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Social robotic wheelchair centered on passenger and pedestrian comfort

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ABSTRACT

The use of robot technology such as robotic wheelchairs is crucial to provide services for super-aging societies. A social issue in current robotic wheelchairs is the lack of passenger and pedestrian comfort considerations. This paper proposes a balanced navigation model for the passenger and pedestrians in terms of social issues regarding wheelchair navigation. The model considers comfort requirements for the passenger and pedestrians and is used to compute social wheelchair paths. Model validation was performed with human participants in the case of a single passenger and a pedestrian where experimental results show that overall comfort should be considered for computing socially accepted paths. Passengers and pedestrians scored the paths computed by the social planner as more comfortable than state of the art shortest paths.

1. Introduction

Powered wheelchairs moving at velocities under 6 km/h are allowed to navigate alongside people and considered as pedestrians by Japanese law. If autonomous robotic wheelchairs are allowed to navigate on pedestrian paths, they must be designed to consider human comfort, that is, the passenger and pedestrians comfort. It is estimated that the world's population over the age of sixty will be doubled by 2050 [1]; the availability of reliable and comfortable autonomous robot vehicles will help providing mobility to the elderly and disabled people promoting equal opportunities for interpersonal interactions and relationships contributing for a healthy society.

In the present there are no general well defined legislations regarding robots [2], still, robots operating in real human environments are required to be safe. Safety is a basic factor to be considered in robotics, but there are also social factors to be considered [3]. The comfort of humans interacting with the robot is crucial given that it determines how human acceptable is the robot. This work presents a human–robot system that considers the human user (passenger) and people around the interaction (pedestrians).

In the literature there are reports of human–robot interactive field research experimentation. For example, robots providing interactive services in museums [4] and shopping services in customer spaces [5]. Also, robots approaching pedestrians in an arcade was reported in [6] and [7]. These robot applications offer services to visitors or customers where research is centered on the robot offering services to targeted humans. There is research in human–robot interactive approaches considering the use of space. For example in [8] human trajectories were extracted to analyze people's typical behaviors. A socially aware motion planner in human-centered environments was presented in [9] and a learning approach for socially-aware robot navigation was presented in [10]; a survey presenting human-aware robot navigation is given in [11]. Recently, an approach for modeling how people feel about territory in order to avoid disturbing possible customers was presented in [12]. The aforementioned works suggest that with the increased deployment of robots in real environments it is necessary to consider human users as the center part of robot development.

One typical example of human–robot interaction is the adequate use of space, specially when navigating from one place to another in human populated environments. This paper reports the use an robotic wheelchair as an example of robots offering services to the users (passengers) while sharing space with outsiders (pedestrians). This work discusses human–robot interaction applied to a self-driving personal passenger vehicle such as a robotic wheelchair. Fig. 1 shows the illustration of the robot user–passenger passing by other people around. The passenger indirectly interacts with other people as they share the same space passing by each other. In this case, the wheelchair should not only center its sensing and processing capabilities to drive safely and comfortably for the passenger, but it should also compute a path to avoid disturbing other people's activities such as walking.

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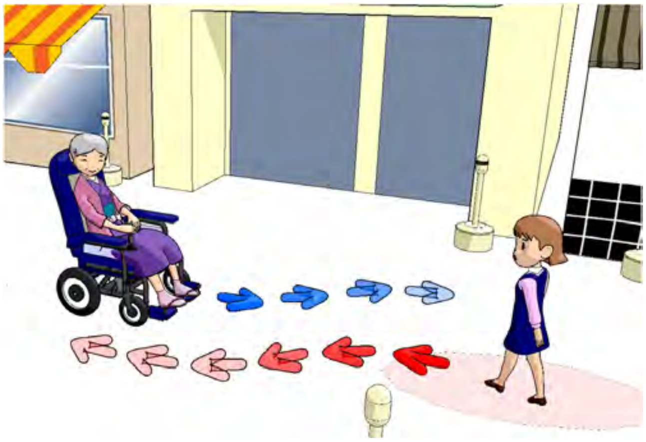

Fig. 1. Illustration of a social robotic wheelchair. A woman comfortably riding her robotic wheelchair while passing by pedestrians in the environment.

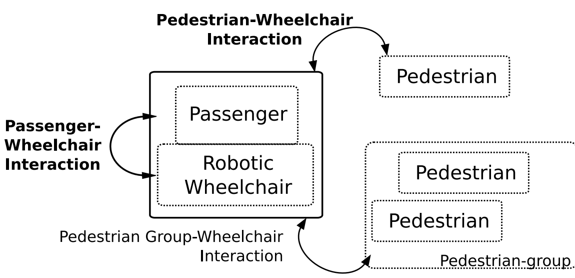

Fig. 2. Passenger–wheelchair–pedestrian navigation interaction. There are three types of interactions with the robot: passenger–wheelchair, pedestrian–wheelchair and pedestrian group–wheelchair interaction.

This paper focuses in the following: (i) Human passenger comfort. (ii) Pedestrian walking comfort. (iii) Computation of robotic wheelchair social paths in accordance to the passenger and pedestrian comfort.

2. Human–wheelchair interaction

As presented in Section 1, robots must consider human preference while planning their actions to keep humans comfortable. This section presents a human–wheelchair interaction paradigm which indicates that besides the robot user (the passenger from now on), it is necessary to consider outsiders (pedestrians). Additionally the relation between human–wheelchair interaction and human comfort is introduced.

A schematic illustration of the human–wheelchair interaction paradigm is shown in Fig. 2. In the paradigm there are three different interactions with the robot. Passenger–wheelchair interaction, pedestrian–wheelchair interaction and pedestrian group–wheelchair interaction. This work presents a study which considers the simplest case with two interactions (in bold letters in Fig. 2): passenger–wheelchair and one pedestrian–wheelchair interactions. Pedestrian group formation falls out of the scope of this work.

2.1. Passenger

This work presents a study centered on a robotic wheelchair where the human user becomes the passenger; therefore, the robotic wheelchair motion should be comfortable for the passenger. In Fig. 1 the woman is the passenger sitting down on the robotic wheelchair.

2.2. Pedestrians

Pedestrians are people who are passing by without having a direct interaction with the passenger or the robotic wheelchair, but notices them. In Fig. 1 the pedestrian is the girl passing by coming from the right.

2.3. Robotic wheelchair

For this work an autonomous robotic wheelchair is utilized to provide transportation to human passengers. Given a global path the robotic wheelchair can localize itself and perform autonomous navigation following the path. This work centers on the global navigation of the wheelchair, therefore, collision avoidance is not utilized; instead the wheelchair is capable to predict its motion, detect possible collisions, slow down and stop in case of imminent collision.

2.4. Navigation comfort

Human comfort is a state of ease, well being and free from stress. It is complicated to have a measurement of comfort given that we are only aware of it when we feel stressed and/or enter the state of discomfort [13,14]. In the work of this paper discomfort factors are minimized to maximize comfort, i.e., we assume that in order to have comfort, uncomfortable situations should be minimized.

There are previous works presenting human-aware robot navigation [11] to avoid uncomfortable situations for humans around the robot. For instance, a motion planner and control approach considering human partner visibility was presented in [15] and a work for human acceptable navigation was presented in [16]. In [17] a model for simulating situations where robot navigates between pedestrians to increase walking comfort is presented. From the point of view of the passenger, there are previous works for computing comfortable paths for the wheelchair [18] and [19] and for dynamic environments the work in [20] presents an approach to smoothly handle moving obstacles in a corridor. The work in this paper considers both cases, the case of a pedestrian walking by the wheelchair and the case of the passenger on the wheelchair.

Regarding pedestrian behavior studies, it has been reported that at low densities people tend to walk close to the center of the corridor, however, as there is people walking in opposite sides in a corridor people tend to choose a side [21]. In the case of lane formation when people walk in opposite sides, people choose a side and tend to walk on the side which is prescribed in vehicular traffic [22]. For instance, in the case of Japan, experimental results suggest that Japanese pedestrians prefer to walk on the left-hand side of corridors [23] which is consistent with vehicle traffic rules. This previous knowledge regarding pedestrian behavior is used to develop the navigation system of this work which is explained in the following section.

3. Wheelchair–pedestrian balanced navigation modeling

This section explains the approach to model wheelchair navigation which takes into consideration the balance between passenger and pedestrian comfort. First the navigation considerations for the passenger on the robotic wheelchair are discussed and comfort factors are presented. Then pedestrian walking flow and walking comfort is discussed. Finally, the approach to model a social navigating wheelchair is explained.

3.1. Passenger comfort

Navigational passenger comfort relates to the feeling of the passenger of not only being safe but feeling free from stress. To

Table 1
Human passenger comfort values.

Parameter	Numerical value
$\dot{x}_{comfortable}$	0.8 m/s
$\dot{\theta}_{comfortable}$	0.6 rad/s
$\ddot{x}_{comfortable}$	0.10 m/s^2
$\ddot{\theta}_{comfortable}$	10 deg/s^2

be comfortable there are studies with robotic wheelchairs that report that the robotic wheelchair motion should be smooth with bounded velocity, acceleration and jerk [24]. In our previous work we have studied and discussed passenger feeling of comfort when riding robotic wheelchair [25]. In this previous work Japanese participants were asked to sit down on a robotic wheelchair and score the level of comfort/discomfort they felt after riding the wheelchair in indoor environments. There were two main findings in the study, a set of robotic wheelchair motion comfort parameters and preferred location within straight corridor environments.

3.1.1. *Wheelchair motion comfort parameters*

The set of motion comfort parameters included wheelchair linear velocity ($\dot{x}$) and acceleration ($\ddot{x}$) and angular velocity ($\dot{\theta}$) and acceleration ($\ddot{\theta}$). The values are summarized in Table 1 for reference.

3.1.2. *Preferred location within straight corridor*

The second finding had to do with the preferred position of the robotic wheelchair in an indoor corridor environment. Experimental results suggested that passengers felt more comfortable to navigate at one side of the corridor leaving the other side free. The model was adjusted to fit equally both sides of a straight corridor without a social rule or preference consideration. In the work reported in this paper the comfort function was fitted as p_{Wc} and is expressed by Eq. (1) where the corridor width (L) is normalized to 1.0. Comfort is also normalized, therefore, more comfortable positions are close to 1.0 and uncomfortable positions are close to 0.0 in the vertical axis.

$$p_{Wc}(y) \propto e^{-U(y)}/\eta \tag{1}$$

$p_{Wc}(y)$ is the comfort of being riding the robotic wheelchair at corridor location y and its graph is shown in Fig. 3. $\eta = 0.604$ is a normalization factor and $U(y)$ is given by the following equation,

$$U(y) = \frac{a}{y} + \frac{a}{L-y} + \left(\frac{y-\delta}{b}\right)^2 \qquad \delta = \begin{cases} c & \text{if } y \le L/2 \\ 1-c & \text{otherwise} \end{cases} \tag{2}$$

where variable y is the current position within corridor's normalized width ($0 < y < 1$), constant c is the preferred position in the corridor. The model can be applied to corridors with normalized width (L) and is shown in Fig. 3 with the following set of parameters: $a = 0.1$, $b = 0.3$, $c = 0.25$ where c indicates the point of maximum comfort.

This result indicates that in the absence of pedestrians, passengers on the wheelchair consider to be at one side of the corridor as slightly more comfortable than in the center. On the other hand, too close to the walls is uncomfortable. This model fits equally both sides of a straight corridor without a social rule or preference consideration.

3.2. *Pedestrian walking comfort*

Pedestrian modeling is complicated given human dynamic characteristics and their usage of space. There are previous studies related to people walking tendencies, for example regarding group formations [26] and regarding behavior of walking [27]. In this work we adopted the pedestrian walking preference model of [23]. This previous work studies the flow of people in indoor Japanese corridor environments and shows that Japanese people prefer to walk at the left-hand side of the corridor (which is also consistent with the traffic convention). The model is given by the equation:

$$p_{Ped}(y) \propto e^{-U_{Ped}(y)}/\eta \tag{3}$$

where $p_{Ped}(y)$ is the comfort of being at location y, parameters are set to match the ones of Section 3.1.2. $U_{Ped}(y)$ is given by the following equation,

$$U_{Ped}(y) = \frac{a}{y} + \frac{a}{L-y} + \left(\frac{y-c}{b}\right)^2. \tag{4}$$

Fig. 4 shows the shape of p_{Ped}. This figure shows that a pedestrian going forward in a corridor will tend to walk on the left-hand side. The further from the left side of the corridor the less comfortable the walk results.

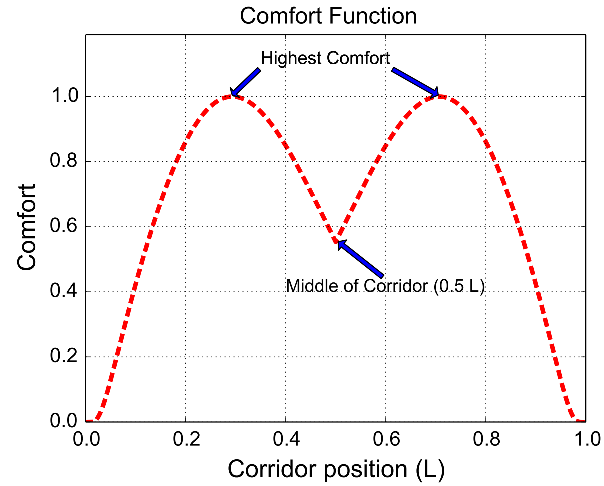

Fig. 3. Comfort model in an indoor corridor environment.

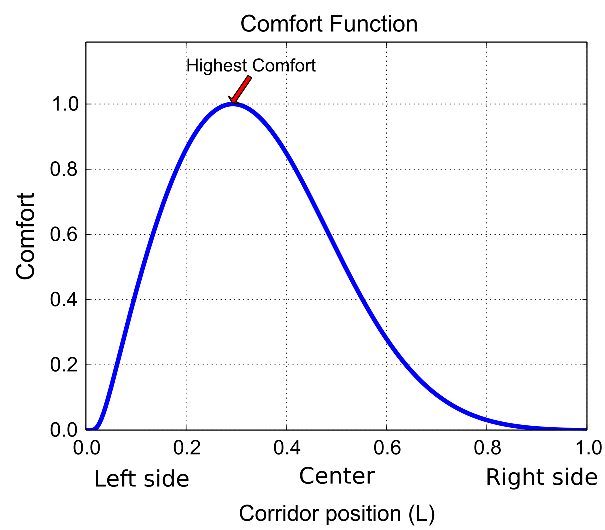

Fig. 4. Pedestrian walking comfort model.

3.3. *Bridging comfort parameters between wheelchair passenger and pedestrian*

This subsection discusses an approach to achieve a balanced navigation wheelchair which takes into consideration the comfort

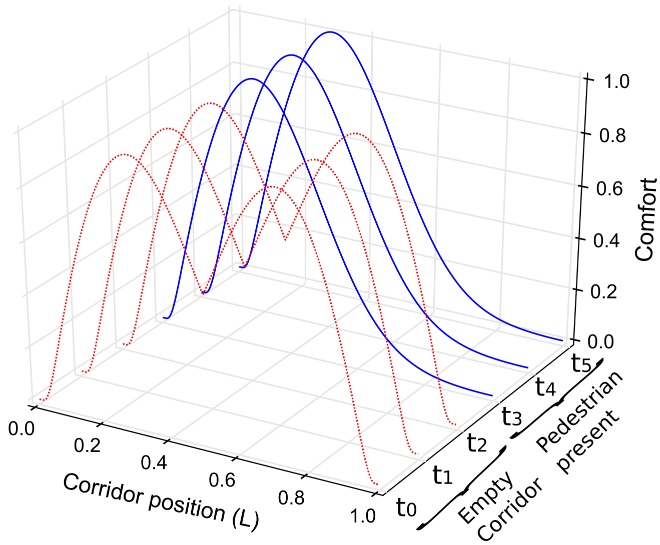

Fig. 5. Comfort model with and without pedestrians.

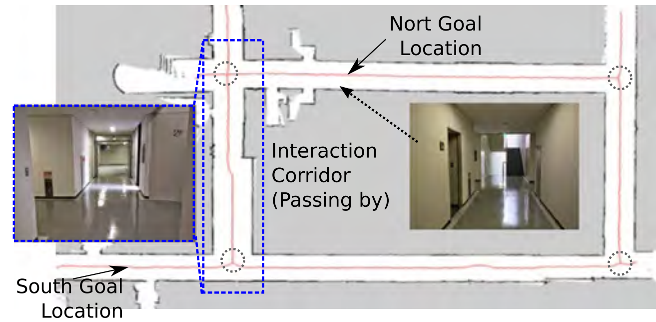

Fig. 6. Indoor corridor environment and its topology. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the passenger and the walking comfort of a pedestrian. The points to be considered in each case are discussed and a balanced navigation comfort model is proposed.

3.3.1. Considerations for the passenger

For the wheelchair passenger the points to be considered are itemized below:

- The wheelchair should follow paths smoothly with bounded velocities and accelerations and zigzag [24].
- Bounded velocities and accelerations are given in Table 1.
- Passengers prefer the wheelchair to navigate at one side of the corridor even in the absence of pedestrians [25].

3.3.2. Considerations for pedestrians

The points to be considered for the pedestrians are:

- Navigate at human traffic-like velocities (humans walk around 1.0 m/s in non-rush hours [21]).
- Avoid zigzag motion effects to avoid pedestrian changing their trajectories (pedestrians have a preferred velocity directed along the corridor [23]).
- Avoid invasion of pedestrian lanes and necessity of avoidance action.

To satisfy these conditions the approach of this paper proposes to model empty corridors with the model of Eq. (1) and corridors with pedestrians with Eq. (3). These equations applied to real corridor environments can be used to compute cost maps to search for comfortable social paths. An illustration of corridor comfort function with and without pedestrians is shown in Fig. 5. The figure shows the comfort of being at certain locations of the corridor (L) depending on the situations at time t. In times t_o, t_1 and t_2 the comfort when there are no pedestrians is showed in red dotted lines. At times t_3, t_4 and t_5 the function in presence of pedestrians is shown in solid blue lines. The approach to apply these functions to build costamps of real environments and compute comfortable social paths is explained in the following section.

4. Experimental method

This section presents the approach to build a navigation system centered on an autonomous wheelchair while passing by pedestrians. The navigation system computes a global path based on a cost map built on top of a geometric map using the model of Section 3.3. A graph based search algorithm (Dijkstra) is used to search for a path based on the human preference cost map. Finally, the motion planner to achieve smooth wheelchair navigation is explained. All the softwares were implemented in the ROS Navigation stack framework [28].

4.1. Extracting corridor information

Real world environments have different types of irregularities, i.e., they do not present completely straight corridors with regular widths. This study centers in modeling straight corridors, therefore, this section presents an approach for corridor width computation based on topological information.

First we extracted the extended Voronoi graph using the algorithm proposed in [29] and computed the nodes and edges of a grid map. The resulting graph node density depends on the resolution of the grid map and the parameters of the width of the robot provided, the wider the robot, the less nodes that will be computed. An example of an indoor corridor environment is shown in Fig. 6. The environment grid map was built with SLAM [30] and its topology is shown in red lines. To compute the width of the corridor the following approach was used:

1. Join two consecutive nodes by straight lines.
2. Compute the angle between consecutive nodes and compute the normal angle.
3. Edges in the topology are formed by cells in the grid map. For each edge cell perform ray-tracing in the direction on the normal until a hit is detected.
4. Compute the distance to the hit or wall (ignore hits to unknown grids in white).
5. Average the distance of all the edge points to the wall between two nodes to obtain the corridor width average (L) of that segment.

4.2. Building a social cost map

As the direction of movement is relevant to choose the side of the corridor to traverse if Eq. (3) is to be applied, the cost map is built depending on the start and goal locations (model of Eq. (1) is independent from moving direction). First, the start and end nodes on the topology are chosen, then the shortest path in the topological graph is computed. As the corridor width L between two nodes was previously computed, the model equation (1) is applied for corridors without pedestrians and Eq. (3) was applied for corridors with pedestrian flow. Comfort model equations were applied to each free cell (white cells in Fig. 6). At the end of the

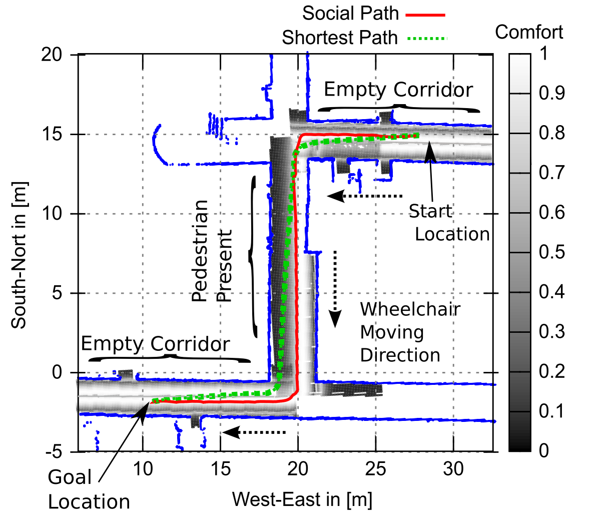

Fig. 7. Indoor experimental evaluation environment where two paths going from north-east to south-west were computed. The social path is shown in bold line and the shortest path in a dotted line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

process each cell's weight is averaged with neighboring cells. The resulting cost map of Fig. 6 when a path starts at the north-eastern part and finishes at the south-west part is shown in Fig. 7.

Comfort equation (1) was applied to the corridors in the north and south sections. These corridors were modeled as empty where the wheelchair equally navigates at the right or left side of the corridor. Comfort equation (3) was applied to the corridor going from north to south where the left-hand side of the corridor is more comfortable than the right-hand side.

4.3. Path planning

We implemented the social cost map as a ROS cost map plugin [31]. Global paths are computed with a standard global planner (Dijkstra) implemented in ROS navigation stack. An example of a social path starting in the north-east corridor and ending in the south-west corridor is shown in red bold lines in Fig. 7.

4.4. Path following with bounded velocities

To avoid zigzag effects, the motion planning of the robotic wheelchair used in this work is based on a closed loop controller for power wheeled steering non-holonomic vehicles with bounded parameters [32] (see Table 1 for comfort parameters). We chose not to use the dynamic window approach in ROS navigation stack given that in the case of proximity to obstacles the wheelchair entered obstacle avoidance mode producing unwanted jerking. From the point of view of the passenger these movements without intuitive explanation are rather uncomfortable.

At the very low level we implemented a safety system which is a simplified version of the dynamic window approach [33] that predicts robot's future possible trajectories, slow down and stop the robot in the case of imminent collision.

5. Experimental procedure, results and discussion

This section explains the experimental procedure to evaluate the navigation framework considering passenger and a single pedestrian comfort. First the robotic wheelchair utilized is described, then the procedure is detailed and finally the results are presented. A discussion regarding experimental results and future works is provided.

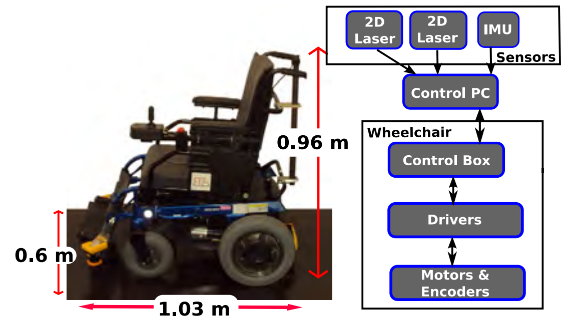

Fig. 8. Autonomous robotic wheelchair equipped with wheel encoders, laser sensors, and inertial measurement unit.

5.1. Robotic wheelchair

The robotic wheelchair used for experimentation is a differential drive powered wheelchair from IMASEN (EMC-250) which is equipped with wheel encoders, two laser sensors (Hokuyo UTM-30LX) and an inertial measurement unit (*VG*400 from crossbow), see Fig. 8. The dimensions of the wheelchair are, width: $R_w = 0.66$ m, length: $R_l = 1.03$ m and height: $R_h = 0.96$ m and it can run at a maximum velocity of 1.6 m/s. The laser sensors are used for map-building, localization, and the IMU sensor to measure accurate angular velocities and the wheel encoders to measure wheel linear velocity. This robot was utilized for the experimental procedure described below.

5.2. Experimental procedure

The quantitative experiments were performed in an indoor environment free from moving obstacles and people (see Fig. 7 for reference). In the experiments participants were called to sit down on the robotic wheelchair and to walk in the corridor passing by the robotic wheelchair.

We called thirty Japanese people (15 females and 15 males whose average age was 22) and were paid for their participation. We used pairs of participants to perform the comparison between social and shortest planned paths. One participant sat on the robotic wheelchair and the other one walked.

The wheelchair was programmed to follow two different conditions of pre-computed global paths:

1. Global paths computed with the standard global planner (Dijkstra) of ROS navigation stack with obstacle inflation set to 0.85.
2. Global paths computed with the proposed social cost map of Section 3 and following the procedure of Section 4.

In both conditions the motion planner of Section 4.4 was utilized. The wheelchair ran from a start to a goal location (Fig. 7) in both directions, north to south and south to north. In a similar manner, the walking participant walked from a start point to a goal point in opposite direction of the wheelchair. The main interaction or passing by between the robotic wheelchair and pedestrian occurred in the central corridor of Fig. 7.

Each participant rode the wheelchair two times, once with the social planner and once with the shortest path. Also, each participant walked towards the social planned wheelchair once and towards the shortest path wheelchair once. Experimental conditions were counter-balanced to avoid order bias regarding direction of movement and paths tested.

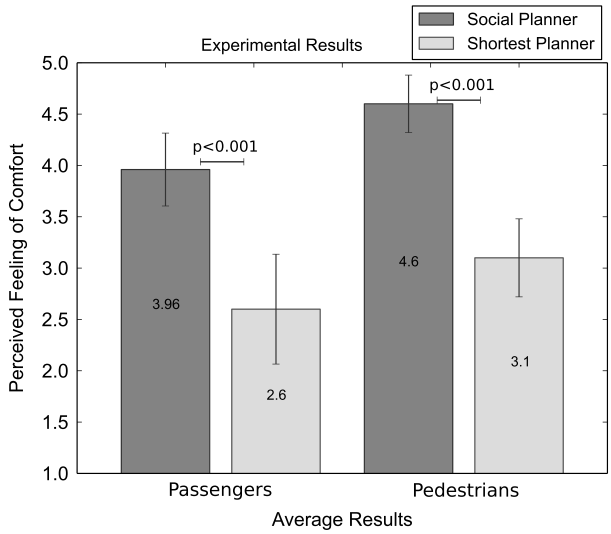

Fig. 9. Experimental results showing the scores of passengers and pedestrians while riding the wheelchair and walking in two conditions: with the social path and the shortest path.

At the end of each run we gave the wheelchair passenger participant and the pedestrian participant a questionnaire in which we asked them to rate how comfortable they felt as they passed by each other from a scale from 5 to 1 with larger values being the most comfortable. The passenger scored the navigational comfort of riding the wheelchair and the pedestrian rated the walking comfort of passing by the robotic wheelchair.

5.3. Experimental results

Experimental results are shown in the graphs of Fig. 9. The run the wheelchair navigated through the social path resulted to be more comfortable for passing by pedestrians with an average value of 3.96 compared to the shortest path framework with an average of 2.6. Average result values with confidence level interval bars are shown in Fig. 9. A t-test revealed that for the passenger, the higher score of the social paths had statistical significance ($F(5.82, 58) = \rho < 0.001$).

Experimental results show that pedestrians found the social path more comfortable than the shortest path. The proposed approach was scored with an average value of 4.6 and the shortest wheelchair path with an average value of 3.1. The t-test showed that pedestrian higher score has statistical significance ($F(6.83, 58) = \rho < 0.001$). In both cases participants scored the walking as comfortable, as the wheelchair ran at a moderate velocity of 0.8 m/s which is slightly slower than human average walking velocities (around 1.0 m/s in non-rush hours [21]). The higher score of the social paths condition indicates that people preferred to stay in the left side of the corridor instead of having to switch sides caring of the trajectory of the robotic wheelchair. In both cases there were no collisions between pedestrians and the robotic wheelchair. In the shortest path case the wheelchair had to stop five different times as the safety algorithm activated when the pedestrian passed too close to it.

Finally, we performed a field demonstration of the proposed method in a Japanese retirement home. The purpose of the demonstration was to observe the pragmatic value of the proposed method in a real environmental context. The environment is shown in Fig. 10. It can be noticed that in more real scenarios corridors are not perfectly straight. Yet, with the proposed approach details of Section 4 comfort cost maps to compute social paths could be built assuming straight corridors.

In this environment as there are pedestrians passing by regularly, the pedestrian model of Eq. (3) was used. Examples of path computations are shown in Figs. 11 and 12. In this experimentation, the staff of the retirement home was not given instructions on how to pass by the wheelchair, still, as far as pedestrians notice that the robotic wheelchair moves at one side of the corridor (in this case left-side), they open space and walked at the opposite side (to their left).

An example of the cost map and the paths of going from northeast corridor to south-east corridor are shown in Fig. 11. The social path is shown in bold red line and the shortest computed path in green. The social path stays on the left side of the path all the way. It can be seen how the green path, even if shorter, will traverse the corridor in diagonal which can result in blocking pedestrians passing by paths.

Another example of cost map and path computation is shown in Fig. 12. In this case, resulting social and shorter paths are similar, however, social path stays on the left lane from start to goal.

5.4. Discussion

The comfort model of this work can only be applied to build social cost maps in straight corridors. At turns in corner or intersections un-modeled grid cell values were assigned a value averaging with neighboring cell values, however, an extension of the model to properly cope with turns is necessary. Also, the outside sections of turns are not modeled as the current method cannot compute corridor width at turns.

The safety system presented in this work can detect and stop the robot in case of imminent collision but it cannot avoid obstacles. A social local planner or social collision avoidance approach needs to be built in order to handle populated environments where pedestrians could be blocking the way.

6. Conclusions and future work

This paper proposed the design of a social robotic wheelchair considering both points of view, the wheelchair passenger and pedestrians around to compute socially accepted paths. A model of human–robot interaction between a robotic wheelchair, a passenger and a pedestrian was proposed where preference parameters reflecting comfort requirements for passengers and pedestrians were discussed. Using comfort scores, a social cost map was built on top a geometric map to compute social paths. Experimental results show that both, the passenger and the pedestrian found the robotic wheelchair following social paths more comfortable than state of the art computed shortest paths.

This paper focused only on the relationship between the robotic wheelchair, the passenger and a pedestrian. It is left for future work to consider study cases with multiple people and model wheelchair behavior when facing multiple pedestrians. The study of human–human interaction influence on wheelchair navigation such as passenger–pedestrian and pedestrian–pedestrian interactions is open for future study.

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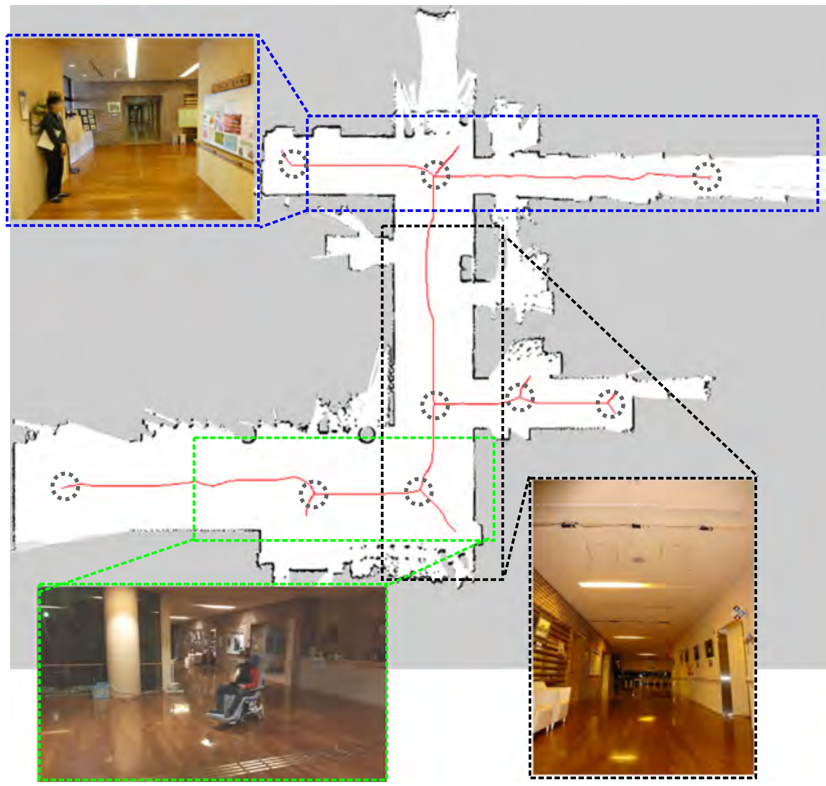

Fig. 10. Grid map of a corridor environment in a private care center in Japan. The red lines show the extended Voronoi graph of the map. Gray dotted circles are the nodes that constitute the topology of the environment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

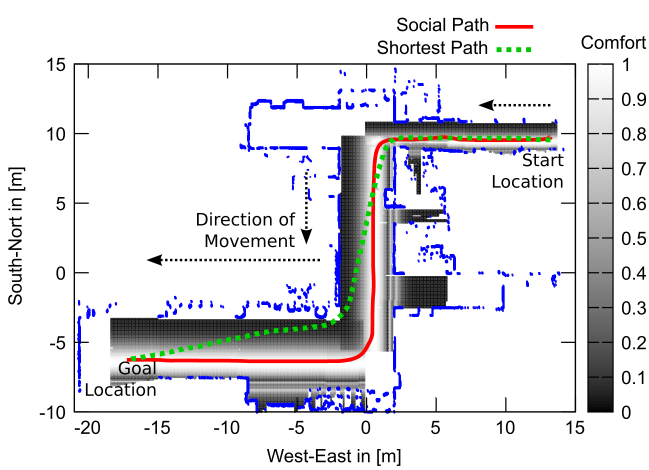

Fig. 11. Two different paths going from north-east to south-west computed with a Dijkstra planner. The social path at the left of the corridor is shown in solid red and the shortest path in a dotted green trajectory.

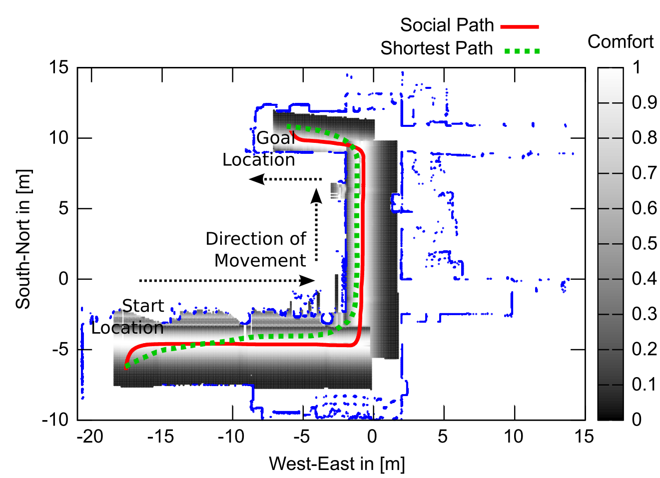

Fig. 12. Social (in solid red) and shortest (in dotted green) paths going from south-west to north-west. In contrast to the shortest path, the social path stays on the left lane from start to goal location.

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