Mobility, Accessibility and Safety of People with Cerebral Palsy

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

1 INTRODUCTION

Cerebral palsy (CP) is a complex medical and non-progressive condition, that is characterized by cognitive and motor disturbances, and it is a consequence of the damage of specific brain areas caused before, during or shortly after birth (Koman et al., 2003). According to the data obtained from the National Health Interview Survey from 1988 (Health Statistics and Health & Human Services, 1988), CP appears as the most disabling clinical situation, involving the largest number of annual medical contacts and also the largest number of hospital admissions during the year. CP is also the most common disability in childhood and the trend is to increase its prevalence over the last decades (Vargus-Adams, 2003). Due to accessibility and quality improvement of medical care provided to individuals with CP, the average life expectancy for this group has increased significantly. Therefore, before 1950 few people with CP survived until adulthood and now is expected that 65% to 90% of children with CP can live past adulthood (Zaffuto-Sforza, 2005). However, despite the increasing prevalence of CP, the medical innovation and development, observed in the 1970s and 1980s, contributed to a significant increase in average life expectancy, which boosted the research to understand how the CP can affect the quality of life (QOL) of these individuals, including their levels of mobility and participation (Kennes et al., 2002; Wake et al., 2003). Research results show that children with CP have a more impaired QOL in all domains when compared with other able-body children (Vargus-Adams, 2003; Varni et al., 2007), but another study concludes that the QOL of this group is only lower in the physical domain and not in the psychological and social domains (Dickinson et al., 2007). The QOL of adults with CP is significantly affected in all domains assessed by The World Health Organization Quality of Life (WHOQOL-BREF): Physical, Psychological, Social Relationships and Environment (Carona et al., 2010). More specifically, when compared to other able-body adults, they reported a lower QOL in the physical domain (mobility) and in the environment domain (participation and/or opportunities for recreation and leisure and transportation).

This work aims to research new technologies that may contribute to the mobility, accessibility and safety improvement of individuals with CP. We aim to provide results to support the design and development of more suitable solutions to improve mobility, accessibility and safety. With the overall goal to char-

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acterize all three factors referred above, this research work was organized as follows: (1) Characterization of subject's mobility, public transportation use and Human-Machine Interface (HMI); (2) Relation between HMIs and powered wheelchair steering performance; (3) Identification of most valued features and limiting factors in the use of powered wheelchairs; (4) Analysis of possible solutions to be implemented in a powered wheelchair. The lack of safety and the difficulty in navigating the powered wheelchair were generally pointed out as the most limiting factors, which means there is the need to develop more suitable solutions to improve navigation and safety. A solution to address both of these problems is to install more sensors in the powered wheelchair, providing additional information of the environment and to introduce a new navigation system based on a collaborative controller that shares the information between the user and the machine. In our case, we decided that Kinect, a sensor that provides 3D information of the environment, has certain features that makes it a potential choice:

- It is a compact and lightweight sensor which provides both RGB and range images;
- It gathers 3D information of the powered wheelchair's surrounding from a 3D field-of view;
- It is a low cost solution;
- It works at a frequency of 30 Hz;
- Operation range acceptable for indoor environments: from 0.6 to 3.5m. However, the use of Kinect to provide environment data to a reactive navigator based on a 2D space representation presents two difficulties: (a) the huge amount of data it provides and (b) the existence of a blind zone both at short distance and because of the narrow horizontal field-of-view (in comparison to laser radial scanners) (Gonzalez-Jimenez et al., 2013). The current research was based on the work done previously under the research project Interface10 - Emergent Interfaces for Improving Accessibility of Persons with Cerebral Palsy (Carona et al., 2012), (Lopes et al., 2013).

2 APPROACH / METHODOLOGY

2.1 Participants

The sample for this study included 16 individuals and was collected at APCC, between December 2013 and March 2014, based on the following inclusion criteria: (1) clinical diagnosis of CP; (2) ability to understand questions and provide answers accordingly; (3) use of a powered wheelchair; (4) minimum age of 15 years. After obtaining APCC's formal authorization, participants were selected by their teams of clinical follow-up, based on the inclusion criteria listed above. Before filling out the questionnaires, all participants gave informed consent.

2.2 Tools

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

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

3 RESULTS

3.1 Sample Characterization

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

The collected sample (n = 16) had an average age of 29,80. The most observed type of CP was spastic

Table 1: Clinical and sociodemographic data.

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

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

3.2 Characterization of Accessibility, Mobility and Support

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

Table 2: Characterization of accessibility, mobility and support.

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

3.3 Experience in Using the HMIs and Powered Wheelchair vs Quality of Performance

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

Table 3: Level of performance with the HMIs.

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

Analyzing Table 3, it is possible to see that all the users of HMIs for computer use and most individuals (62,50%) using the HMIs required for steering the powered wheelchair, considered themselves in a level 5 of performance. Most of the subjects (81,25%) in this research use a joystick to help the navigation of the powered wheelchair.

Many of the users (43,75%) were classified as level 4 in terms of steering performance of the powered wheelchair and also, that a significant percentage (37,50%) were classified as level 5.

3.4 Most Valued Features and Limiting Factors in the Use of Assistive Technologies for Mobility

In Table 4 we can see that the most valued features of a powered wheelchair are its comfort and structure (68,75%), easy navigation and wheelchair control (56,25%) and finally, safety (43,75%). The main limiting factors in a powered wheelchair are the difficulty in reverse drive (37,50%) and building/vehicle access (31,25%). Also 12,50% of the individuals complained about the lack of safety.

Table 4: Most valued features and limiting factors in a powered wheelchair.

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

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

The powered wheelchair inadequacy (75,00%), the limitations of the vehicles (31,25%) and the vehicle adaptation costs (25,00%) on one hand, and the lack of adapted transports and complexity of its use (both referred by all the public transportation users),

Table 5: Limiting factors in the use of assistive technologies for mobility.

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

on the other hand, were the main limiting factors mentioned for the use of private and public transportation, respectively.

The results above can be seen in Table 5. We were able to get a perception of the mobility and accessibility difficulties and also concluded that many of the complaints were related with the lack of safety and how relevant this issue is or related with the lack of an appropriate assistive navigation system to help maneuvering the powered wheelchair.

3.5 Possible Improvements of the Powered Wheelchair

Since one of the goals of this research is to help improve the QOL of people with CP, the subjects of this study were asked if their powered wheelchair could be improved in any way, and almost all of them answered positively (93,75%), as seen in Table 6.

In Table 7 is possible to see the most requested improvements: aid for reverse drive (40,00%), collision

Table 6: Powered wheelchair improvement.

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

avoidance (26,67%), a warning during reverse driving (26,67%), reverse driving information (26,67%), comfort/structure improvement (20,00%), assistance in navigation in more complicated places (13,33%).

Table 7: Most requested powered wheelchair improvements.

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

Table 8 shows the least requested powered wheelchair improvements. With the results mentioned in Table 7, we can conclude that most of the suggested improvements (57,14%) affect safety and could be solved by installing more sensors in the powered wheelchair and by introducing a new navigation system.

Table 8: Least requested powered wheelchair improvements.

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

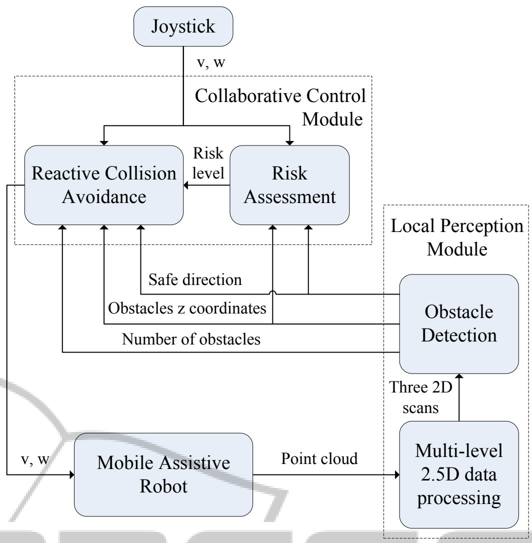

Figure 1: Block diagram of the ANS architecture.

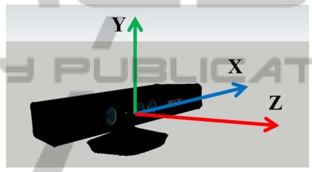

Figure 2: X, Y and Z coordinates of the installed Kinect sensor.

4 ASSISTIVE NAVIGATION SYSTEM

In this section we describe the proposed solution for the control and safe navigation of the powered wheelchair structured in the Assistive Navigation System (ANS) shown in Figure 1, which integrates a human-machine collaborative controller. The ANS requires an effective model of the local environment, obtained through the use of a Kinect sensor.

4.1 Local Perception

The Local Perception Module is composed by the multi-level 2.5D data processing and obstacle detection submodules.

4.1.1 Multi-level 2.5D Data Processing

The 3D depth data (point cloud) received from Kinect, is divided into three 2.5D horizontal scans (one for the top, one for the middle and one for the bottom) to decrease the computational complexity. The 2.5D scans are composed by the minimum measured distance in each column of depth data (Z-array). The minimum distance for each 2.5D scan is computed by

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

where j is the respective column number in the depth image (Rockey, 2013). Y and X locations for the corresponding Z elements are respectively provided in 480x1 and 640x1 arrays. Since the robot can only move in the X-Z plane, the Y (height) coordinate is ignored (see Figure 2). The data in Z and X arrays indicate the nearest obstacle locations regardless of the vertical position of obstacles.

An example of the Kinect point cloud and resulting 2.5D scans (2.5D scan resulting from the entire 3D field-of-view and multilevel 2.5D scans) obtained by the proposed method, as well as the 2D scan of the environment provided by a 2D laser range finder are shown in Figure 3.

Kinect has the disadvantage of close range blind spot, and, due to that, it is not reliable when obstacles are closer than 0.6 meters and it is blind in distances less than 0.5 meters. The 3D depth data from Kinect is condensed into three 2.5D scans, corresponding to the top, middle and bottom volumes. With this methodology it is possible to identify obstacles at three different height levels, which allows the Mobile Assistive Robot (MAR) to identify and approach certain obstacles such as tables or desks and at the same time, avoiding obstacles that could threaten its safety.

4.1.2 Obstacle Detection

The obstacle detection methodology is based on the VFH method (Borenstein and Koren, 1991). Each of the three 2.5D scans provided in the previous step is divided into 5 angular sectors, which are analyzed to find the closest obstacle in each sector. The number of obstacles and the distance to each obstacle are obtained through the analysis of the 2.5D scans. Therefore, if an obstacle in a certain sector has a value (distance) less than a given threshold, it will be considered as an actual obstacle that can endanger the user safety, or that can be approached, depending on the user's intent and on the 2.5D scan under analysis.

A second analysis is performed to detect the sector(s) with highest obstacle density. This information is then provided to the reactive collision avoidance module, indicating the obstacle weight values of each sector.

4.2 Collaborative Control

The Collaborative Control Module has a central role in the ANS. It decides, according to the perceived situation, whether to give all the power to the user or to the machine, or to merge user and machine inputs. It is composed by Risk Assessment and Reactive Collision Avoidance submodules.

4.2.1 Risk Assessment

This submodule evaluates the current situation and makes an appropriate decision according to the information obtained by the Local Perception module (see Figure 1). The algorithm selects the sector with the closest obstacle (the most dangerous sector) among all sectors, and classifies the current situation according to the relative position of the MAR to that sector:

- Obstacles at a distance greater than 0.9 m present no risk to the user (risk level 0).

- Obstacles that are located between 0.6 and 0.9 m are classified as potential obstacles. Obstacles in this class are later sub-divided in medium risk obstacles, those located in a distance between 0.75 and 0.9 meters (risk level 1 or 2), and high risk obstacles those located in a distance between 0.6 and 0.75 meters (risk level 3 or 4).

- Obstacles at a distance less than 0.6 m represent eminent danger (risk level 5).

The current direction taken by MAR also affects the risk level classification. User can move towards the obstacle or go away from obstacles. The closer the obstacles are, the greater is the risk.

4.2.2 Reactive Collision Avoidance

The main objective of the Reactive Collision Avoidance submodule is to avoid the obstacles in the vicinity of the MAR. The algorithm takes into account the number of obstacles in the sectors, the safest direction to follow, the distance to the obstacle and the angular and linear speed commands that the user is providing to the MAR. It acts as a Traded Controller and effectively denies or allows the user commands or acts as a Shared Controller by combining the robot navigation commands with the user commands. It assists user for maneuvering in more complicated situations as well as avoiding collision in order to achieve a better level of safety. The rules composing the reactive navigation are:

- Traded Control - in this case the steering control is fully delegated to the user or to the MAR: 1) When there are no obstacles in risky area, the user commands are followed, constrained by a maximum speed value due to safety reasons; 2) If an obstacle is endangering the user safety, the MAR stops and turns until a safe direction is found.

- Shared Control - in this case the control is shared between the user and the MAR: 1) When the user is in a medium risk situation the maximum linear speed is

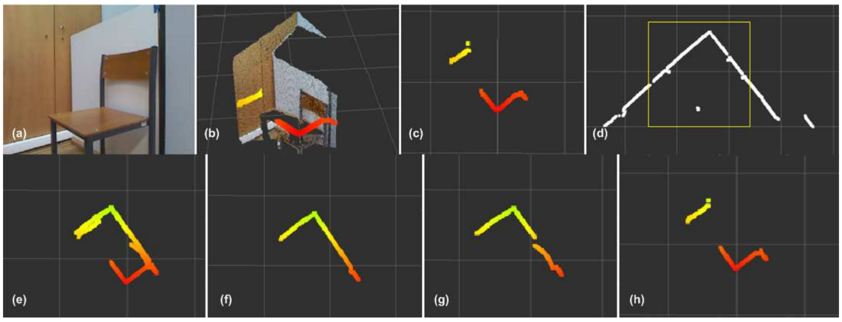

Figure 3: (a) Kinect RGB image, (b) Kinect's pointcloud and the 2.5D scan resulting from the entire 3D field-of-view, (c) the Kinect's 2.5D scan resulting from the 3D field-of-view, (d) 2D scan from Hokuyo URG-04LX laser scanner with the Kinect's field-of-view highlighted in yellow, (e) sum of the three level 2.5D scans provided by Kinect, f) the top 2.5D scan, g) the middle 2.5D scan and h) the bottom 2.5D scan.

reduced for safety reasons. When the user is moving towards an obstacle the linear speed is even more reduced and varies with distance; 2) In a high risk situation, the reactive navigation will affect both linear and angular speeds. Linear speed is reduced proportionally to the MAR distance to the obstacle. The MAR rotates towards a safe direction, which is chosen according to the sectors with lower obstacle density.

The reactive navigation module was developed in a way to lead the MAR avoid deadlocks (U-shaped obstacles), by using a short term memory, which stores the number of perceived obstacles in the robot's vicinity. RobChair (Lopes et al., 2012), (Lopes et al., 2013) was the MAR used in the experiments (see Figure 4). An example of a trajectory performed in a real test experiment is shown in Figure 5. Some situations can be underlined:

Situation 1: In this situation, the user successfully approached the table. The MAR identified it as a safe situation since this obstacle had the features (height) of a table. The control was delegated to the user.

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

Situation 5: Shared control was activated since the user tried to approach the side of a table. Once the user was navigating slower than in the previous situations, traded control was not activated since the shared controller commands were able to deviate the MAR and avoid collision with the obstacle.

Figure 4: RobChair - Mobile Assistive Robot.

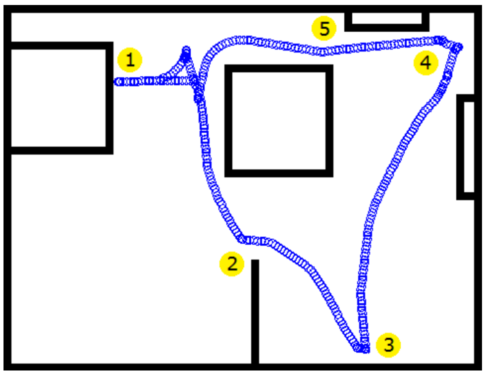

Figure 5: MAR navigation trajectory in ISR test scenario.

5 CONCLUSION AND FUTURE WORK

This paper presents the characterization of mobility, accessibility and safety in a group of individuals with Cerebral Palsy. The results suggest that user experience in steering the powered wheelchair is a decisive factor for a good level of performance. Younger users can have increased troubles driving the powered wheelchair due to the lack of experience, therefore contributing to a more complex navigation and compromised safety. Combining these results with the suggested improvements by the users, we concluded that the lack of safety and the difficulty in navigating the powered wheelchair were the most limiting factors, in general, and also the most suggested (57,14%) to be improved. The ANS was tested both in simulated environment conditions and in real conditions. The promising results show that the collaborative controller and other modules of the ANS architecture compose a structure on which it is worth continuing to devote research effort.

Future work includes adding short range sensors for close distances, improving the collaborative control methodology to allow safe navigation in human environments, and also solving other remaining issues pointed out by powered wheelchair users. Getting a larger user sample could also point us toward future research directions.

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