_i$  to a virtual "positive" obstacle in the horizontal plane as shown on Figure 5.2.

As shown on Figure 5.2b,



(a) Sensor  $s_i$  measuring distance to the floor in the case of a negative obstacle.

(b) Negative obstacle position represented by a virtual "positive" obstacle .

Figure 5.2 – Detection of obstacles. From a "negative" obstacle in the vertical plane to a "positive" obstacle in the horizontal plane

- let  $\mathcal{F}_{s'_i}(S'_i, \vec{X}'_i, \vec{Y}'_i, \vec{Z}'_i,)$  be the frame attached to the virtual sensor  $s'_i$ ,
- let  $x'_i$  be the distance to the virtual "positive" obstacle along the sensor  $s'_i$   $x$ -axis (*i.e.* the distance to the virtual "positive" obstacle in the horizontal plane),

Moreover, let  ${}^r\mathbf{t}_{s'_i}$  be the translation vector between  $\mathcal{F}_{s'_i}$  and  $\mathcal{F}_R$  such that

$${}^r\mathbf{t}_{s'_i} = \begin{bmatrix} a'_i \\ b'_i \\ 0 \end{bmatrix} = \begin{bmatrix} a_i \\ b_i \\ 0 \end{bmatrix} \quad (5.2)$$

The rotation matrix  ${}^{s'_i}\mathbf{R}_r$  relative to the sensor  $s'_i$  frame  $\mathcal{F}_{s'_i}$  with respect to the robot frame  $\mathcal{F}_R$  is such that

$${}^{s'_i}\mathbf{R}_r = \begin{bmatrix} \cos \theta_i & \sin \theta_i & 0 \\ -\sin \theta_i & \cos \theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (5.3)$$

The translation  ${}^{s'_i}\mathbf{t}_r$  between the robot  $\mathcal{F}_R$  frame and the sensor  $s'_i$  frame  $\mathcal{F}_{s'_i}$  is obtained from  ${}^{s'_i}\mathbf{R}_r$  with

$${}^{s'_i}\mathbf{t}_r = {}^{s'_i}\mathbf{R}_r {}^r\mathbf{t}_{s'_i}. \quad (5.4)$$

From  ${}^{s'_i}\mathbf{R}_r$  and  ${}^{s'_i}\mathbf{t}_r$ , the velocity screw transformation matrix defined in equation (2.5) is given by

$${}^{s'_i}\mathbf{W}_r = \begin{bmatrix} {}^{s'_i}\mathbf{R}_r & [{}^{s'_i}\mathbf{t}_r]_{\times} {}^{s'_i}\mathbf{R}_r \\ \mathbf{0}_{3 \times 3} & {}^{s'_i}\mathbf{R}_r \end{bmatrix}. \quad (5.5)$$

with  $[\ ]_{\times}$  being the skew matrix expression.

The velocity  $\mathbf{v}_{s'_i}$  of the sensor  $s'_i$  in the sensor frame  $\mathcal{F}_{s'_i}$  is derived from the robot 2-DoF control input  $\mathbf{u}$  in the robot frame using

$$\mathbf{v}_{s'_i} = {}^{s'_i}\mathbf{T}_r \mathbf{u}, \quad (5.6)$$

with

$${}^{s'_i}\mathbf{T}_r = {}^{s'_i}\mathbf{W}_r {}^r\mathbf{J}_r, \quad (5.7)$$

where  ${}^r\mathbf{J}_r$  is the robot jacobian defined in equation (2.7).

As shown in Figure 5.3,

- let  $h_{s_i}$  be the sensor  $s_i$  height from ground,
- let  $h_{i_n}$  be the height of the negative obstacle,
- let  $h_{i_p}$  be the height of the positive obstacle,
- let  $H_{i_n} = h_{s_i} + h_{i_n}$  be the sensor  $s_i$  height from negative obstacle level,
- let  $H_{i_p} = h_{s_i} - h_{i_p}$  be the sensor  $s_i$  height from positive obstacle level.

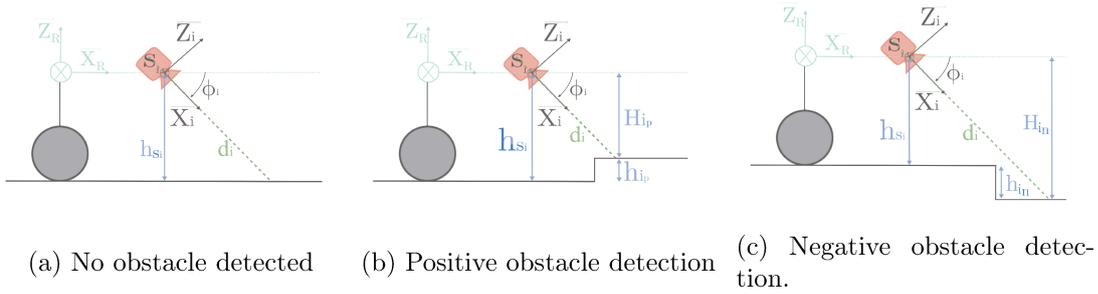


Figure 5.3 – Negative obstacle detection.

In order to compute the distance  $x'_i$  from the distance  $d_i$  measured by the sensor  $s_i$ , thresholds are defined on the value of  $d_i$ , namely  $d_{i_p}$  and  $d_{i_n}$  being respectively the maximum distance to a positive obstacle and the minimum distance to a negative obstacle. This way, we can consider that there is no obstacle to detect as long as the distance  $d_i$  measured by the sensor  $s_i$  is such that  $d_{i_p} \leq d_i \leq d_{i_n}$ . Then, detection is such that we can distinguish 3 cases:

**Case 1** When  $d_{i_p} \leq d_i \leq d_{i_n}$ , the distance to the obstacle is defined as  $x'_i = x_m$  where  $x_m$  is the maximum distance a sensor can measure.

**Case 2**  $h_{i_p}$  is defined as the minimum height of a positive obstacle we observe. Then we detect a positive obstacle when

$$d_i < d_{i_p} = \frac{h_{s_i} - h_{i_p}}{\cos(\phi_i)} = \frac{H_{i_p}}{\cos(\phi_i)}, \quad (5.8)$$

leading to define the distance to the obstacle as

$$x'_i = d_i \cos(\phi_i). \quad (5.9)$$

**Case 3**  $h_{i_n}$  is defined as the minimum height of a negative obstacle we observe, then we detect a negative obstacle when

$$d_i > d_{i_n} = \frac{h_{s_i} + h_{i_n}}{\cos(\phi_i)} = \frac{H_{i_n}}{\cos(\phi_i)}, \quad (5.10)$$

leading to define the distance to the obstacle as

$$x'_i = h_{s_i} \cos(\phi_i). \quad (5.11)$$

It is to be noted that the definition of thresholds required by this method necessitates an extrinsic calibration of the sensors as sensor position information is used in our calculations.

This first method aims to compute distances to negative obstacle the same way distances to "positive" obstacles were computed in the work presented in chapter 4.

### 5.3.2 Control method

A virtual sensor  $s'_i$  detects a virtual "positive" obstacle in the frame  $\mathcal{F}_{s'_i}$ . This configuration is identical to the framework presented in section 4.1, therefore, the velocity controller is very similar. The shared control task is designed to exponentially decrease the error  $e_{s'_i}$  by means of a velocity controller. Here, we use the same velocity controller, *i.e.*

$$\dot{x}'_i \geq -\lambda e_{s'_i} \quad (5.12)$$

where  $e_{s'_i} = x'_i - x'^*_i$  the difference between the estimated distance to the obstacle  $x_i$  its desired value  $x'^*_i$  and  $\lambda \in \mathbb{R}^{+*}$  is a gain.

As  $\dot{x}'_i = \mathbf{L}_{x'_i}{}^{s'_i} \mathbf{T}_r \mathbf{u}$ , we obtain

$$\mathbf{L}_{x'_i}{}^{s'_i} \mathbf{T}_r \mathbf{u} \geq -\lambda e_{s'_i}. \quad (5.13)$$

The interaction matrix has the same expression as the one given in equation (4.13), *i.e.*

$$\mathbf{L}_{x'_i} = [-1 \ 0 \ 0 \ 0 \ 0 \ 0]. \quad (5.14)$$

Moreover, considering

$${}^{s'_i}\mathbf{T}_r = {}^{s'_i}\mathbf{W}_r {}^r\mathbf{J}_r = \begin{bmatrix} \cos \theta_i & b_i \cos \theta_i - a_i \sin \theta_i \\ -\sin \theta_i & -a_i \cos \theta_i - b_i \sin \theta_i \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \quad (5.15)$$

*i.e.*

$$\mathbf{J}_{s'_i} \mathbf{u} \geq -\lambda e_{s'_i}, \quad (5.16)$$

where  $\mathbf{J}_{s'_i} = \mathbf{L}_{x'_i} {}^{s'_i}\mathbf{T}_r$  the sensor  $s'_i$  jacobian introduced in equation (2.10).

The system (5.16) is a linear equation system which can admit an infinity of solutions in the form of a 2D half-plane in the wheelchair velocity domain. Indeed, since  $\mathbf{J}_{s'_i} \in \mathbb{R}^{1 \times 2}$  and  $\mathbf{u} = [v \ \omega]^T$ , we can rewrite inequation (5.16) as

$$J_{s'_i}^v v + J_{s'_i}^\omega \omega \geq -\lambda e_{s'_i} \quad (5.17)$$

with  $J_{s'_i}^v \in \mathbb{R}$  and  $J_{s'_i}^\omega \in \mathbb{R}$  such that  $\mathbf{J}_{s'_i} = \begin{bmatrix} J_{s'_i}^v & J_{s'_i}^\omega \end{bmatrix}^T$ .

Therefore, the computation of the desired velocity input  $\mathbf{u}_{cmd}$  consists of the following optimization problem

$$\begin{cases} \mathbf{u}_{cmd} = \min_{\mathbf{u}} f(\mathbf{u}_{op}, \mathbf{u}) \\ \mathbf{A} \mathbf{u} \geq \mathbf{B} \end{cases} \quad (5.18)$$

$$\text{with } \mathbf{A} = \begin{bmatrix} \mathbf{A}_0 \\ \mathbf{A}_1 \\ \vdots \\ \mathbf{A}_{N-1} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{s'_0} \\ \mathbf{J}_{s'_1} \\ \dots \\ \mathbf{J}_{s'_{N-1}} \end{bmatrix} \text{ and } \mathbf{B} = \begin{bmatrix} B_0 \\ B_1 \\ \vdots \\ B_{N-1} \end{bmatrix} = \begin{bmatrix} -\lambda e_{s'_0} \\ -\lambda e_{s'_1} \\ \dots \\ -\lambda e_{s'_{N-1}} \end{bmatrix}.$$

with  $N$  the number of sensors,  $i \in 0, \dots, N-1$ ,  $\mathbf{J}_{s'_i} = \mathbf{L}_{x'_i} {}^{s'_i}\mathbf{T}_r$  the sensor  $s'_i$  the Jacobian introduced in equation (2.10), and  $\lambda \in \mathbb{R}^{+*}$  a gain.

As shown in section 4.1, shared control takes the form of the minimization of a cost function  $f$  under the inequality constraints  $\mathbf{A} \mathbf{u} \geq \mathbf{B}$  in the form of a weighted euclidean norm corresponding to the minimization of the euclidean distance between the input  $\mathbf{u}$  and the user input  $\mathbf{u}_{op}$  such that

$$f(\mathbf{u}_{op}, \mathbf{u}) = \alpha(v - v_{op})^2 + \beta(\omega - \omega_{op})^2 \quad (5.19)$$

where  $\alpha \geq 0$  and  $\beta \geq 0$ .

### 5.3.3 Simulations

In order to validate the framework formulated above, we here present a simulation trial. The aim of this simulation is to assess the ability of the power wheelchair to correct its trajectory along a curb edge while user translational and rotational velocity inputs are set at their maximum values thus directing the wheelchair towards the curb edge.

#### 5.3.3.1 Simulation framework

The simulation was run with the driving simulator presented in chapter 3. The virtual wheelchair (Figure 5.5b) is here equipped with 4 detection modules consisting of 3 distance sensors each, located at each corner of the virtual wheelchair (Figure 5.5a). The virtual environment shown on Figure 5.4 consists of a L-shaped 15 cm height, 1.2 m wide and 5 m long sidewalk with a right turn at its end. The velocity parameters of the wheelchair are chosen with respect to typical commercially-available wheelchair velocity parameters. Then, the maximum forward speed is set to  $0.5 \text{ m}\cdot\text{s}^{-1}$  and the maximum rotational speed is set to  $0.5 \text{ rad}\cdot\text{s}^{-1}$ .

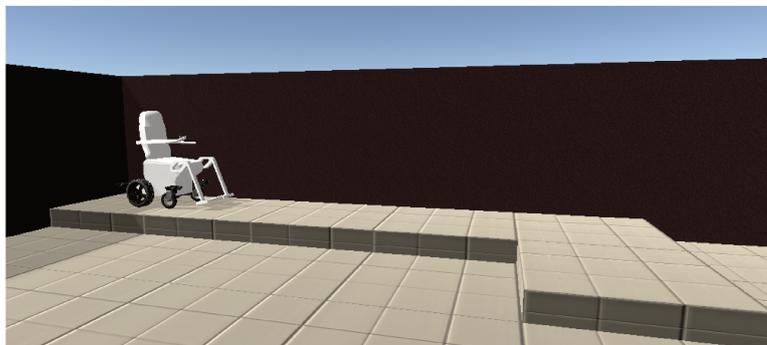


Figure 5.4 – Virtual environment for the simulation.

The virtual power wheelchair actuation is implemented using the generic ROS framework presented in chapter 3.

#### 5.3.3.2 Simulation results

The virtual wheelchair starts from the position shown on Figure 5.6a i.e. at the beginning of the sidewalk and parallel to the curb. The user's linear and angular inputs are constant and equal to the maximum speed of the wheelchair. This leads the wheelchair to go forward and turn right at maximum speed.

At the beginning, no negative obstacle is detected thus the wheelchair is going towards the curb. Then, when the curb is detected, the linear velocity progressively decreases and the rotational velocity is modified in order to follow the curb. When the wheelchair drives parallel to the curb, the linear velocity increases as there is no danger to fall from the curb. The rotational velocity is maintained to zero as long as the wheelchair is detecting the curb on its right. Then, when the wheelchair arrives at

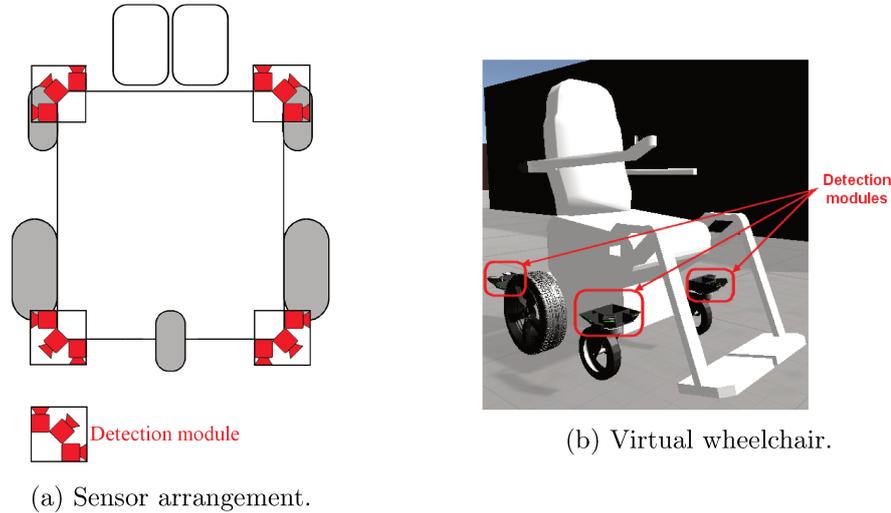


Figure 5.5 – Wheelchair setup for the simulation.

the point where there is  $90^\circ$  turn to the right, it turns right and stops when it detects the drop-off at the end of the sidewalk in front of it.

## 5.4 Experiment

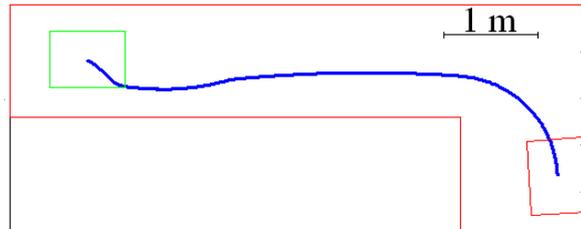
In the context of the Inria Associate Team ISI4NAVE (<https://team.inria.fr/isi4nave>). I was invited twice to spend 2 months in the UCL Aspire CREATE laboratory to perform tests on their wheelchair in the UCL PAMELA experimental environment (<https://www.ucl.ac.uk/transport-institute/lab/PAMELA>).

### 5.4.1 Experimental setup

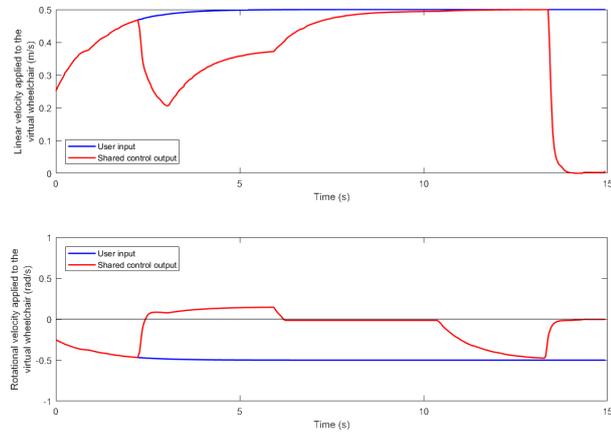
The proposed solution was tested on a commercially available Typhoon II power wheelchair from Invacare. We had previously modified Invacare’s DX controller to intercept the user input and adjust the control signals before sending them to the motors, allowing us to implement and test various shared control algorithms on the platform [ETD<sup>+</sup>17]. The algorithm itself runs on an embedded Beagle-Bone Black (AM335x 1GHz ARM Cortex-A8 processor) running ROS on Linux. For this experiment, the wheelchair linear and angular velocities were restricted to 0.5 m/s and 0.5 rad/s respectively.

For the detection, we used Time-of-Flight (ToF) VL53L0X laser-ranging sensors from STMicroelectronics. Unlike conventional infrared sensors, these sensors are low-cost and provide accurate distance measurement whatever the target reflectance. It can measure absolute distances up to 2 meters with a field of view of 25 degrees. The Beagle-Bone board uses an I2C bus for sensor control and data transfer.

The presented method necessitates an extrinsic calibration of the sensors as we use



(a) Simulated trajectory for the wheelchair



(b) Forward and rotational velocities applied to the wheelchair

Figure 5.6 – Simulation results: (a) represents the trajectory of the virtual wheelchair in the simulated environment which we recorded for visualization purpose only. The rectangles represent the wheelchair at the beginning (green) and at the end (red) of the simulation. (b) represents the corrected forward and rotational velocities during the simulation.

the sensor position information in our distance calculations. Here, we rigidly attached the detection modules to the wheelchair frame thus ensuring a fixed position of the sensors.

The power wheelchair actuation is implemented using the generic ROS framework presented in chapter 3 adapted to the control of real power wheelchair prototype. The adapted framework is presented in Figure 5.8. The proposed framework is composed of the following 3 ROS nodes, namely:

- Sensor ROS node. This node replaces the Display ROS node used for simulations. This node manages sensor measurements.
- Control ROS node. This node manages the computation of the velocity control input to be applied to the wheelchair.
- Controller ROS node. This ROS node manages input controller data collection,



Figure 5.7 – (a) Power wheelchair equipped with detection module prototypes. (b) Detection module prototype (bottom view). Each detection module is composed of 3 ToF sensor boards inclined at 45 degrees to the vertical.

here the standard wheelchair joystick commands. In addition to the framework presented in simulation, this node also manages direct control of the wheelchair by sending the computed shared control output to the wheelchair power module.

#### 5.4.2 Experiment environment

We tested our solution in UCL’s Pedestrian Accessibility Mobility and Environment Laboratory (PAMELA), which is a modular platform consisting of 36 modules that can be adjusted to simulate different street environments. For our work, we arranged the modules in order to simulate a 1.2 m wide, 8 m long and 15 cm height sidewalk (Figure 5.9).

#### 5.4.3 Experiment results

An example of results obtained from a trial on the sidewalk within the PAMELA facility is shown on Figure 5.10. For each trial, we used the same initial conditions as during the simulations: the wheelchair starts parallel to the curb at the beginning of the sidewalk.

As shown on Figure 5.10, the wheelchair starts to drive towards the curb as there is no drop-off detected *i.e.* no constraint deduced from the sensors. While no drop off is detected, the wheelchair linear and rotational velocities are at maximum values *i.e.* control inputs are directly applied to the wheelchair. Then, when a drop-off is detected, the linear velocity decreases in order to avoid falling down the curb and the rotational velocity is modified to achieve a rotation placing the wheelchair parallel to the curb. When the wheelchair is parallel to the curb, the linear velocity increases as there is no risk of falling down a curb in the forward direction.

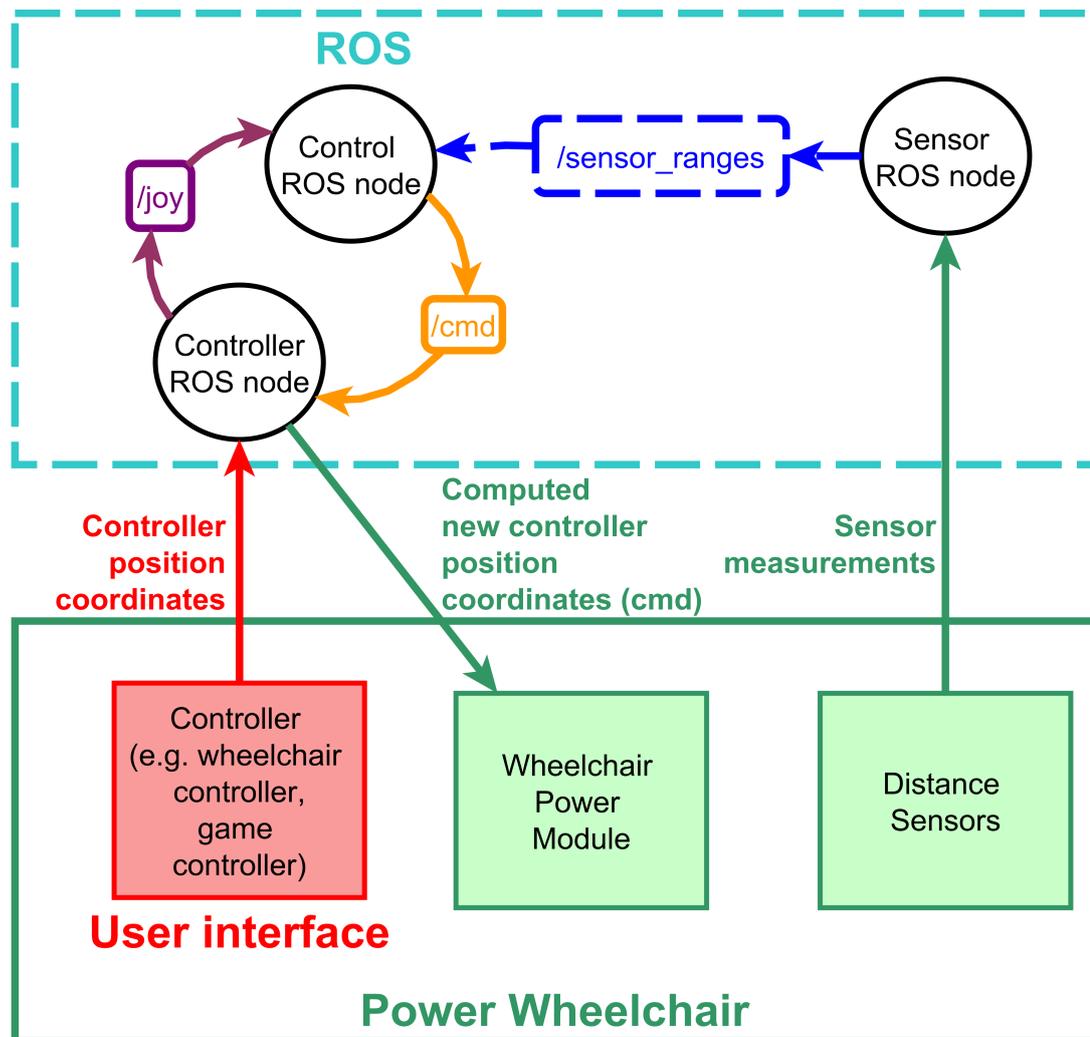


Figure 5.8 – Generic ROS framework adapted to the control of the real power wheelchair.

The experiment we performed within the PAMELA facility allowed us to assess the performances of our solution for assisted power wheelchair navigation on a sidewalk while embedded on a real wheelchair. We were able to validate our detection method and to avoid from falling down a curb while driving. These results bring a proof of concept of our assistive solution for power wheelchair navigation on a sidewalk.

#### 5.4.4 Conclusion

This method allows the wheelchair to progressively correct the trajectory of the wheelchair in an environment consisting of "negative" obstacles. By using low-cost sensors attached to the power wheelchair frame with an orientation towards the floor, we are able to measure a distance from each distance sensor  $s_i$  to the floor. By defining thresholds on the

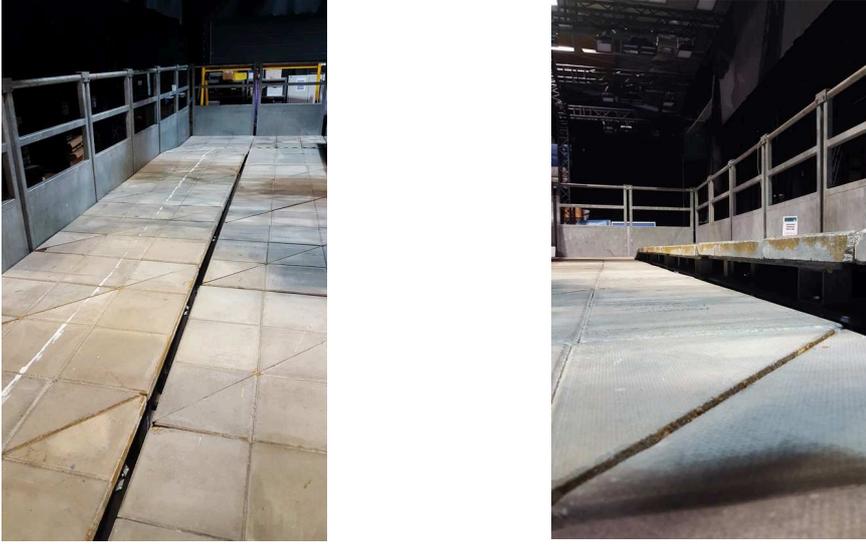


Figure 5.9 – Experiment environment on the PAMELA platform.

measured distances to the floor, we can determine if the wheelchair detects a "negative" or a "positive" obstacle and if the obstacle is crossable or not, depending on its height (*i.e.* between the 2 threshold values). These vertical obstacles are virtually considered as positive obstacles which would be detected by the same sensor attached at the same location but with no orientation towards the floor. A distance  $x'_i$  from the wheelchair to the virtual corresponding "positive" obstacle in the horizontal plane is then deduced from the measurement  $d_i$  of the  $s_i$  sensor. Therefore, the control framework is similar to the method of navigation assistance presented in section 4.1. Then, as shown in simulation and in real tests, the wheelchair behaves the same way it would behave in an indoor environment with respect to a close obstacle. Indeed, when the regulation of the wheelchair control input is applied while detecting a drop-off, the wheelchair velocity is regulated the same way it would be regulated if detecting a "positive" obstacle at the same distance in an indoor environment.

This method thus allows "negative" obstacles avoidance by means of trajectory correction achieved by control input regulation. Indeed, when a "positive" or "negative" difference of elevation is detected and identified as greater than a pre-determined threshold, the wheelchair control input is regulated with the aim to avoid the detected obstacle. If the difference of elevation is lower than a pre-determined threshold, the user keeps full control of the vehicle.

## 5.5 Outdoor navigation assistance method

The first method presented in section 5.3 is a direct application of the mathematical principle presented in chapter 4 applied to the outdoor navigation task. This first proof method provided a validation of the proposed detection framework both in simulation

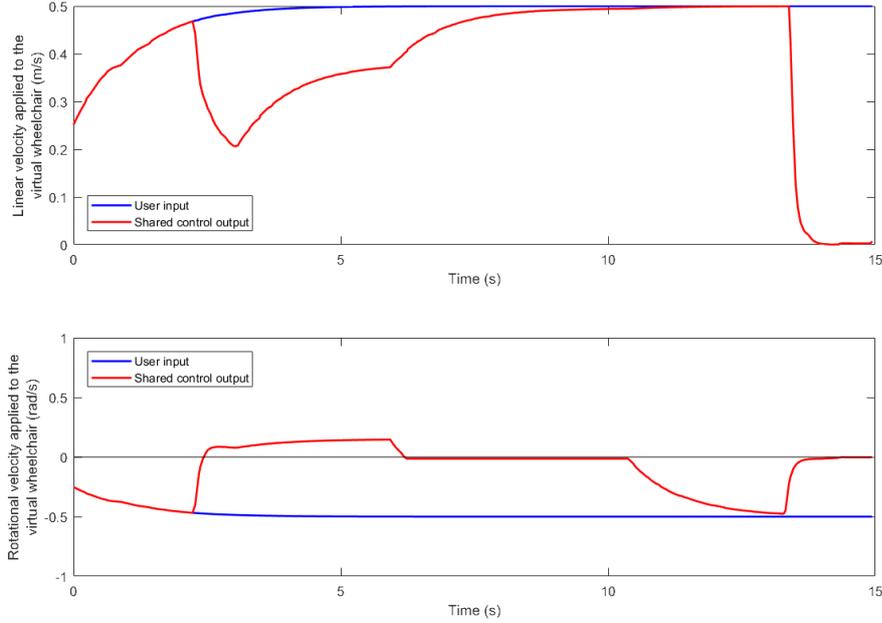


Figure 5.10 – Experiment results: (a) linear user input (blue) and shared control output (red) velocities (b) rotational user input (blue) and shared control output (red) velocities.

and real tests. Based on these results, we can confidently rely on the technical choices made in terms of hardware and shared control method to design a more elaborated prototype. Indeed, this navigation assistance method in an environment consisting of "negative" obstacles can be improved by directly incorporating the differences of elevations into the interaction matrix: the idea is then to take into account the local floor orientations measured by multi-zone distance sensors. Therefore, there is no need of using thresholds to determine the crossability of a negative obstacle.

### 5.5.1 Modeling

The rotation matrix  ${}^{s_i}\mathbf{R}_r$  relative to sensor  $s_i$  frame  $\mathcal{F}_{s_i}$  with respect to the robot frame  $\mathcal{F}_R$  is given by

$${}^{s_i}\mathbf{R}_r = {}^{s_i}\mathbf{R}_r(\phi_i){}^{s_i}\mathbf{R}_r(\theta_i) \quad (5.20)$$

with

$${}^{s_i}\mathbf{R}_r(\phi_i) = \begin{bmatrix} \cos \phi_i & 0 & -\sin \phi_i \\ 0 & 1 & 0 \\ \sin \phi_i & 0 & \cos \phi_i \end{bmatrix} \quad \text{and} \quad {}^{s_i}\mathbf{R}_r(\theta_i) = \begin{bmatrix} \cos \theta_i & \sin \theta_i & 0 \\ -\sin \theta_i & \cos \theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (5.21)$$

The translation  ${}^{s_i}\mathbf{t}_r$  between the robot  $\mathcal{F}_R$  frame and the sensor  $s_i$  frame  $\mathcal{F}_{s_i}$  is obtained from  ${}^{s_i}\mathbf{R}_r$  with

$${}^{s_i}\mathbf{t}_r = {}^{s_i}\mathbf{R}_r {}^r\mathbf{t}_{s_i}. \quad (5.22)$$

From  ${}^{s_i}\mathbf{R}_r$  and  ${}^{s_i}\mathbf{t}_r$ , the velocity screw transformation matrix defined in equation (2.5) is given by

$${}^{s_i}\mathbf{W}_r = \begin{bmatrix} {}^{s_i}\mathbf{R}_r & [{}^{s_i}\mathbf{t}_r]_{\times} {}^{s_i}\mathbf{R}_r \\ \mathbf{0}_{3 \times 3} & {}^{s_i}\mathbf{R}_r \end{bmatrix}. \quad (5.23)$$

with  $[\ ]_{\times}$  being the skew matrix expression.

The velocity  $\mathbf{v}_{s_i}$  of the sensor  $s_i$  in the sensor frame  $\mathcal{F}_{s_i}$  is derived from the robot 2-DoF control input  $\mathbf{u}$  in the robot frame using

$$\mathbf{v}_{s_i} = {}^{s_i}\mathbf{T}_r \mathbf{u}, \quad (5.24)$$

with

$${}^{s_i}\mathbf{T}_r = {}^{s_i}\mathbf{W}_r {}^r\mathbf{J}_r, \quad (5.25)$$

where  ${}^r\mathbf{J}_r$  is the robot jacobian defined in equation (2.7).

### 5.5.2 Detection method and features extraction

In this method, we want to extract relevant information from each sensor distance measurement. Multi-zone distance sensors such as VL53L1 infrared sensors (section 2.2.1) are able to measure multiple distances within different regions of interest. It is therefore possible to estimate local floor orientations for each sensor and by extension changes of elevations. This leads to the definition of two features in the form of angles characterizing the orientation of the detected floor area. As shown on Figure 5.11, let  $(\alpha_{x_i}, \alpha_{y_i})$  be the set of angles defining the orientation of the floor with respect to the wheelchair  $O X_r Y_r$  plane with  $\alpha_{x_i}$  and  $\alpha_{y_i}$  being defined respectively around the sensor  $s_i$   $X_i$ -axis and  $Y_i$ -axis.

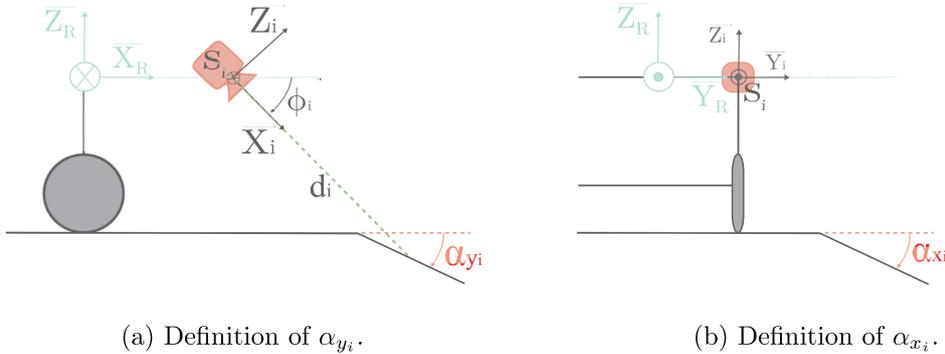


Figure 5.11 – Definition of  $\alpha_{x_i}$  and  $\alpha_{y_i}$ .

### 5.5.3 Velocity regulation controller design

In this part, we present a sensor-based semi-autonomous wheelchair velocity regulation method. The idea is to progressively adapt the wheelchair control input to avoid hazardous situations caused by "negative" obstacles. To do so, we define the error  $e_{s_i}$  for each sensor  $s_i$  such that  $e_{s_i} = d_i - d_i^*$  where  $d_i, d_i^* \in \mathbb{R}^+$  are respectively the distance measured by a sensor  $s_i$  to the floor and a configurable fixed value corresponding to the maximum allowed distance from the sensor  $s_i$  to the floor.

#### 5.5.3.1 Interaction matrix computation

With the 2 features  $\alpha_{x_i}$  and  $\alpha_{y_i}$  determined during the feature extraction process (section 5.5.2), we can design a dedicated control law that regulates the error  $e_{s_i}$  by taking into account local floor area orientation into each sensor  $s_i$  interaction matrix.

For the present case, the interaction matrix  $\mathbf{L}_{d_i}$  which theoretical formulation is such that

$$\mathbf{L}_{d_i} = \begin{bmatrix} -1 & \frac{\tan \alpha_{x_i}}{\sin \phi_i} & \frac{1}{\tan(\phi_i + \alpha_{y_i})} & 0 & \frac{d_i}{\tan(\phi_i + \alpha_{y_i})} & d_i \frac{\tan(\alpha_{x_i})}{\sin \phi_i} \end{bmatrix}. \quad (5.26)$$

#### 5.5.3.2 Shared control method

The objective is to regulate the wheelchair velocity control input to avoid hazardous situations involving "negative" obstacles when needed while still allowing full control to the user when there is no "negative" obstacle close to the wheelchair. The proposed method consists in gradually activating the regulation of each distance sensor  $s_i$  feature  $d_i$  to a desired value  $d_i^*$  corresponding to the distance measured when no "negative" obstacle is detected. This is achieved by using a safe interval  $[d_i^{s-}, d_i^{s+}]$  that we define to trigger the sensor-based servoing when the distance  $d_i$  leaves this interval. This hybrid control law method has been introduced in [KC11] and applied to wheelchair navigation in [PKB14] within a wall avoidance task. The idea here is to adapt this framework to our semi-autonomous navigation task in an environment consisting of "negative" obstacles.

The proposed sensor-based control law aims to keep the distance feature  $d_i$  within the interval  $[d_i^{s-}, d_i^{s+}]$

$$\dot{d}_i = h_{d_i} \mathbf{L}_{d_i} \mathbf{v}_{s_i} \quad (5.27)$$

with  $\mathbf{L}_{d_i} \in \mathbb{R}^{1 \times 6}$  the interaction matrix introduced in [ECR92] and  $h_{d_i} \in \mathbb{R}^{+*}$  a varying weight associated to the distance feature  $d_i$ . The weight  $h_{d_i}$  associated to  $d_i$  is such that  $h_{d_i} \in [0, 1]$ . A null weight leads to no regulation of the error  $e_i = d_i - d_i^*$  by the sensor-based servoing. Therefore, the term  $h_{d_i}$  allows to activate or deactivate the control law when desired. In order to gradually activate the control law when the feature  $d_i$  is leaving the safe interval  $[d_i^{s-}, d_i^{s+}]$ , we propose here to define the weight  $h_{d_i}$  by the following smooth function

$$h_{d_i}(d_i) = \begin{cases} \left(1 - \cos\left(\pi \frac{d_i - d_i^{s+}}{d_i^+ - d_i^{s+}}\right)\right) / 2 & \text{if } d_i^{s+} < x < d_i^+ \\ 0 & \text{if } d_i^{s-} < x < d_i^{s+} \\ \left(1 - \cos\left(\pi \frac{d_i - d_i^{s-}}{d_i^- - d_i^{s-}}\right)\right) / 2 & \text{if } d_i^- < x < d_i^{s-} \\ 1 & \text{otherwise} \end{cases} \quad (5.28)$$

where  $[d_i^-, d_i^+] \supset [d_i^{s-}, d_i^{s+}]$  is a tolerated interval whose fixed limits represent the distance values corresponding to distances measured to obstacles the wheelchair should avoid. The evolution of the weighting term  $h_{d_i}$  is given in Figure 5.12.

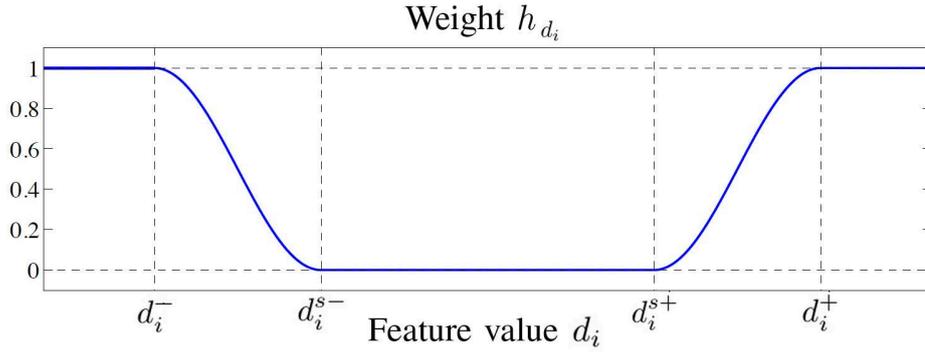


Figure 5.12 – Weighting function  $h_{d_i}$  defined for feature  $d_i$ . The weight is null in the safe interval and smoothly increases up to 1 in the tolerated intervals  $[d_i^-, d_i^{s-}]$  and  $[d_i^{s+}, d_i^+]$ .

For each sensor  $s_i$ , we have the formulation

$$\dot{d}_i \geq -\lambda e_{s_i}, \quad (5.29)$$

where  $\lambda \in \mathbb{R}^{+*}$  is a gain.

This way,  $\dot{d}_i$  is constrained by a minimum value  $-\lambda e_{s_i}$ . When considering the relationship  $\dot{d}_i = \mathbf{L}_{d_i}^{s_i} \mathbf{T}_r \mathbf{u}$  between the 2 DoF wheelchair control input  $\mathbf{u}$  and the variation  $\dot{d}_i$  of the distance  $d_i$  measured by the sensor  $s_i$ , we obtain

$$h_{d_i} \mathbf{L}_{d_i}^{s_i} \mathbf{T}_r \mathbf{u} \geq -\lambda e_{s_i} \quad (5.30)$$

*i.e.*

$$\mathbf{J}_{s_i} \mathbf{u} \geq -\lambda e_{s_i}, \quad (5.31)$$

where  $\mathbf{J}_{s_i} = h_{d_i} \mathbf{L}_{d_i}^{s_i} \mathbf{T}_r$  is the sensor  $s_i$  Jacobian.

### 5.5.4 Simulations

In this section, simulation results are presented. The proposed simulations were performed as a first step to develop the proposed solution of power wheelchair navigation assistance on a sidewalk.

#### 5.5.4.1 Simulation framework

The virtual wheelchair (Figure 5.5b) is here equipped with a total of 12 distance sensors divided into 4 detection modules placed at each corner of the virtual wheelchair (Figure 5.5a). The virtual environment is displayed on a computer screen as it is only used to demonstrate the properties of the proposed solution for assisted power wheelchair navigation on a sidewalk. As shown on Figure 5.13, it consists of a 20 cm height sidewalk. The velocity parameters of the wheelchair are chosen to mimic a typical commercially-available wheelchair, such that the maximum forward speed is  $0.7\text{ m}\cdot\text{s}^{-1}$  and the maximum rotational speed is  $0.5\text{ rad}\cdot\text{s}^{-1}$ .

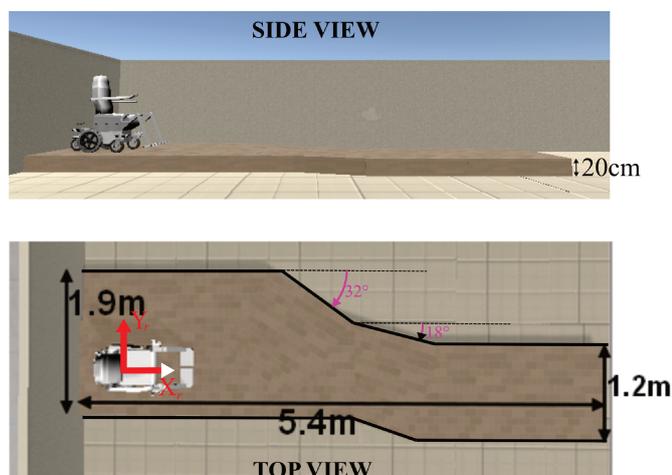


Figure 5.13 – Virtual environment for the simulation.

#### 5.5.4.2 Simulation results

Different wheelchair trajectory corrections obtained during the simulations performed in the virtual environment shown in Figure 5.13 are displayed in Figure 5.14.

Here, we will detail the result for the third trial which best demonstrates the performances of the proposed solution. The virtual wheelchair starts from the position shown on Figure 5.15. The user's linear and angular inputs are constant and respectively set to the maximum linear velocity value and zero for angular velocity. This leads the wheelchair to go forward at maximum speed.

At the beginning, no negative obstacle is detected thus the wheelchair is going towards the curb. Then, when the curb is detected, the linear velocity progressively

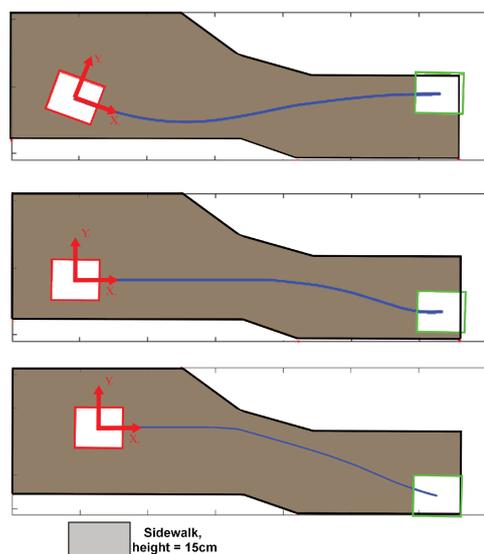


Figure 5.14 – Wheelchair corrected trajectory for different initial positions.

decreases and the rotational velocity is modified in order to follow the curb. When the wheelchair drives parallel to the curb, the linear velocity increases as there is no danger to fall from the curb. Then, when the wheelchair is driving close to the curb drop-off, an adaptation of both velocities is performed in order to provide a curb-following behavior. When the wheelchair arrives at the end of the corridor in front of a drop-off, it stops and prevents the fall.

## 5.6 Discussion

The first method is a direct application of the shared control framework given in chapter 4. Non-crossable obstacles are determined by using the definition of thresholds on the measured distance, which considers "negative" obstacles as virtual walls to avoid collisions with. The properties of this method are demonstrated with a simulation performed on the simulator presented in chapter 3. The second method is also a sensor-based control method but, contrary to the first proposed method, directly uses the sensors distance measurements to the floor in the computation of the shared control of the wheelchair. This framework has been tested with a simulation performed on the simulator presented in chapter 3. Moreover, the second method is currently under tests in real outdoor environments (Figure 5.16).

## 5.7 Conclusion

In this chapter, we proposed 2 sensor-based semi-autonomous methods for safe wheelchair navigation in an environment consisting of "negative" obstacles. Both methods use low-

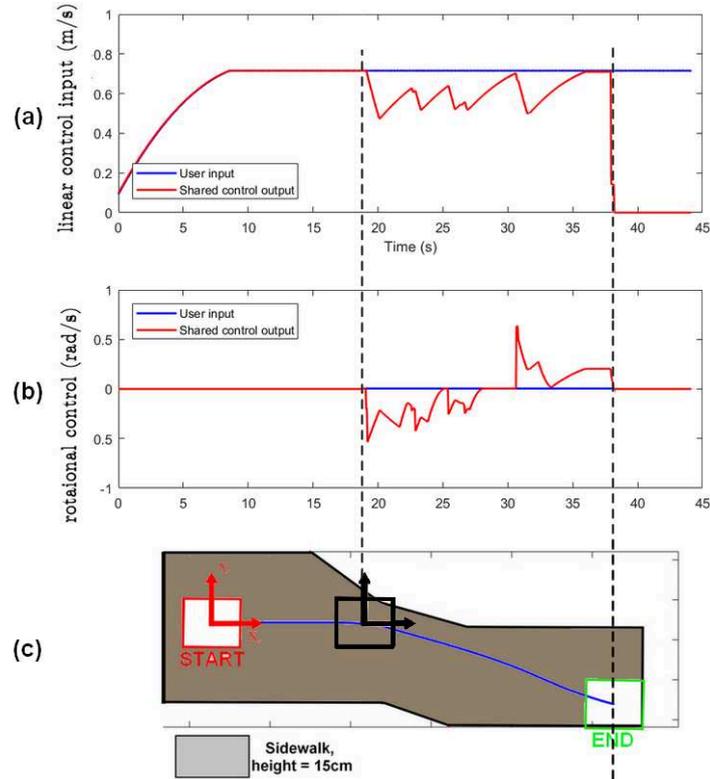


Figure 5.15 – Simulation results: (a) Forward velocity applied to the wheelchair (b) Rotational velocity applied to the wheelchair (c) Representation of the trajectory of the virtual wheelchair in the simulated environment (which we recorded for visualization purpose only). The rectangles represent the wheelchair at the beginning (red) and at the end (green) of the simulation.

cost distance sensors. The difference of detection relied on the extraction of features.

In the first method, an obstacle was defined by a difference of elevation which the wheelchair cannot cross safely. In order to determine if the sensor was detecting no obstacle, a positive obstacle or a negative obstacle, thresholds have been applied on the distance measured by distance sensors oriented towards the floor in order to define "crossable" obstacles. When a measured distance corresponds to a non-crossable "negative" obstacle, it is translated into a virtual distance from a virtual positive obstacle in the horizontal plane, thus acting as an indoor detection. hence, we then simply use the same control framework as for our indoor semi-autonomous navigation assistance method presented in chapter 4.

The second control system relied on a more complex task consisting in regulating the velocity when detecting floor orientations. This method aims to slightly reduce the wheelchair velocity input while encountering a crossable slope and to correct the wheelchair trajectory when approaching a too steep slope or a drop-off.

While achieving similar avoidance behavior with respect to curbsides within the



Figure 5.16 – On going tests of the second method in real outdoor environment.

proposed simulations on sidewalks, the 2 methods differ in their ability to negotiate ramps. Indeed, the second method has been designed to detect all types of changes of elevations by estimating local floor orientations. It therefore aims to provide smooth assistance in the form of velocity regulation while negotiating ramps.

The shared control model presented here is flexible, computationally inexpensive and independent of the range measurement sensor type. Moreover, this work showed the versatility of our method and encourages us to go further in our research process.

## Chapter 6

# Augmented experience: a promising tool for rehabilitation

This chapter demonstrates the design of an additional smart power wheelchair functionality providing feedback while driving a robotized wheelchair. The proposed feedback framework brings additional information to the user by means of haptic information. The idea is to assist people with disabilities to get navigation information they cannot take from the environment because of visual and/or cognitive impairments. The proposed augmented driving experience is designed to be an additional layer to the navigation assistance control input regulation methods which have been proposed in previous chapters 4 and 5. Within this additional functionality, two types of haptic feedbacks can be designed in the form of haptic guidance (feedback delivered to the user without wheelchair control input regulation) or haptic feedback (feedback delivered to the user combined with wheelchair control input regulation).

In this chapter, we demonstrate the validity of such a framework in the scope of indoor wheelchair navigation with a modified haptic feedback gaming joystick controller that provides haptic guidance. The objective is to compute a regulated control input delivered by means of haptic feedback to the user instead of being directly applied to the wheelchair. Thus, the user has full control of the wheelchair, and trajectory is no longer corrected by the control input regulation method. Instead, the proposed method aims to *augment* user operation in such a manner that it ensures user full control while receiving haptic feedback information acting as a clue to safely control the wheelchair.

The contents of this chapter have been presented at the SMC 2018 Conference [C.3].

## 6.1 Introduction

### 6.1.1 Context and motivations

Wheelchair navigation assistance can be provided in an autonomous or semi-autonomous manner to the user while driving the wheelchair. Within such a framework, the system directly fully or partially takes the control of the wheelchair to ensure a safe navigation. While allowing the wheelchair to navigate safely, these control methods do not provide information to the user about the behavior of the wheelchair. Indeed, the control input is obtained from an internal computation based on information measured by the sensors attached to the wheelchair. In the case of semi-autonomous navigation assistance, the behavior of the wheelchair can be different from the user input *i.e.* intention. Consequently, such a situation can be confusing for the wheelchair user: no information is given to the user about the wheelchair behavior, which can be in some cases be inconsistent with user intention.

While navigation assistance methods aim to be undetectable by users while driving, some patients would greatly benefit from a better understanding of the navigation information while driving [LSS10]. Therefore, another way of providing navigation support is to communicate relevant information to the user through a dedicated and adapted feedback interface.

### 6.1.2 Related works and clinical motivations

Providing feedback information (visual, auditory or haptic/tactile) has been shown to have additional benefits for learning and rehabilitation purposes [LSS10].

In the robotics field, feedback information is often communicated through haptic interfaces, especially for human robot interaction applications. Indeed, applying forces, vibrations, or motions to the user interface allows to communicate information between a user and a remote environment. Typically, this can be useful for robot teleoperation, interaction with a virtual environment or even remote surgery [Sto01][Lic07][KK15].

In the assistive robotics field, this type of feedback is typically used for people with visual impairments [LM08][JCE<sup>+</sup>14], where haptic information compensates for the lack of visual information and thus allows the user to improve his/her interaction with the external environment. In particular, some studies have also shown the benefits of using haptic feedback for motor rehabilitation [BGRS02][CCL10].

It is then possible to create a communication channel between the user and the system he/she is using. This feedback provides additional information to users during their interaction such that their experience or their performances can be enhanced. Moreover, as such a feedback can improve user understanding while performing a given task, haptic feedback could be seen as an effective rehabilitation tool to train severely disabled people to drive a powered wheelchair [CR08]. In particular, by providing additional information about the environment, haptic feedback could be a useful tool for the rehabilitation of people with hemispatial neglect [TOM<sup>+</sup>15]. Indeed, hemispatial neglect is described as an attention disorder which arises as a result of injury to the cerebral cortex. This results in a lack of awareness of a hemispace (*i.e.* one side of

space) therefore having severe effects on the ability to interact with and respond to the environment [Ker06].

Some research has been undertaken on the use of haptic feedback for power wheelchair driving but are only focused on a specific line following task [MCFR10][CA12]. In [PLB00], the authors evaluated the impact of force feedback on user performance while driving a power wheelchair in a virtual environment. Results of trials with people with disability showed fewer collisions while the feedback was activated. Van der Poorten et al. [VPDR<sup>+</sup>12] also developed a haptic feedback algorithm for power wheelchair driving relying on the definition of a collision-free paths computed from a local map of the environment. Similar work has been done in [MAC<sup>+</sup>15] where a grid-based method is used to compute free directions in the built local map that defines the force feedback parameters. Such systems typically use Potential Field Methods relying on the definition of a local map of the environment requiring information classically measured by expensive sensors such as laser range finder.

### 6.1.3 Objective

We were challenged by our clinical collaborators to develop a haptic assistance method able to provide navigation information notification while driving. Such a tool has particularly been recommended by occupational therapists to assist the learning of driving abilities for patients having visuo-spatial and attentional impairments, particularly people with unilateral neglect.

The proposed haptic navigation assistance method takes the form of an additional functionality to the navigation assistance methods which have been previously introduced in this manuscript both for indoor navigation assistance (chapter 4) and outdoor navigation (chapter 5).

In this chapter, the properties of the proposed haptic navigation assistance method are demonstrated within the scope of indoor navigation which has been presented in chapter 4. This method aims to communicate relevant information to the user through a haptic controller device as the user steers the wheelchair. To do so, we define the relevant information to be delivered to the user as the difference between user control input which is the control input computed by the driving assistance algorithm.

When designing such feedback assistance for power wheelchair navigation, two types of methods can be distinguished:

- haptic feedback: this method consists in communicating feedback information to the user through the haptic controller while at the same time semi-autonomously taking over the control of wheelchair when approaching an obstacle. With this method, the user receives feedback about the difference between his/her velocity input and the control input which is applied to the wheelchair by the shared-control assistance solution. In this case, the user partially controls the wheelchair and collisions cannot occur. This method aims to improve user understanding of the behavior of the system while still correcting the trajectory.
- haptic guidance: this method consists in communicating feedback information

to the user through the haptic controller without taking over the control of wheelchair. With this method, the user receives feedback about the difference between his/her velocity input and the control input which would be applied to the wheelchair if the shared-control assistance was activated. In this case, the user has full control of the wheelchair and collisions can occur.

In this chapter, I will present the first step of the augmented experience method design, implementation, tests and validation.

## 6.2 Method

### 6.2.1 Framework

The aim of the proposed haptic guidance method is to communicate feedback information to the user through a haptic controller without taking over the control of wheelchair. With this method, user receives feedback about the difference between his/her velocity input and the control input which would be applied to the wheelchair if the shared-control assistance was activated. To do so, the proposed method relies on the same mathematical modeling and values computation as the indoor navigation assistance method presented in chapter 4.

Therefore, based on the results presented in section 4.1, we make use of

- $\mathbf{u}_{op} = (v_{op}, \omega_{op})$ , the user desired control input,
- $\mathbf{u}_{cmd} = (v_{cmd}, \omega_{cmd})$ , the computed wheelchair control input value which computation from sensor measurements constraints is given in equation (4.39)

As shown in Section 4.1,  $\mathbf{u}_{op}$  and  $\mathbf{u}_{cmd}$  are respectively within a forbidden area and an allowed area in the wheelchair velocity domain such as depicted in Figure (4.14).

### 6.2.2 Haptic guidance algorithm

As mentioned previously in this chapter, relevant information to be delivered to the user while driving is defined as the difference between his/her velocity input and the control input which would be applied to the wheelchair if the shared-control assistance was activated. Practically, this information is communicated through the haptic controller in the form of the direction to which the user should put the joystick in order to keep a safe navigation.

This information can be extracted from the mathematical framework presented in section 6.2.1 in the form of a force vector in the wheelchair velocity domain. Let  $\vec{\mathbf{k}}$  be the vector from  $\mathbf{u}_{op}$  to  $\mathbf{u}_{cmd}$  in the wheelchair velocity domain (Figure 6.1). The force feedback vector  $\vec{\mathbf{F}}$  to be applied to the user interface will be computed from this information.

We define  $\vec{\mathbf{k}}(r_k, \theta_k)$  and  $\vec{\mathbf{F}}(r, \theta)$  in polar coordinates with respectively  $r_k$  and  $r$  their magnitudes and  $\theta_k$  and  $\theta$  their directions. This representation leads to the following properties:

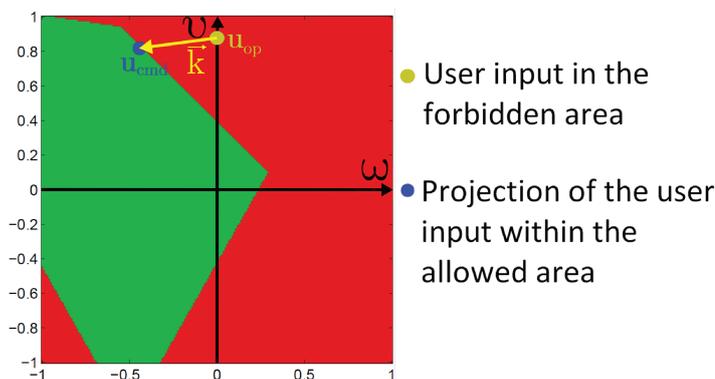


Figure 6.1 – The algorithm output corresponds to the projection of user input within the allowed area.  $\vec{k}$  represents the vector from the user input to the algorithm output.

- force direction is the same as the direction of the vector  $\vec{k}$  in the wheelchair velocity domain, leading to  $\theta = \theta_k$ ,
- we define the force magnitude such that  $r = \alpha r_k$  with
  - $\alpha > 0$  a proportional gain which can be modified to adapt the force magnitude to the user strength,
  - $r_k = \|\vec{k}\|$  the euclidean distance between  $\mathbf{u}_{op}$  and  $\mathbf{u}_{cmd}$  in the wheelchair velocity domain so that

$$\|\vec{k}\| = \sqrt{(u_{op} - u_{cmd})^2 + (\omega_{op} - \omega_{cmd})^2}. \quad (6.1)$$

This way, the force guides the user towards a joystick position for which the resulting user input is safe. Force magnitude is then proportional to the distance between user input and its projection onto the allowed area.

The user is at the same time notified that there is a danger of collision and is guided to a joystick position corresponding to safe input. It is to be emphasized that the user has full control of the wheelchair and can maintain his/her desired joystick position. The information communicated in the form of force feedback is only an indication of the risk-free joystick position the most compliant with his/her intention. Such a solution is then mainly meant to be used for learning or rehabilitation purposes.

### 6.3 Simulations

In this section, results of the very first step in the development of the haptic guidance solution are presented. A simulation is performed with on the power wheelchair driving which I previously developed 3. In this framework, the user operates a force feedback joystick to drive a virtual robotized wheelchair in a virtual environment. The framework

has been designed to be directly compliant with a monitor screen display, a Virtual Reality room or a Head Mounted Device and is presented in more details in chapter 3.

### 6.3.1 Simulation conditions

The virtual environment is displayed on a computer screen as it is only used to demonstrate the properties of the proposed haptic guidance solution. The virtual environment used for this simulation is shown on Figure 6.2. It consists of a 1.5 m wide and 10 m long corridor with 4 obstacles. The virtual wheelchair starts from the beginning of the corridor facing the top wall with an angle of  $60^\circ$ . The wheelchair is here equipped with 22 virtual sensors positioned all around the virtual wheelchair according to Figure 6.3a.

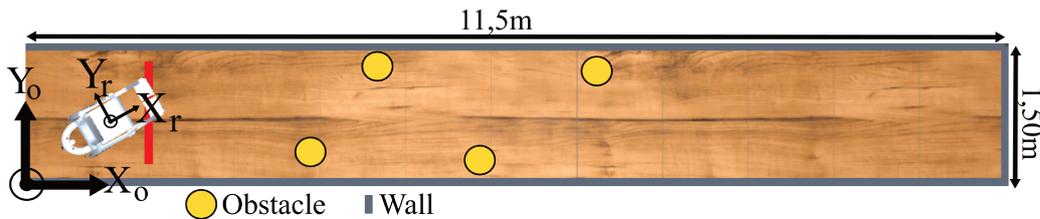


Figure 6.2 – Top view of the map used for simulation.

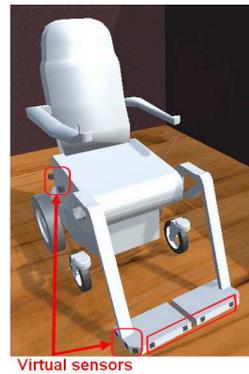
The user is sitting in front of the computer screen and controls the virtual wheelchair (Figure 6.3a) by operating a force feedback joystick (Figure 6.3c). The user view during the simulation is shown in Figure 6.3d. The force feedback game controller is a commercially available joystick from Microsoft, which I modified and adapted to match wheelchair driving constraints by implementing automatic centering and reducing the number of degrees of freedom to 2.

In order to emphasize the properties of the proposed force feedback solution, the user voluntarily tries to collide with the virtual obstacles while steering the wheelchair.

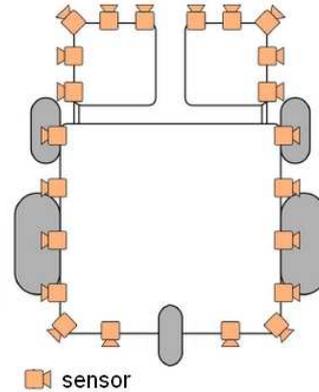
### 6.3.2 Simulation results

Simulation results are presented in Figure 6.4. Figure 6.4a shows the trajectory of the wheelchair during the simulation. Blue arrows represent the force vectors which are sent to the user through the force feedback joystick while driving. Figure 6.4b represents the rotational and linear velocity inputs. No collisions were recorded during this simulation.

In Figure 6.4, in part A, we observe that as long as the user is driving towards the wall on his left, he is being notified that there is a risk of collision by means of forces directly towards the opposite direction. Then, when the user modifies the angular velocity input, both the magnitude and direction of the force progressively decrease. When the wheelchair becomes parallel to the walls, as there is no risk of collision anymore (typically in D and H parts), the user does not receive any force feedback anymore. In B and E parts, as the user drives towards the obstacle on his right, the algorithm then sends forces towards the left direction. We can observe the impact of this additional information on the angular velocity. Indeed the decreasing of the angular velocity input



(a) Virtual wheelchair.



(b) Sensor positioning.



(c) Simulation setup.



(d) User view during the simulation.

Figure 6.3 – Virtual environment and simulation setup.

associated with a slight increase of the linear input shows that the user is adapting his joystick input while receiving force feedback information. We can observe similar results in C and F parts where the user drives toward the obstacle on his left.

The proposed simulation demonstrates well the properties of the proposed framework as it provides relevant force feedback. Indeed, forces communicated to the user through the haptic joystick indicate a safe input while the user is voluntarily controlling the wheelchair towards obstacle. Experimental results will be shown in the next section 6.4.

## 6.4 Experiment

As power wheelchair users can have weak upper limb strength and/or tremors, it is mandatory to ask able-bodied participants to evaluate our haptic guidance solution before being able to obtain ethical approval regarding trials with people with disabilities. In this pilot study including 4 able-bodied participants, the impact of navigation assistance in the form of haptic guidance solution is assessed.

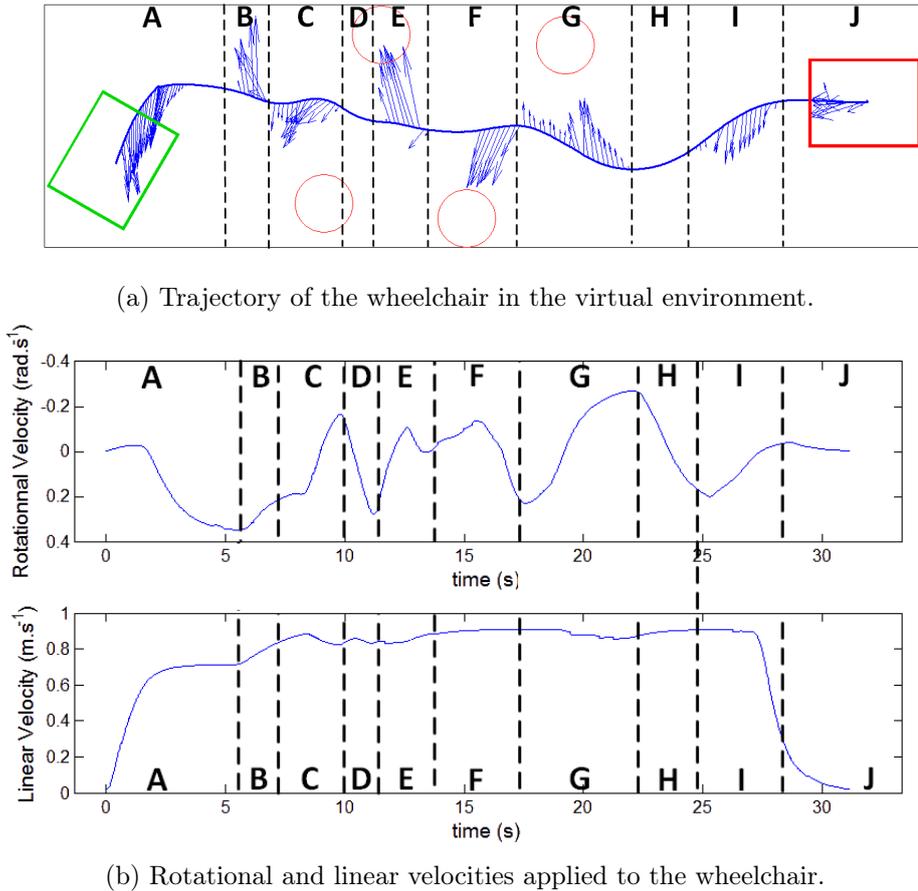


Figure 6.4 – Simulation results.

### 6.4.1 Experimental setup

We used the same wheelchair as in chapter 4, a power wheelchair that we equipped with the same force feedback joystick as the one used for the simulation. Although it is the same wheelchair, the sensor configuration has been upgraded: we empirically determined an optimal configuration composed of 22 sensors. Those sensors were installed on the wheelchair at the same location as in the simulation setup previously described (Figure 6.3b).

The obstacle course I designed for this experiment (Figure 6.5) is similar to the one used for the simulation (Figure 6.2) but is more challenging as paths are narrower than the one used in simulation and it contains a turn around maneuver.

The power wheelchair actuation is implemented using the generic ROS framework presented in chapter 3 adapted to the haptic control of the adapted haptic interface. This adapted framework is presented in Figure 6.7. The proposed framework is composed of the following 3 ROS nodes, namely:

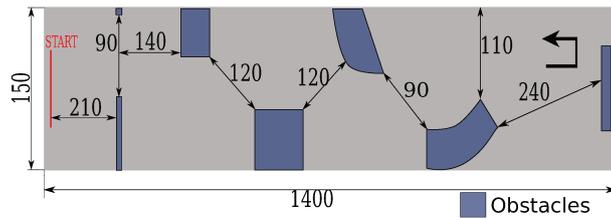


Figure 6.5 – Obstacle course, values correspond to distances in centimeters.

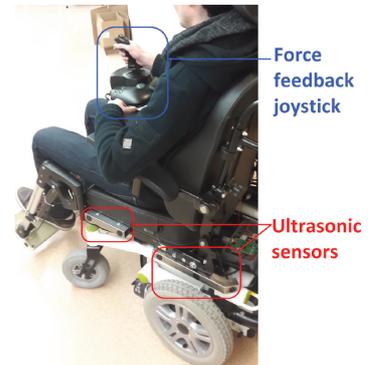


Figure 6.6 – Participant driving on the obstacle course.

- Sensor ROS node. This node replaces the Display ROS node used for simulations. This node manages sensor measurements.
- Haptic ROS node. This node manages the computation of the haptic control input to be applied to the haptic interface.
- Controller ROS node. This ROS node manages input controller data collection, here the standard wheelchair joystick commands.

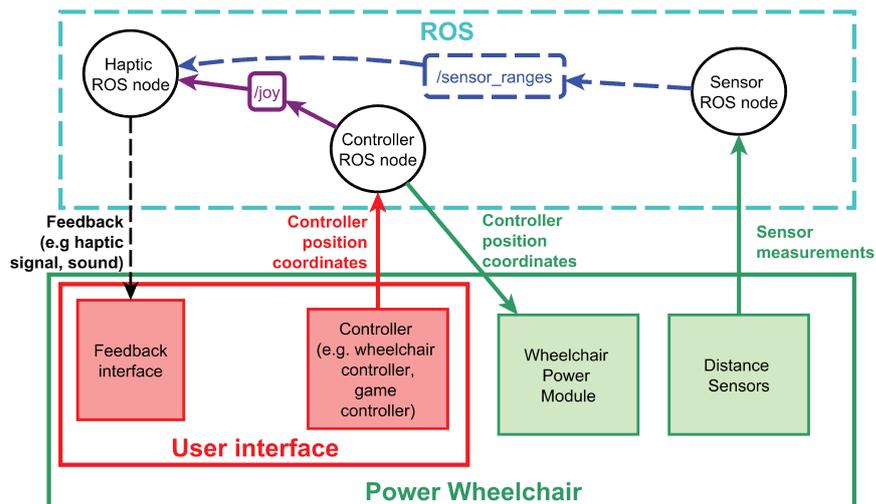


Figure 6.7 – Generic ROS framework adapted to the control of the haptic interface.

### 6.4.2 Experiment protocol

Participants were asked to drive a power wheelchair with the force feedback joystick (Figure 6.6) an obstacle course made with cardboard boxes (Figure 6.5). Participants

completed the course twice: once with haptic guidance and once without haptic guidance. The given instructions were

- driving along the obstacle course and go back,
- performing the obstacle course the faster they could without colliding with the obstacles.

For each trial, the haptic guidance module can be activated or not. We counter-balanced the order of activation of the haptic guidance for each participant in order to avoid the learning effect.

### **6.4.3 Data Collection**

#### **6.4.3.1 Haptic guidance solution data**

We use ROS to automatically record data during the trials. Here we recorded user input, the related risk-free input computed by the algorithm and force magnitude and direction. We also recorded the number of collisions as well as time completion.

#### **6.4.3.2 User feedback**

After completing the obstacle courses, participants were asked to answer the USE questionnaire [Lun01] which consists in a 30 items Likert scale. The Questionnaire is composed of 4 sections: Usefulness (U), Ease of Use (EU), Ease of Learning (EL) and Satisfaction (S).

### **6.4.4 Experiment results**

This section presents the results of the experiment we performed. 4 able-bodied participants aged from 22 to 38 years old have volunteered to participate to this pilot study.

#### **6.4.4.1 User performance**

In order to evaluate the impact of the proposed haptic guidance solution on user performances while driving the power wheelchair, we recorded the number of collisions that occurred during the experiment with and without force feedback (Fig. 6.8a) as well as completion time.

As we can see, fewer collisions occurred while haptic guidance was activated. With the haptic guidance activated, all participants collided with the same obstacle. In fact, these collisions only occurred during a turn around maneuver which was really difficult as the space was very narrow compared to the length of the wheelchair. Moreover, there was no significant difference between time completion values with and without force feedback.

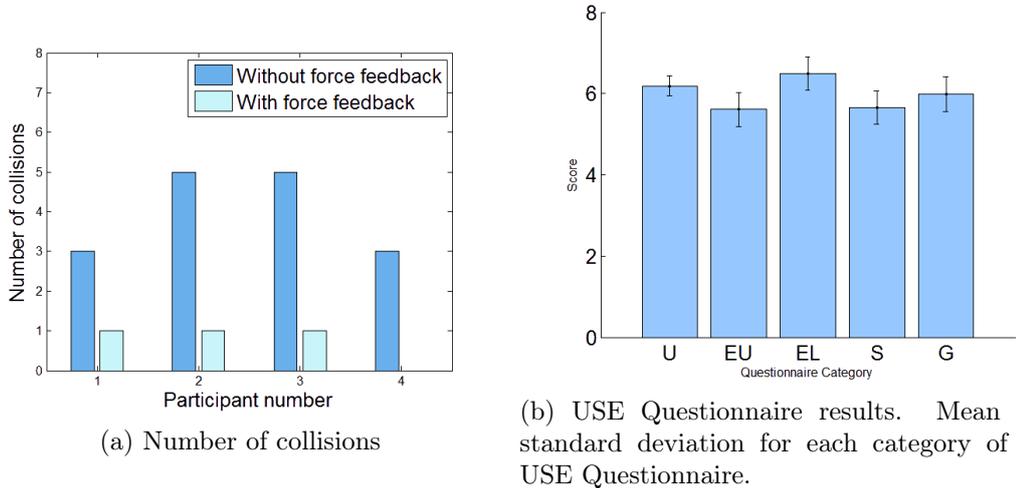


Figure 6.8 – Experiment results.

#### 6.4.4.2 User feedback

USE Questionnaire results are presented in Figure 6.8b. Mean and standard deviation ( $M \pm SD$ ) values are given for each category. The best score is for the ease of learning with  $6.5 \pm 0.41$  and worst score is for the ease of use with  $5.61 \pm 0.42$ . Global questionnaire score is  $5.99 \pm 0.43$ .

Participants reported to be rather satisfied with the proposed haptic guidance solution. They felt the information given by the joystick was relevant and helpful for the navigation task. In particular, they reported having benefited from the haptic guidance while performing the turn around maneuver as it warned them while getting too close to obstacles and allowed them to better judge distances when obstacles were not easily visible as the force increased while approaching the obstacle with an unsafe joystick input. However, even if driving performances have been significantly increased, additional information provided by the force feedback joystick was not totally sufficient to avoid collisions during the turn around maneuver. Nevertheless, it globally incited participants to adapt their command and generally decreased the collision impact speed. Finally, participants did not report having felt any pain or discomfort while using the force feedback joystick but they reported to be unsatisfied with the haptic interface form factor itself: they found it difficult to manipulate because of its dimensions.

## 6.5 Discussion

Although the joystick provided satisfying guidance forces, participants encountered some difficulties to manipulate the wheelchair with it, in particular because of its dimensions. Indeed, this joystick is a game controller and has not been designed for power wheelchair control. It was used only for the algorithm validation purpose. Another issue was encountered with the game controller is that we were limited to 50Hz for the force

generation while haptic interfaces typically run at higher frequencies (users can perceive force variations up to 1KHz [TSEC94]). This led to a lack of smoothness of the force feedback.

High scores obtained with the USE questionnaire show that the participants were rather satisfied with the haptic guidance solution. Moreover, they found it helpful, particularly for the turn around maneuver. As expected, they felt that the joystick was giving them additional information about the environment. While approaching an obstacle, they perceived the force as an indication of the risk of collision inducing them to reduce their speed and to modify joystick direction. While maneuvering the wheelchair, they perceived the feedback as an inducement to move the joystick in the right direction.

These preliminary results show the proof-of-concept of the proposed haptic guidance solution as a tool for learning or rehabilitation purpose. Indeed, it incited the participants to adapt speed and direction to avoid collisions and allowed them to better understand the environment around the wheelchair, particularly while maneuvering in narrow spaces. Results of the experiment show that additional information in the form of forces sent through the wheelchair controller is associated with a significant decrease of the number of collisions without increasing the completion time.

## 6.6 Conclusion

The proposed haptic guidance solution for power wheelchair assisted navigation has been validated with 4 able-bodied participants during an experiment on an obstacle course with and without haptic guidance activation. This pilot study was mandatory to provide a proof-of-concept of the method. This step is necessary to obtain an approval from a national ethical committee in order to perform trials with people with disability.

While driving the wheelchair on the obstacle course, the number of collisions significantly decreased while haptic guidance was activated, thus providing a proof-of-concept of the proposed framework. In addition, this pilot study allowed us to identify the remaining shortcomings of the proposed system system. Evidently, the game controller we used to validate our robotic solution is not adapted to wheelchair control. These results initiated another project in which I took part to design a dedicated force feedback joystick adapted to user needs and which dimensions are compliant with wheelchair standards (Figure 6.9).

Future work will therefore focus on the improvement of the haptic interface for better feedback. Then, other studies with larger samples of able-bodied participants will be conducted before clinical trials with power wheelchair regular users, once approved by an ethical committee.

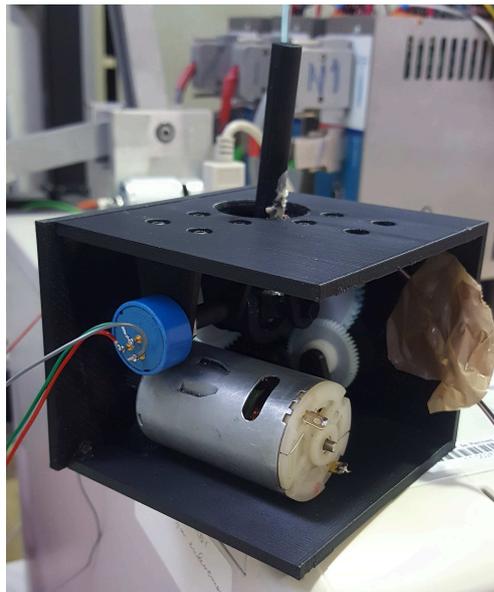


Figure 6.9 – Homemade dedicated force feedback joystick adapted to user needs.



# Conclusion

In this thesis we covered several aspects of robotic assistance for wheelchair navigation. In Chapter 1, we first presented the clinical, social and robotic challenges resulting from the context of powered mobility issues. In Chapter 2, we provided a review on existing smart power wheelchair solutions as well as technical requirements and guidelines learned from past projects in order to give the right direction to this thesis.

In chapter 3, we proposed the design of a powered mobility simulator, not only aiming to support the design of new assistive solutions but also to assist therapists for clinical assessment and rehabilitation. The proposed assisted powered mobility simulator relies on a generic and modular ROS framework allowing quick development and integration of new functionalities. It can be displayed on multiple virtual display devices such as Head Mounted Devices (HMD) or immersive platforms, like the Immersia virtual room located in Rennes. The user operates a virtual wheelchair in the environment with a standard wheelchair controller while seating on a real wheelchair fixed on the platform. User satisfaction and experiential validity have been assessed through 2 experimental studies conducted in collaboration with therapists and involving able-bodied participants. The results of these studies show encouraging outcomes and benefits of the simulator for future clinical use.

In Chapter 4, we addressed the issue of safe navigation within indoor environments. We first provided an introduction to sensor-based control by demonstrating the properties of the classical autonomous method applied to the power wheelchair in simulation. Then, we adapted sensor-based control techniques to semi-autonomously regulate the velocity of a power wheelchair. The idea of this shared control method is to compute velocity regulation from constraints which are deduced from distance sensor measurements all around the wheelchair. The velocity regulation is progressively applied to the wheelchair by means of a blending method respecting as much as possible user intention. Therefore, while approaching an obstacle, the wheelchair velocity control input is modified: a smooth trajectory correction is generated. In this chapter, we detail the clinical experiment of the proposed solution embedded on a standard power wheelchair conducted within the Rehabilitation Center Pôle Saint Hélier with regular users. The results of this preliminary study led to validate the proposed framework.

In Chapter 5, we applied a sensor-based semi-autonomous control framework for

"negative" obstacle avoidance. Two methods using distance sensors oriented towards the floor are presented. The first method is a direct application of the shared control framework given in chapter 4. Non-crossable obstacles are determined by using the definition of thresholds on the measured distance. The "negative" obstacles which are considered non-crossable with respect to these thresholds are considered as virtual obstacles to avoid collisions with. The properties of this method are demonstrated with a simulation performed on the powered mobility simulator presented in chapter 3. The second method is also a sensor-based control method but, contrary to the previously proposed method, it directly uses distances to the floor and local floor orientation estimation is deduced from sensor measurements to regulate the wheelchair velocity. This framework has also been designed and tested using the powered mobility simulator presented in chapter 3. While achieving similar avoidance behavior with respect to curbsides, the 2 methods differ in their ability to negotiate ramps. In particular, the second method has been designed to detect all types of changes of elevations by estimating local floor orientations. It therefore aims to provide smooth assistance in all situations while navigating on a sidewalk with respect to curbsides but also ramps and slopes.

In Chapter 6, we proposed an augmented driving experience solution by providing adapted haptic feedback to the user while driving. We then present the pilot study we conducted to validate the haptic guidance solution. In this study, 4 able-bodied participants operated the wheelchair on an obstacle course with and without haptic guidance. The results and participants feedback from this preliminary study gave a proof-of-concept of the proposed haptic guidance solution as a promising tool for learning or rehabilitation purpose. Indeed, the proposed solution allowed better understanding of the surrounding environment when participants did not notice the presence of an obstacle, particularly while maneuvering in narrow spaces.

In the following, we will discuss the main outcomes of this thesis work, starting with highlighting the strong positive impact of user and clinicians involvement in the assistive solutions development process. Moreover we will highlight the benefits of the proposed generic framework within research and collaborative work present and future perspectives. Then, we discuss the technical perspectives for future works on smart powered mobility solutions development. Finally, we address the ethical considerations and issues encountered in this work which would have to be addressed in the future to cross the gap between technical validity assessment and clinical validation as well as use by end-users.

**A successful collaboration with clinicians and users.** This thesis work has been a rich experience as it allowed clinicians' and users' knowledge, expertise and expectations to be considered in every development stage of the different solutions proposed in this work. Firstly, regular interactions with clinicians and patients have allowed me to better understand the clinical and social implications of disability. Indeed, the sharing of medical knowledge from which I have benefited by being in contact with therapists allowed me to better understand the mechanisms of the human brain, particularly the

visuo-spatial and cognitive functions which take part in the major part of the daily-life of every individual. Learning this made me able to be aware of the multiple issues that an individual with visuo-spatial or cognitive impairments experiences in daily-life. In particular, the impact of such deficiencies on driving abilities and independence has been fully considered during all stages of this thesis work. The interactions experienced within this collaboration thus ensured an effective and useful approach to developing new support solutions. Consequently, each solution proposed in this work has been discussed with clinicians to be the most adequate to clinical reality.

Firstly, all the proposed solutions require user action to work. Indeed, while autonomous solutions could appear to be the safest option to assist the navigation of people with visuo-spatial and/or cognitive impairments, clinicians emphasize that user control of the wheelchair with a classical input interface is crucial during the driving task. On the one hand, it allows user intention to be respected and in the other hand it allows to soliciting remaining functions, which is very important to prevent functioning loss. Therefore, the navigation assistance methods proposed in this work implement shared-control providing smooth wheelchair velocity regulation when approaching an obstacle. In addition, it has never been considered to integrate additional functionalities to the assistive solutions because even the simplest additional task can represent a significant challenge for people with impairments of the executive, attentional or memory functions.

Finally, while testing solutions with regular users such as the indoor navigation assistance framework or with occupational therapists with the haptic controller, feedback has been very encouraging thus showing the strong positive impact of integrating users and clinicians within the development of assistive solutions.

**A generic framework.** The results of this thesis are encouraging and show the strong positive impact of the collaboration with end-users and clinical experts in the development of assistive technologies. In this work, multiple assistive solutions have been designed for end-user and clinician use. All the solutions that have been developed along this thesis work were designed to be generic in order to foster rapid and easy development as well as collaborative work. While industrialization of these solutions requires integration and low-cost embedded system engineering, all the research and development process has been done using the middleware ROS. Such a generic framework is particularly beneficial within the collaborations taking part of the ISI4NAVE associated team and ADAPT Interreg Project. As part of the ISI4NAVE project, such framework allowed to quickly and easily adapt our proposed shared control framework to the UCL wheelchair and perform driving tests on the PAMELA platform. As part of the ADAPT project, the generic framework allows us to easily switch from simulation to real conditions by interchanging the nodes performing virtual or real wheelchair control and sensing. Moreover, while providing this generic framework within the scope of a recent ADAPT technical meeting, we were able to achieve collaborative development with multiple partners. Indeed, we were able to quickly adapt the omnivision-based navigation method from the MIS laboratory located at UPJV University to a standard wheelchair with our ROS framework. Moreover, our partners from the University of

Kent were able to easily take the control of a standard wheelchair with our control framework.

**Technical perspectives.** While proof-of-concepts and preliminary tests were provided, there still remain significant technical improvements to integrate into the proposed solutions. First, the proposed powered mobility simulator has to be improved in terms of physical validity before conducting new experiential validity assessment or even testing with regular users. Indeed, while providing rather satisfying sense of immersion, there still remain a sense of sickness taking the form of nausea and/or headache during and/or after tests on the virtual platform. Future works on the simulator may improve physical validity by means of better simulator technical features. Works in which I took part have already started on the design of a wheelchair physical engine in order to be able to better implement wheelchair-related dynamical effects such that caster wheel effects which are well-known to strongly impact navigation comfort with a real wheelchair. Moreover, as part of the ADAPT Interreg Project, a physical platform will soon be going to be incorporated within the powered mobility simulator to provide relevant physical sensations transcribing the dynamical behavior of the virtual wheelchair within the scene. These two on-going improvement works are interrelated as they will provide driving sensations consistent with the interaction of the virtual with the virtual environment. Moreover, thanks to the proposed generic framework, these improvements will be easy to integrate within the simulator as they can take the form of additional functionalities. Finally, future work may consider the feedback already collected from the participants within the 2 studies conducted as part of this thesis.

In addition, recent technical advances in sensor technology bring new perspectives for the integration of shared control solutions to standard wheelchairs. Indeed, while a first solution for semi-autonomous assisted navigation in indoor environment presented in chapter 4 was developed with ultrasonic detection technology, this classically used type of sensors offers a low-cost and low-power consumption alternative to other distance sensors, they remain particularly difficult to integrate onto a power wheelchair because of their size and electronically design issues such as Electromechanical Compatibility (EMC) designs. Moreover, despite a sufficient number of sensors covering the entire area around the wheelchair, there still remains missed detections on some surfaces and specific configurations because of the inherent properties of ultrasonic waves. In this context, the new generation of infrared VL53L1 Time-of-Flight (ToF) sensors from STMicroelectronics brings new perspectives for assisted navigation in indoor as well as outdoor environments. Indeed, these sensors provide infrared-based detection range up to 4 meters and multizone detection as well as the small size and easiness of integration. A first prototype for outdoor navigation assistance equipped with this type of sensors 5 is currently under tests and shows promising perspectives for industrial design and detection robustness.

As for the haptic guidance framework, multiple improvements can be considered. Firstly, as mentioned in chapter 6, a new force feedback joystick is under development (Figure 6.9). While the mechanical design has recently been assembled and corresponds to

wheelchair form factor requirements, new tests with able-bodied participants are required before obtaining an approval from a national ethical committee before testing this prototype with people with disability. The haptic feedback method has been tested with occupational therapists from the rehabilitation center Pôle Saint Hélier. Their positive feedback was encouraging and inciting future tests to assess the impact of such a tool on driving performances.

Finally, future works on the proposed navigation assistance methods may consider improving the control law in order to better match user intention. To this aim, the integration of a user driving behavior model such as the one presented in [?] may be investigated.

**Towards clinical experimentation.** In the following, we will discuss ethical considerations and ethical issues towards clinical experimentation which have been an integral part of this thesis work. While the technological perspectives suggest significant advances in the field of smart powered mobility technologies, the French legislation remains a strong obstacle to clinical experimentations and thus to robotic solution diffusion in rehabilitation centers, specialized facilities or even at home. Indeed, since November 2016, the French legislation requires clinical research involving human beings to obtain an approval from a national ethical committee. However, while obtaining ethical approvals for medical intervention experimentation is a classical process, it is much more complicated when a study involves a robotic wheelchair prototype that should be tested with people with disability. Therefore, there is a huge gap between tests with able-bodied participants to assess the technical validity of a robotic prototype and the clinical evaluation of the benefits of such an assistive technology within a rehabilitation context. Finally, while such solutions aim to improve the Quality of Life of people with disability by providing them more mobility, the assessment of such assistive technologies impact on daily-life requires that they are already available for wide use. However, to be able to be distributed on the market, such solutions would have to be clinically validated. We then face a "snake biting its tail off" issue which will have to be addressed with clinical experts in the future.



# Bibliography

- [ACR09] Ifedayo A Adelola, Sara L Cox, and Abdur Rahman. Virtual environments for powered wheelchair learner drivers: Case studies. *Technology and Disability*, 21(3):97–106, 2009.
- [ACS<sup>+</sup>11] Philippe S Archambault, Jodie Ng Fuk Chong, Gianluca Sorrento, François Routhier, and Patrick Boissy. Comparison of powered wheelchair driving performance in a real and in a simulated environment. In *Virtual Rehabilitation (ICVR), 2011 International Conference on*, pages 1–7. IEEE, 2011.
- [AKAMP13] BHK Alexandra Korotchenko and PEng Alex Mihailidis PhD. Power mobility with collision avoidance for older adults: User, caregiver, and prescriber perspectives. *Journal of rehabilitation research and development*, 50(9):1287, 2013.
- [ARO17] Abdulaziz Alshaer, Holger Regenbrecht, and David O’Hare. Immersion factors affecting perception and behaviour in a virtual reality power wheelchair simulator. *Applied Ergonomics*, 58:1–12, 2017.
- [ATC<sup>+</sup>12] Philippe S Archambault, Stéphanie Tremblay, Sarah Cachecho, François Routhier, and Patrick Boissy. Driving performance in a power wheelchair simulator. *Disability and Rehabilitation: Assistive Technology*, 7(3):226–233, 2012.
- [AWLW05] Kaarin J Anstey, Joanne Wood, Stephen Lord, and Janine G Walker. Cognitive, sensory and physical factors enabling driving safety in older adults. *Clinical psychology review*, 25(1):45–65, 2005.
- [BAK<sup>+</sup>13] Patrice Boucher, Amin Atrash, Sousso Kelouwani, Wormser Honoré, Hai Nguyen, Julien Villemure, François Routhier, Paul Cohen, Louise Demers, Robert Forget, et al. Design and validation of an intelligent wheelchair towards a clinically-functional outcome. *Journal of neuro-engineering and rehabilitation*, 10(1):58, 2013.
- [BAS01] Mary Ellen Buning, Jennifer A Angelo, and Mark R Schmeler. Occupational performance and the transition to powered mobility: A pilot study. *American Journal of Occupational Therapy*, 55(3):339–344, 2001.

- [BBB<sup>+</sup>06] C Bryanton, J Bosse, Marie Brien, Jennifer Mclean, Anna McCormick, and Heidi Sveistrup. Feasibility, motivation, and selective motor control: virtual reality compared to conventional home exercise in children with cerebral palsy. *Cyberpsychology & behavior*, 9(2):123–128, 2006.
- [BBL<sup>+</sup>94] David A Bell, Johann Borenstein, Simon P Levine, Yoram Koren, Lincoln A Jaros, et al. An assistive navigation system for wheelchairs based upon mobile robot obstacle avoidance. In *ICRA*, pages 2018–2022, 1994.
- [BCM<sup>+</sup>07] Matt Bailey, Andrew Chanler, Bruce Maxwell, Mark Micire, Katherine Tsui, and Holly Yanco. Development of vision-based navigation for a robotic wheelchair. In *Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on*, pages 951–957. IEEE, 2007.
- [BF95] Johann Borenstein and Liqiang Feng. Correction of systematic odometry errors in mobile robots. In *Intelligent Robots and Systems 95. 'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on*, volume 3, pages 569–574. IEEE, 1995.
- [BGRS02] J Broeren, M Georgsson, M Rydmark, and K Stibrant Sunnerhagen. Virtual reality in stroke rehabilitation with the assistance of haptics and telemedicine. In *Proceedings of the 4th International Conference on Disability, Virtual Reality and Associated Technologies*, pages 71–76, 2002.
- [BPG<sup>+</sup>15] Marie Babel, François Pasteau, Sylvain Guégan, Philippe Gallien, Benoît Nicolas, Bastien Fraudet, Sophie Achille-Fauveau, and Daniel Guillard. Handiviz project: clinical validation of a driving assistance for electrical wheelchair. In *Advanced Robotics and its Social Impacts (ARSO), 2015 IEEE International Workshop on*, pages 1–6. IEEE, 2015.
- [BV10] Joydeep Biswas and Manuela Veloso. Wifi localization and navigation for autonomous indoor mobile robots. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pages 4379–4384. IEEE, 2010.
- [CA12] Xi Chen and Sunil K Agrawal. Assisting versus repelling force-feedback for human learning of a line following task. In *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on*, pages 344–349. IEEE, 2012.
- [CATT<sup>+</sup>09] José E Capó-Aponte, Leonard A Temme, H Lee Task, Alan R Pinkus, Melvyn E Kalich, Allan J Pantle, and Clarence E Rash. Visual perception and cognitive performance. *Helmet-Mounted Displays: Sensation, Perception and Cognitive Issues*, pages 335–390, 2009.
- [CBF<sup>+</sup>14] Luca Cavanini, Flavia Benetazzo, Alessandro Freddi, Sauro Longhi, and Andrea Monteriu. Slam-based autonomous wheelchair navigation system for aal scenarios. In *Mechatronic and Embedded Systems and Applications*

- (MESA), *2014 IEEE/ASME 10th International Conference on*, pages 1–5. IEEE, 2014.
- [CCL10] Kup-Sze Choi, Chum-Ming Chow, and King-Hung Lo. A rehabilitation method with visual and haptic guidance for children with upper extremity disability. In *International Conference on Computers for Handicapped Persons*, pages 77–84. Springer, 2010.
- [CFS17] Joshua Q Coburn, Ian Freeman, and John L Salmon. A review of the capabilities of current low-cost virtual reality technology and its potential to enhance the design process. *Journal of Computing and Information Science in Engineering*, 17(3):031013, 2017.
- [CG97] M Corcoran and Laura Gitlin. The role of the physical environment in occupational performance. *Occupational therapy: Enabling function and well-being*, pages 337–359, 1997.
- [CH06] François Chaumette and Seth Hutchinson. Visual servo control. i. basic approaches. *IEEE Robotics & Automation Magazine*, 13(4):82–90, 2006.
- [CJW<sup>+</sup>11] Wan-Yin Chen, Yuh Jang, Jung-Der Wang, Wen-Ni Huang, Chan-Chia Chang, Hui-Fen Mao, and Yen-Ho Wang. Wheelchair-related accidents: relationship with wheelchair-using behavior in active community wheelchair users. *Archives of physical medicine and rehabilitation*, 92(6):892–898, 2011.
- [CK97] Kok Seng Chong and Lindsay Kleman. Accurate odometry and error modelling for a mobile robot. In *Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on*, volume 4, pages 2783–2788. IEEE, 1997.
- [CLS<sup>+</sup>10] Fernando A Auat Cheein, Natalia Lopez, Carlos M Soria, Fernando A di Sciascio, Fernando Lobo Pereira, and Ricardo Carelli. Slam algorithm applied to robotics assistance for navigation in unknown environments. *Journal of neuroengineering and rehabilitation*, 7(1):10, 2010.
- [CM13] Tom Carlson and Jose del R Millan. Brain-controlled wheelchairs: a robotic architecture. *IEEE Robotics & Automation Magazine*, 20(1):65–73, 2013.
- [Coo95] R.A. Cooper. Intelligent control of power wheelchairs. *IEEE Engineering in Medicine and Biology Magazine*, 14(4):423–431, July 1995.
- [CR08] Laura Marchal Crespo and David J Reinkensmeyer. Haptic guidance can enhance motor learning of a steering task. *Journal of motor behavior*, 40(6):545–557, 2008.

- [CS07] James M Coughlan and Huiying Shen. Terrain analysis for blind wheelchair users: Computer vision algorithms for finding curbs and other negative obstacles. In *CVHI*, 2007.
- [CSJ<sup>+</sup>02] Rory A Cooper, Donald M Spaeth, Daniel K Jones, Michael L Boninger, Shirley G Fitzgerald, and Songfeng Guo. Comparison of virtual and real electric powered wheelchair driving using a position sensing joystick and an isometric joystick. *Medical engineering & physics*, 24(10):703–708, 2002.
- [CSU05] Noel Cass, Elizabeth Shove, and John Urry. Social exclusion, mobility and access 1. *The sociological review*, 53(3):539–555, 2005.
- [CTC<sup>+</sup>02] Rory A Cooper, Tricia Thorman, Rosemarie Cooper, Michael J Dvorznak, Shirley G Fitzgerald, William Ammer, Guo Song-Feng, and Michael L Boninger. Driving characteristics of electric-powered wheelchair users: how far, fast, and often do people drive? *Archives of physical medicine and rehabilitation*, 83(2):250–255, 2002.
- [CVM16] Judy Cawood, Surona Visagie, and Gubela Mji. Impact of post-stroke impairments on activities and participation as experienced by stroke survivors in a western cape setting. *South African Journal of Occupational Therapy*, 46(2):10–15, 2016.
- [DGR13] Sangita Devi, Soumya Goyal, and Savita Ravindra. Evaluation of environmental barriers faced by wheelchair users in india. *Disability, CBR & Inclusive Development*, 24(3):61–74, 2013.
- [Dia13] Adele Diamond. Executive functions. *Annual review of psychology*, 64:135–168, 2013.
- [DJF02] Geneviève Daigneault, Pierre Joly, and Jean-Yves Frigon. Executive functions in the evaluation of accident risk of older drivers. *Journal of Clinical and Experimental Neuropsychology*, 24(2):221–238, 2002.
- [DMC<sup>+</sup>12] Artemisa Rocha Dores, Maria João Miranda, Irene Palmares Carvalho, Liliana Mendes, Fernando Barbosa, António Coelho, Liliana de Sousa, and Alexandre Castro Caldas. Virtual city: neurocognitive rehabilitation of acquired brain injury. In *Information Systems and Technologies (CISTI), 2012 7th Iberian Conference on*, pages 1–4. IEEE, 2012.
- [DPBC19] Louise Devigne, François Pasteau, Marie Babel, and Tom Carlson. A shared control solution for safe assisted power wheelchair navigation in an environment consisting of negative obstacles: a proof of concept. In *Robotics and Automation (ICRA), 2019 IEEE International Conference on*. IEEE, 2019.

- [DRI<sup>+</sup>17] Julieta Dascal, Mark Reid, Waguih William Ishak, Brennan Spiegel, Jennifer Recacho, Bradley Rosen, and Itai Danovitch. Virtual reality and medical inpatients: a systematic review of randomized, controlled trials. *Innovations in clinical neuroscience*, 14(1-2):14, 2017.
- [DSF03] A Davies, LH De Souza, and AO Frank. Changes in the quality of life in severely disabled people following provision of powered indoor/outdoor chairs. *Disability and Rehabilitation*, 25(6):286–290, 2003.
- [DWLS00] Louise Demers, Rhoda Weiss-Lambrou, and Bernadette Ska. Item analysis of the quebec user evaluation of satisfaction with assistive technology (quest). *Assistive Technology*, 12(2):96–105, 2000.
- [DWLS02] Louise Demers, Rhoda Weiss-Lambrou, and Bernadette Ska. The quebec user evaluation of satisfaction with assistive technology (quest 2.0): an overview and recent progress. *Technology and Disability*, 14(3):101–105, 2002.
- [dWSB12] Carlos Canudas de Wit, Bruno Siciliano, and Georges Bastin. *Theory of robot control*. Springer Science & Business Media, 2012.
- [ECR92] Bernard Espiau, François Chaumette, and Patrick Rives. A new approach to visual servoing in robotics. *IEEE Transactions on Robotics and Automation*, 8(3):313–326, 1992.
- [EFNDS07] Subhadra Evans, Andrew O Frank, Claudius Neophytou, and Lorraine De Souza. Older adults’ use of, and satisfaction with, electric powered indoor/outdoor wheelchairs. *Age and ageing*, 36(4):431–435, 2007.
- [EM10] Kara Edwards and Annie McCluskey. A survey of adult power wheelchair and scooter users. *Disability and Rehabilitation: Assistive Technology*, 5(6):411–419, 2010. PMID: 20450455.
- [EMR<sup>+</sup>09] Eric Emerson, Ros Madden, Janet Robertson, Hilary Graham, Chris Hatton, and Gwynnyth Llewellyn. Intellectual and physical disability, social mobility, social inclusion & health. 2009.
- [ETD<sup>+</sup>17] Chinemelu Ezech, Pete Trautman, Louise Devigne, Valentin Bureau, Marie Babel, and Tom Carlson. Probabilistic vs linear blending approaches to shared control for wheelchair driving. In *IEEE Int. Conf. on Rehabilitation Robotics, ICORR’17*, 2017.
- [Eva00] Rosemary Evans. The effect of electrically powered indoor/outdoor wheelchairs on occupation: a study of users’ views. *British Journal of Occupational Therapy*, 63(11):547–553, 2000.
- [Eva09] Graeme Evans. Accessibility, urban design and the whole journey environment. *Built environment*, 35(3):366–385, 2009.

- [EVD16] Francis Eustache, Armelle Viard, and Béatrice Desgranges. The mneseis model: Memory systems and processes, identity and future thinking. *Neuropsychologia*, 87:96–109, 2016.
- [FJJ<sup>+</sup>18] Clément Favey, Villanueva José, Liam Jordan, Roger Leroux, Zogaghi Aziz, and René Farcy. Télémétrie laser multifaisceaux pour le fauteuil électrique semi-autonome. In *IFRATH 2018-10ème Conférence sur les Aides Techniques pour les Personnes en Situation de Handicap, Handicap*, pages 1–6, 2018.
- [FPRARM15] Jorge Fuentes-Pacheco, José Ruiz-Ascencio, and Juan Manuel Rendón-Mancha. Visual simultaneous localization and mapping: a survey. *Artificial Intelligence Review*, 43(1):55–81, 2015.
- [FRMM13] Ryan Fomiatti, Janet Richmond, Lois Moir, and Jeannine Millstead. A systematic review of the impact of powered mobility devices on older adults’ activity engagement. *Physical & Occupational Therapy in Geriatrics*, 31(4):297–309, 2013.
- [Git15] Laura N Gitlin. Environmental adaptations for individuals with functional difficulties and their families in the home and community. In *International handbook of occupational therapy interventions*, pages 165–175. Springer, 2015.
- [Gon14] Frédéric Goncalves. *Conception d’un environnement virtuel avec adaptation de l’immersion pour la simulation de conduite en fauteuil roulant*. PhD thesis, Université de Versailles-Saint Quentin en Yvelines, 2014.
- [HABC12] Mohammed-Amine Hadj-Abdelkader, Guy Bourhis, and Brahim Cherki. Haptic feedback control of a smart wheelchair. *Applied Bionics and Biomechanics*, 9(2):181–192, 2012.
- [Har04] Peta Hardy. Powered wheelchair mobility: An occupational performance evaluation perspective. *Australian Occupational Therapy Journal*, 51(1):34–42, 2004.
- [Har06] Sandra G Hart. Nasa-task load index (nasa-tlx); 20 years later. In *Proceedings of the human factors and ergonomics society annual meeting*, volume 50, pages 904–908. Sage Publications Sage CA: Los Angeles, CA, 2006.
- [HB16] Pierro Hirsch and François Bellavance. Pilot project to validate the transfer of training of driving skills learned on a high fidelity driving simulator to on-road driving. 2016.
- [HBBC96] Patrick Hebert, Stephane Betge-Brezetz, and Raja Chatila. Decoupling odometry and exteroceptive perception in building a global world map

- of a mobile robot: The use of local maps. In *Robotics and Automation, 1996. Proceedings., 1996 IEEE International Conference on*, volume 1, pages 757–764. IEEE, 1996.
- [HDP<sup>+</sup>15] Christopher J Headleand, Thomas Day, Serban R Pop, Panagiotis D Ritsos, and Nigel W John. Challenges and technologies for low-cost wheelchair simulation. Eurographics Workshop on Visual Computing for Biology and Medicine, 2015.
- [HLS<sup>+</sup>03] ST Hayashi, Edmund F LoPresti, RC Simpson, Illah Nourbaksh, and David Miller. An inexpensive, alternative, drop-off detection solution. In *Proceedings of the RESNA 2003 Annual Conference*. Citeseer, 2003.
- [How17] Matt C Howard. A meta-analysis and systematic literature review of virtual reality rehabilitation programs. *Computers in Human Behavior*, 2017.
- [HWM13] Tuck-Voon How, Rosalie H Wang, and Alex Mihailidis. Evaluation of an intelligent wheelchair system for older adults with cognitive impairments. *Journal of neuroengineering and rehabilitation*, 10(1):90, 2013.
- [IL95] Dean P Inman and Ken Loge. Teaching motorized wheelchair operation in virtual reality. In *Proceedings of the 1995 CSUN Virtual Reality Conference*, 1995.
- [ISIK09] Takuma Ito, Motoki Shino, Takenobu Inoue, and Minoru Kamata. Development of a powered wheelchair driving simulator for research and development use. *Journal of mechanical systems for transportation and logistics*, 2(2):90–101, 2009.
- [Jaf82] David L Jaffe. An ultrasonic head position interface for wheelchair control. *Journal of Medical Systems*, 6(4):337–342, 1982.
- [JCE<sup>+</sup>14] M Gail Jones, Gina Childers, Brandon Emig, Joel Chevrier, Hong Tan, Vanessa Stevens, and Jonathan List. The efficacy of haptic simulations to teach students with visual impairments about temperature and pressure. *Journal of Visual Impairment & Blindness (Online)*, 108(1):55, 2014.
- [KASB<sup>+</sup>94] R Lee Kirby, Stacy A Ackroyd-Stolarz, Murray G Brown, Susan A Kirkland, and Donald A MacLeod. Wheelchair-related accidents caused by tips and falls among noninstitutionalized users of manually propelled wheelchairs in nova scotia. *American Journal of Physical Medicine & Rehabilitation*, 73(5):319–330, 1994.
- [KC11] Olivier Kermorgant and François Chaumette. Combining ibvs and pbvs to ensure the visibility constraint. In *IROS*, pages 2849–2854, 2011.

- [KDM<sup>+</sup>04] R Lee Kirby, Debbie J Dupuis, Angela H MacPhee, Anna L Coolen, Cher Smith, Krista L Best, Allison M Newton, Anita D Mountain, Donald A MacLeod, and James P Bonaparte. The wheelchair skills test (version 2.4): measurement properties. *Archives of physical medicine and rehabilitation*, 85(5):794–804, 2004.
- [Ker06] Georg Kerkhoff. *Plasticity in spatial neglect-Recovery and rehabilitation*, volume 24. IOS Press, 2006.
- [Kha86] Oussama Khatib. Real-time obstacle avoidance for manipulators and mobile robots. In *Autonomous robot vehicles*, pages 396–404. Springer, 1986.
- [KK15] Jacqueline K Koehn and Katherine J Kuchenbecker. Surgeons and non-surgeons prefer haptic feedback of instrument vibrations during robotic surgery. *Surgical endoscopy*, 29(10):2970–2983, 2015.
- [KKS<sup>+</sup>12] R Kizony, M Korman, G Sinoff, E Klinger, N Josman, and PM Sharky. Using a virtual supermarket as a tool for training executive functions in people with mild cognitive impairment. In *Proceedings of the 9th International Conference on Disability, Virtual Reality and Associated Technologies*, pages 41–46. University of Reading, Reading, England, 2012.
- [KKS<sup>+</sup>13] Evelyne Klinger, Abdelmajid Kadri, Eric Sorita, J-L Le Guiet, Pauline Coignard, Philippe Fuchs, Laure Leroy, Nicolas Du Lac, Fabrice Servant, and P-A Joseph. Agathe: A tool for personalized rehabilitation of cognitive functions based on simulated activities of daily living. *IRBM*, 34(2):113–118, 2013.
- [KMLB17] Ananda Sankar Kundu, Oishee Mazumder, Prasanna K Lenka, and Subhasis Bhaumik. Design and performance evaluation of 4 wheeled omni wheelchair with reduced slip and vibration. *Procedia Computer Science*, 105:289–295, 2017.
- [KOA<sup>+</sup>18] Fary Khan, Mayowa Ojo Owolabi, Bhasker Amatya, Talhatu Kolapo Hamzat, Adesola Ogunniyi, Helen Oshinowo, Alaeldin Elmalik, and Mary P Galea. Challenges and barriers for implementation of the world health organization global disability action plan in low-and middle-income countries. *Journal of rehabilitation medicine*, 50(4):367–376, 2018.
- [KRA<sup>+</sup>14] Dahlia Kairy, Paula W Rushton, Philippe Archambault, Evelina Pituch, Caryne Torkia, Anas El Fathi, Paula Stone, François Routhier, Robert Forget, Louise Demers, et al. Exploring powered wheelchair users and their caregivers’ perspectives on potential intelligent power wheelchair

- use: a qualitative study. *International journal of environmental research and public health*, 11(2):2244–2261, 2014.
- [LBJ<sup>+</sup>99] Simon P Levine, David A Bell, Lincoln A Jaros, Richard C Simpson, Yoram Koren, and Johann Borenstein. The navchair assistive wheelchair navigation system. *IEEE transactions on rehabilitation engineering*, 7(4):443–451, 1999.
- [LF14] Roslyn Livingstone and Debra Field. Systematic review of power mobility outcomes for infants, children and adolescents with mobility limitations. *Clinical rehabilitation*, 28(10):954–964, 2014.
- [LGF<sup>+</sup>08] Isabelle Laffont, Bruno Guillon, Christophe Fermanian, Sophie Pouillot, Alexia Even-Schneider, François Boyer, Maria Ruquet, Philippe Aegerter, Olivier Dizien, and Frédéric Lofaso. Evaluation of a stair-climbing power wheelchair in 25 people with tetraplegia. *Archives of physical medicine and rehabilitation*, 89(10):1958–1964, 2008.
- [Lic07] S Lichiardopol. A survey on teleoperation. *University of Eindhoven, Department Mechanical Engineering Dynamics and Control Group Eindhoven*, 2007.
- [LL17] Jesse Leaman and Hung Manh La. A comprehensive review of smart wheelchairs: past, present, and future. *IEEE Transactions on Human-Machine Systems*, 47(4):486–499, 2017.
- [LM08] Orly Lahav and David Mioduser. Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. *International Journal of Human-Computer Studies*, 66(1):23–35, 2008.
- [LPIB12] Charlotte Löfqvist, Cecilia Pettersson, Susanne Iwarsson, and A Brandt. Mobility and mobility-related participation outcomes of powered wheelchair and scooter interventions after 4-months and 1-year use. *Disability and Rehabilitation: Assistive Technology*, 7(3):211–218, 2012.
- [LPN13] Ana C Lopes, Gabriel Pires, and Urbano Nunes. Assisted navigation for a brain-actuated intelligent wheelchair. *Robotics and Autonomous Systems*, 61(3):245–258, 2013.
- [LSS10] Mindy F Levin, Heidi Sveistrup, and S Subramanian. Feedback and virtual environments for motor learning and rehabilitation. *Schedae*, 1:19–36, 2010.
- [Lun01] Arnold M Lund. Measuring usability with the use questionnaire12. *Usability interface*, 8(2):3–6, 2001.
- [LW92] AT Lefkowicz and WW Wierwille. Validation of a pc-based perspective-view wheelchair simulator. *RESNA Proceedings*, pages 415–417, 1992.

- [LXXZ18] Yuncheng Lu, Zhucun Xue, Gui-Song Xia, and Liangpei Zhang. A survey on vision-based uav navigation. *Geo-spatial information science*, 21(1):21–32, 2018.
- [MAC<sup>+</sup>15] Y Morère, MA Hadj Abdelkader, K Cosnuau, G Guilmois, and G Bourhis. Haptic control for powered wheelchair driving assistance. *IRBM*, 36(5):293–304, 2015.
- [MBC<sup>+</sup>18] Yann Morère, Guy Bourhis, Kévin Cosnuau, Georges Guilmois, Emilie Rumilly, and Emmanuelle Blangy. View: a wheelchair simulator for driving analysis. *Assistive technology*, (just-accepted), 2018.
- [MCB13] W Ben Mortenson, Laura Hurd Clarke, and Krista Best. Prescribers’ experiences with powered mobility prescription among older adults. *American Journal of Occupational Therapy*, 67(1):100–107, 2013.
- [MCFR10] Laura Marchal-Crespo, Jan Furumasu, and David J Reinkensmeyer. A robotic wheelchair trainer: design overview and a feasibility study. *Journal of neuroengineering and rehabilitation*, 7(1):40, 2010.
- [MDBM10] Luis Montesano, Marta Díaz, Sonu Bhaskar, and Javier Minguez. Towards an intelligent wheelchair system for users with cerebral palsy. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18(2):193–202, 2010.
- [MDCD13] Harshal P Mahajan, Brad E Dicianno, Rory A Cooper, and Dan Ding. Assessment of wheelchair driving performance in a virtual reality-based simulator. *The journal of spinal cord medicine*, 36(4):322–332, 2013.
- [MF01] Gilles Malaterre and Jacky Fréchaux. Etude de la validité des simulateurs de conduite par comparaison de tâches réalisées en situation réelle et en simulation. *Facteurs perceptifs dans les activités de transport*, (82), 2001.
- [MFR<sup>+</sup>14] Yann Morère, C Fritsch, S Remy, B Maertens de Noordhout, and Guy Bourhis. Simulateur de conduite en fauteuil électrique: application à des personnes atteintes de sclérose en plaques. In *Handicap 2014 8 ème Edition Paris, 11-13 juin 2014 «Les technologies d’assistance: de la compensation à l’autonomie»*, 2014.
- [MHV05] Christian Mandel, Kai Huebner, and Tilman Vierhuff. Towards an autonomous wheelchair: Cognitive aspects in service robotics. In *Proceedings of Towards Autonomous Robotic Systems (TAROS 2005)*, pages 165–172, 2005.
- [MIO01] Y Matsumotot, Tomoyuki Ino, and T Ogsawara. Development of intelligent wheelchair system with face and gaze based interface. In *Robot and Human Interactive Communication, 2001. Proceedings. 10th IEEE International Workshop on*, pages 262–267. IEEE, 2001.

- [MK09] Aniket Murarka and Benjamin Kuipers. A stereo vision based mapping algorithm for detecting inclines, drop-offs, and obstacles for safe local navigation. In *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*, pages 1646–1653. Citeseer, 2009.
- [MM14] Vipul H Mistry and Ramji Makwana. Survey: Vision based road detection techniques. *Int. J. Comput. Sci. Inf. Technol*, 5:4741–4747, 2014.
- [MMB<sup>+</sup>05] William B Mortenson, William C Miller, Jeanette Boily, Barbara Steele, Leslie Odell, Erin M Crawford, and Guylaine Desharnais. Perceptions of power mobility use and safety within residential facilities. *Canadian Journal of Occupational Therapy*, 72(3):142–152, 2005.
- [MSD<sup>+</sup>11] Harshal Mahajan, Donald M Spaeth, Brad E Dicianno, Diane M Collins, Michael L Boninger, and Rory A Cooper. Comparison of virtual wheelchair driving performance of people with traumatic brain injury using an isometric and a conventional joystick. *Archives of physical medicine and rehabilitation*, 92(8):1298–1304, 2011.
- [NGSK17] Joanne Nunnerley, Swati Gupta, Deborah Snell, and Marcus King. Training wheelchair navigation in immersive virtual environments for patients with spinal cord injury—end-user input to design an effective system. *Disability and Rehabilitation: Assistive Technology*, 12(4):417–423, 2017.
- [NLN<sup>+</sup>13] María-Dolores Navarro, Roberto Lloréns, Enrique Noé, Joan Ferri, and Mariano Alcañiz. Validation of a low-cost virtual reality system for training street-crossing. a comparative study in healthy, neglected and non-neglected stroke individuals. *Neuropsychological rehabilitation*, 23(4):597–618, 2013.
- [NPM<sup>+</sup>16] Vishnu K Narayanan, François Pasteau, Maud Marchal, Alexandre Krupa, and Marie Babel. Vision-based adaptive assistance and haptic guidance for safe wheelchair corridor following. *Computer Vision and Image Understanding*, 149:171–185, 2016.
- [O<sup>+</sup>80] World Health Organization et al. International classification of impairments, disabilities, and handicaps: a manual of classification relating to the consequences of disease, published in accordance with resolution wha29. 35 of the twenty-ninth world health assembly, may 1976. 1980.
- [O<sup>+</sup>93] World Health Organization et al. World health organization meeting on the international classification of impairments, disabilities and handicaps, december 7-10, 1993, pan american health organization headquarters, washington, dc: executive summary. 1993.

- [O<sup>+</sup>01] World Health Organization et al. *International classification of functioning, disability and health: ICF*. Geneva: World Health Organization, 2001.
- [O<sup>+</sup>15] World Health Organization et al. Wheelchair service training package for managers. 2015.
- [OASL18] Tatiana Ogourtsova, Philippe Archambault, Samir Sangani, and Anouk Lamontagne. Ecological virtual reality evaluation of neglect symptoms (evens): Effects of virtual scene complexity in the assessment of post-stroke unilateral spatial neglect. *Neurorehabilitation and neural repair*, 32(1):46–61, 2018.
- [OGR09] Judy M Opalek, Vickie L Graymire, and Deidre Redd. Wheelchair falls: 5 years of data from a level i trauma center. *Journal of trauma nursing*, 16(2):98–102, 2009.
- [OO<sup>+</sup>05] World Health Organization, World Health Organization, et al. Disability and rehabilitation who action plan 2006–2011. *Department of Injuries and Violence Prevention [VIP]*. Pabrano, 9, 2005.
- [Pau81] Richard P Paul. *Robot manipulators: mathematics, programming, and control: the computer control of robot manipulators*. Richard Paul, 1981.
- [PBS13] François Pasteau, Marie Babel, and Rafiq Sekkal. Corridor following wheelchair by visual servoing. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, pages 590–595. IEEE, 2013.
- [PKB14] François Pasteau, Alexandre Krupa, and Marie Babel. Vision-based assistance for wheelchair navigation along corridors. In *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, pages 4430–4435. IEEE, 2014.
- [PLB00] James L Prothro, Edmund F LoPresti, and David M Brienza. An evaluation of an obstacle avoidance force feedback joystick. In *RESNA 2000 Annual Conference*, pages 27–30, 2000.
- [PNBC16] François Pasteau, Vishnu K Narayanan, Marie Babel, and François Chaumette. A visual servoing approach for autonomous corridor following and doorway passing in a wheelchair. *Robotics and Autonomous Systems*, 75:28–40, 2016.
- [RHT16] Joachim Rix, Stefan Haas, and José Teixeira. *Virtual prototyping: Virtual environments and the product design process*. Springer, 2016.

- [RMSL11] Jorge Rios-Martinez, Anne Spalanzani, and Christian Laugier. Understanding human interaction for probabilistic autonomous navigation using risk-rrt approach. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, pages 2014–2019. IEEE, 2011.
- [Rod15] N. Rodriguez. Development of a wheelchair simulator for children with multiple disabilities. In *3rd IEEE VR International Workshop on Virtual and Augmented Assistive Technology (VAAT)*, pages 19–21, March 2015.
- [ROS15] Laura A Rice, Cherita Ousley, and Jacob J Sosnoff. A systematic review of risk factors associated with accidental falls, outcome measures and interventions to manage fall risk in non-ambulatory adults. *Disability and rehabilitation*, 37(19):1697–1705, 2015.
- [RPM<sup>+</sup>15] Simon Richir, Samuel Pineau, Éric Monacelli, Frédéric Goncalves, Benjamin Malafosse, Claude Dumas, Alain Schmid, and Jérôme Perret. Design of portable and accessible platform in charge of wheelchair feedback immersion. In *Virtual Reality (VR), 2015 IEEE*, pages 389–390. IEEE, 2015.
- [RVSP09] Bernhard E Riecke, Aleksander Väljamäe, and Jörg Schulte-Pelkum. Moving sounds enhance the visually-induced self-motion illusion (circular vection) in virtual reality. *ACM Transactions on Applied Perception (TAP)*, 6(2):7, 2009.
- [Sal11] Benjamin Salatin. *Electric powered wheelchair driving outdoors: The identification of driving obstacles & strategies and the development of an advanced controller*. PhD thesis, University of Pittsburgh, 2011.
- [SBS<sup>+</sup>09] Anna-Liisa Salminen, Åse Brandt, Kersti Samuelsson, Outi Töytäri, and Antti Malmivaara. Mobility devices to promote activity and participation: a systematic review. *Journal of rehabilitation medicine*, 41(9):697–706, 2009.
- [Sch03] Thomas W Schubert. The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness. *Zeitschrift für Medienpsychologie*, 15(2):69–71, 2003.
- [Sch10] Ulrike Schultze. Embodiment and presence in virtual worlds: a review. *Journal of Information Technology*, 25(4):434–449, 2010.
- [SD97] E Steinfeld and GS Danford. Environment as a mediating factor in functional assessment. *Functional assessment and outcome measures for the rehabilitation health professional*, pages 37–56, 1997.
- [SEB91] Claude Samson, Bernard Espiau, and Michel Le Borgne. *Robot control: the task function approach*. Oxford University Press, 1991.

- [Sim05] Richard C Simpson. Smart wheelchairs: A literature review. *Journal of rehabilitation research and development*, 42(4):423, 2005.
- [SL02] Richard C Simpson and Simon P Levine. Voice control of a powered wheelchair. *IEEE Transactions on neural systems and rehabilitation engineering*, 10(2):122–125, 2002.
- [SLC08] Richard C Simpson, Edmund F LoPresti, and Rory A Cooper. How many people would benefit from a smart wheelchair? *Journal of Rehabilitation Research & Development*, 45(1), 2008.
- [SLH<sup>+</sup>04] Richard Simpson, Edmund LoPresti, Steve Hayashi, Illah Nourbakhsh, and David Miller. The smart wheelchair component system. *Journal of Rehabilitation Research and Development*, 41(3B):429, 2004.
- [SO11] Tom Shakespeare and Alana Officer. cognitiv. *Disabil Rehabil*, 33(17-18):1491, 2011.
- [SS11] Sharon Eve Sonenblum and Stephen Sprigle. Distinct tilting behaviours with power tilt-in-space systems. *Disability and Rehabilitation: Assistive Technology*, 6(6):526–535, 2011.
- [SSMS17] Dylan Schwesinger, Armon Shariati, Corey Montella, and John Spletzer. A smart wheelchair ecosystem for autonomous navigation in urban environments. *Autonomous Robots*, 41(3):519–538, 2017.
- [Sto01] Robert J Stone. Haptic feedback: A brief history from telepresence to virtual reality. In *Haptic Human-Computer Interaction*, pages 1–16. Springer, 2001.
- [Str97] Dorothy Strickland. Virtual reality for the treatment of autism. *Studies in health technology and informatics*, pages 81–86, 1997.
- [SW14] Kersti Samuelsson and Ewa Wressle. Powered wheelchairs and scooters for outdoor mobility: a pilot study on costs and benefits. *Disability and Rehabilitation: AT*, 9(4):330–334, 2014.
- [SWDC17] S Andrea Sundaram, Hongwu Wang, Dan Ding, and Rory A Cooper. Step-climbing power wheelchairs: A literature review. *Topics in spinal cord injury rehabilitation*, 23(2):98–109, 2017.
- [TACA09] Y Touati, A Ali-Cherif, and B Achili. Smart wheelchair design and monitoring via wired and wireless networks. In *Industrial Electronics & Applications, 2009. ISIEA 2009. IEEE Symposium on*, volume 2, pages 920–925. IEEE, 2009.
- [TDG<sup>+</sup>10] Lei Tang, Songyi Dian, Gangxu Gu, Kunli Zhou, Suihe Wang, and Xinghuan Feng. A novel potential field method for obstacle avoidance

- and path planning of mobile robot. In *Computer Science and Information Technology (ICCSIT), 2010 3rd IEEE International Conference on*, volume 9, pages 633–637. IEEE, 2010.
- [TOM<sup>+</sup>15] Miguel A Teruel, Miguel Oliver, Francisco Montero, Elena Navarro, and Pascual González. Multisensory treatment of the hemispatial neglect by means of virtual reality and haptic techniques. In *International Work-Conference on the Interplay Between Natural and Artificial Computation*, pages 469–478. Springer, 2015.
- [TSEC94] Hong Z Tan, Mandayam A Srinivasan, Brian Eberman, and Belinda Cheng. Human factors for the design of force-reflecting haptic interfaces. *Dynamic Systems and Control*, 55(1):353–359, 1994.
- [UPFC<sup>+</sup>10] C. Urdiales, J. M. Peula, M. Fdez-Carmona, C. Barrué, E. J. Pérez, I. Sánchez-Tato, J. C. del Toro, F. Galluppi, U. Cortés, R. Annichiaricco, C. Caltagirone, and F. Sandoval. A new multi-criteria optimization strategy for shared control in wheelchair assisted navigation. *Autonomous Robots*, 30(2):179–197, October 2010.
- [VPDR<sup>+</sup>12] Emmanuel B Vander Poorten, Eric Demeester, Eli Reekmans, Johan Philips, Alexander Hüntemann, and Joris De Schutter. Powered wheelchair navigation assistance through kinematically correct environmental haptic feedback. In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pages 3706–3712. IEEE, 2012.
- [WBM99] GG Whiteneck, CA Brooks, and D Melick. The creation of the craig hospital inventory of environmental factors (chief). *Englewood Cliffs (CO): Craig Hospital*, 1999.
- [WHFM<sup>+</sup>04] Gale G Whiteneck, Cynthia L Harrison-Felix, David C Mellick, CA Brooks, Susan B Charlifue, and Ken A Gerhart. Quantifying environmental factors: A measure of physical, attitudinal, service, productivity, and policy barriers1. *Archives of physical medicine and rehabilitation*, 85(8):1324–1335, 2004.
- [WHOAG99] Classification World Health Organization Assesment and Epidemiology Group. *ICIDH-2: International classification of functioning and disability*. WHO, Assesment, Classification and Epidemiology Group, 1999.



# List of Figures

1	Autoriser la conduite de fauteuil roulant [AWLW05]. . . . .	11
1.1	Enabling power wheelchair driving [AWLW05]. . . . .	21
2.1	TopChair step climbing wheelchair. . . . .	28
2.2	Laser range finder sensor example. . . . .	30
2.3	Ultrasonic sensor. . . . .	31
2.4	Infrared sensors. . . . .	32
2.5	Standard 6 wheels power wheelchair (Quickie Salsa M <sup>2</sup> ). . . . .	37
2.6	Modeling of the robotic wheelchair. . . . .	38
3.1	Scene from the view simulator [MBC <sup>+</sup> 18]. . . . .	43
3.2	Scene from the miWe simulator [ACS <sup>+</sup> 11]. . . . .	44
3.3	Real and virtual wheelchairs. Red frames indicate sensor positions. . . . .	45
3.4	Immersia is one of the largest VR research platforms in the world. It is composed of 4 large screens on which images are projected for a total volume of approximately 90m <sup>3</sup> . The 3D rendering is achieved by using active stereoscopic method associated with shutter glasses. 16 infrared cameras track the moving objects on the platform. . . . .	46
3.5	Input commands are collected using the Controller ROS node and used by the Control ROS node to compute the commands to apply to the virtual wheelchair. The Display node handles the display of the VE as well as the commands to the virtual wheelchair actuators. . . . .	47
3.6	Power wheelchair assisted navigation simulator framework. . . . .	48
3.7	User sitting on a real power wheelchair placed on the immersive platform. . . . .	48
3.8	Obstacle course taken from [HWM13] in the VE. . . . .	49
3.9	Obstacle course designed for the experiment. . . . .	50
3.10	Average IPQ score for each category. Global represents the global score. Error bars indicate standard deviation. . . . .	51
3.11	NASA-TLX scores M represents the mean value over the 9 participants. . . . .	51
3.12	Number of collisions for each participant on both obstacle courses with and without driving assistance activated. . . . .	52
3.13	Completion time for each participant on both obstacle courses with and without driving assistance activated. . . . .	53
3.14	Circuit designed for this study. . . . .	55

3.15	Driving circuit setup in the real condition. . . . .	56
3.16	Driving circuit setup in the virtual condition. . . . .	56
3.17	Participant driving the virtual wheelchair in the VE while seating on a real wheelchair. . . . .	57
3.18	Mechanical platform for enhanced virtual experience. . . . .	61
4.1	Definition of the robot and sensor frames. . . . .	65
4.2	Case of frontal and lateral sensors: $\alpha_{z_i} \simeq 0$ . . . . .	67
4.3	Examples of corner sensor detection while navigating along a wall. Purple cones represent sensors field of view. . . . .	68
4.4	Corner sensor $s_i$ arrangement. . . . .	69
4.5	Calculation of $\alpha_{z_i}$ with $\theta_i = \frac{\pi}{4}$ . . . . .	69
4.6	Evolution of $e_{s_i}$ , $v$ and $\omega$ in simulation. . . . .	71
4.7	Half plane in the velocity domain . . . . .	74
4.8	Convex polygon in the wheelchair velocity domain . . . . .	74
4.9	Half plane in the velocity domain . . . . .	75
4.10	Definition of $\mathbf{P}_0$ and $\mathbf{P}_1$ . . . . .	75
4.11	Definition of $\mathbf{P}_2$ and $\mathbf{P}_3$ . . . . .	75
4.12	Simulated algorithm . . . . .	78
4.13	Simulation results: (4.13b) and (4.13c) represent the corrected forward velocity and rotational velocity with respect to the timeline of the obstacle avoidance represented in (4.13a). . . . .	79
4.14	Example of allowed/forbidden areas during the simulation . . . . .	80
4.15	Ecological circuit. . . . .	82
4.16	Driving circuit. . . . .	83
4.17	Ultrasonic sensors on the power wheelchair. . . . .	84
4.18	Dedicated interface for clinicians. . . . .	84
5.1	Wheelchair modeling and sensor arrangement. . . . .	94
5.2	Detection of obstacles. From a "negative" obstacle in the vertical plane to a "positive" obstacle in the horizontal plane . . . . .	95
5.3	Negative obstacle detection. . . . .	96
5.4	Virtual environment for the simulation. . . . .	99
5.5	Wheelchair setup for the simulation. . . . .	100
5.6	Simulation results: (a) represents the trajectory of the virtual wheelchair in the simulated environment which we recorded for visualization purpose only. The rectangles represent the wheelchair at the beginning (green) and at the end (red) of the simulation. (b) represents the corrected forward and rotational velocities during the simulation. . . . .	101
5.7	(a) Power wheelchair equipped with detection module prototypes. (b) Detection module prototype (bottom view). Each detection module is composed of 3 ToF sensor boards inclined at 45 degrees to the vertical. . . . .	102
5.8	Generic ROS framework adapted to the control of the real power wheelchair. . . . .	103
5.9	Experiment environment on the PAMELA platform. . . . .	104

5.10	Experiment results: (a) linear user input (blue) and shared control output (red) velocities (b) rotational user input (blue) and shared control output (red) velocities. . . . .	105
5.11	Definition of $\alpha_{x_i}$ and $\alpha_{y_i}$ . . . . .	106
5.12	Weighting function $h_{d_i}$ defined for feature $d_i$ . The weight is null in the safe interval and smoothly increases up to 1 in the tolerated intervals $[d_i^-, d_i^{s-}]$ and $[d_i^{s+}, d_i^+]$ . . . . .	108
5.13	Virtual environment for the simulation. . . . .	109
5.14	Wheelchair corrected trajectory for different initial positions. . . . .	110
5.15	Simulation results: (a) Forward velocity applied to the wheelchair (b) Rotational velocity applied to the wheelchair (c) Representation of the trajectory of the virtual wheelchair in the simulated environment (which we recorded for visualization purpose only). The rectangles represent the wheelchair at the beginning (red) and at the end (green) of the simulation.	111
5.16	On going tests of the second method in real outdoor environment. . . . .	112
6.1	The algorithm output corresponds to the projection of user input within the allowed area. $\vec{\mathbf{k}}$ represents the vector from the user input to the algorithm output. . . . .	117
6.2	Top view of the map used for simulation. . . . .	118
6.3	Virtual environment and simulation setup. . . . .	119
6.4	Simulation results. . . . .	120
6.5	Obstacle course, values correspond to distances in centimeters. . . . .	121
6.6	Participant driving on the obstacle course. . . . .	121
6.7	Generic ROS framework adapted to the control of the haptic interface. . . . .	121
6.8	Experiment results. . . . .	123
6.9	Homemade dedicated force feedback joystick adapted to user needs. . . . .	125





## AVIS DU JURY SUR LA REPRODUCTION DE LA THESE SOUTENUE

**Titre de la thèse:**

Solutions robotiques bas coût pour l'aide à la navigation en fauteuil roulant électrique : vers une contribution dans le champ de la rééducation neurologique

**Nom Prénom de l'auteur : DEVIGNE LOUISE**

**Membres du jury :**

- Monsieur REMY-NERIS Olivier
- Monsieur GALLIEN Philippe
- Monsieur ALAMI Rachid
- Madame BABEL Marie
- Monsieur MOUADDIB El Mustapha
- Monsieur BOURHIS Guy
- Monsieur CARLSON Tom

Président du jury : *Guy BOURHIS*

Date de la soutenance : 06 Décembre 2018

Reproduction de la these soutenue

- Thèse pouvant être reproduite en l'état  
 Thèse pouvant être reproduite après corrections suggérées

Fait à Rennes, le 06 Décembre 2018

Signature du président de jury

*G. BOURHIS*

Le Directeur,

*[Signature]*  
M'hamed DRISSI



*[Signature]*

**Titre :** Solutions robotiques bas coût pour l'aide à la navigation en fauteuil roulant électrique : vers une contribution dans le champ de la rééducation neurologique

**Mots clés :** contrôle basé capteurs, fauteuil roulant intelligent, handicap, robotique de réadaptation, contrôle partagé, assistance semi-autonome à la navigation

**Résumé :** Alors que l'utilisation d'un fauteuil roulant permet aux personnes en situation de handicap de compenser une perte de la mobilité, certaines personnes se voient privées de l'utilisation d'un fauteuil roulant électrique. En effet, la présence de troubles cognitifs ou de la perception visuelle altère la capacité à conduire sans danger. Dans ce contexte, l'accès à la mobilité peut être amélioré par l'apport d'aides techniques adaptées permettant de compenser la perte de mobilité dans tous types d'environnements. Alors que les premiers travaux sur les fauteuils roulants intelligents datent du début des années 80, aucune solution n'est à ce jour sur le marché ou dans les centres de rééducation. Ce travail vise à proposer un ensemble de solutions d'aide à la conduite de fauteuil roulant électrique conçu en collaboration

Le développement de telles aides techniques constitue de multiples défis robotiques mêlant techniques de détection innovantes et méthodes de contrôle partagé avec l'utilisateur. Dans ce travail, un simulateur de conduite visant à appuyer la recherche et le développement de nouvelles solutions robotiques est proposé. Puis des solutions bas coût d'assistance semi-autonome à la conduite en intérieur et en extérieur sont détaillées. L'évaluation avec des participants sains nous permet de valider les méthodes mathématiques mises en oeuvre et de fournir des preuves de concept des solutions proposées. Enfin, les premières évaluations cliniques avec des usagers au Pôle MPR Saint Hélier montrent la validation de la méthode proposée en termes de satisfaction des utilisateurs.

**Title :** Low-cost robotic solutions for safe assisted power wheelchair navigation: towards a contribution to neurological rehabilitation

**Keywords:** sensor-based control, smart power wheelchair, disability, rehabilitation robotics, shared control, semi-autonomous navigation assistance

**Abstract:** While the use of a wheelchair allows people with disabilities to compensate for a loss of mobility, people with severe disabilities are denied the use of a power wheelchair. Indeed, cognitive or visual perception impairments can affect the ability to drive safely. In this context, access to mobility can be improved by providing appropriate assistive technologies to compensate for loss of mobility in all types of environments. While the first research on smart wheelchairs dates back to the early 1980s, no solutions have yet been proposed on the market or in rehabilitation centers and other specialized structures. This work aims to propose a set of solutions for power wheelchair navigation assistance designed in close collaboration with users and therapists. The development of such

assistive solutions faces multiple robotic challenges combining innovative detection techniques, shared control with the user. In this work, a driving simulator supporting research and development of new robotic solutions for wheelchair navigation assistance is proposed. Then low-cost semi-autonomous assistance solutions for navigation assistance in indoor and outdoor environments are detailed. The evaluation with able-bodied participants allows to validate the mathematical methods and provide proof of concept of the proposed solutions. Finally, the first clinical evaluations with regular users at Pôle MPR Saint Hélier show the validation of the proposed framework in terms of user satisfaction.