2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

# Human-Comfortable Navigation for an Autonomous Robotic Wheelchair

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*Abstract*— **Reliable autonomous navigation is an active research topic that has drawn the attention for decades, however, human factors such as navigational comfort has not received the same level of attention. This work proposes the concept of "comfortable map" and presents a navigation approach for autonomous passenger vehicles which in top of being safe and reliable is comfortable. In our approach we first extract information from users preference related to comfort while sitting on a robotic wheelchair under different conditions in an indoor corridor environment. Human-comfort factors are integrated to a geometric map generated by SLAM framework. Then a global planner computes a safe and comfortable path which is followed by the robotic wheelchair. Finally, an evaluation with 29 participants using a fully autonomous robotic wheelchair, showed that more than 90% of them found the proposed approach more comfortable than a shortest-path state of the art approach.**

## I. INTRODUCTION

Autonomous navigation has been an active topic in robotics for decades. Navigation in indoor environments has been vastly studied producing fully autonomous systems in dynamic environments such as [1] in museums and [2] in supermarket environments. Also, research in recent years has produced fully autonomous navigating outdoor robots that can ask for directions to arrive to their destinations [3] and systems that can navigate recognizing and describing urban spaces [4]. Research regarding autonomous navigation for passenger vehicles has also being addressed; in the shape of robotic wheelchairs [5] and cart robots. Moreover, the DARPA Grand and Urban Challenges systems showed that long term navigation is feasible with current technology.

In the state of the art for autonomous navigation, robotic systems compute their position towards environmental maps previously built with SLAM techniques [6][7], plan their paths from their current position to desired goals, detect and avoid obstacles [8][9] and perform motion planning to arrive to the destination. All of these systems achieved collision free ("safe") navigation, however, "human comfort factor" for navigation has almost not received attention.

There are works regarding human-wheelchair collaboration in which navigational assistance is provided for the driver in real time generating safe trajectories [10], adapting to the variations of user performance [11] and with haptic guidance algorithms [12]. Differently from these works, this paper is centered in the elaboration of an environmental comfort model.

This research was supported by the Ministry of Internal Affairs and Communications with a contract entitled 'Novel and innovative R&D making use of brain structures." All the authors are with the Advanced Telecommunications Research Institute International, Kyoto, Japan

Only few works have addressed the importance of human comfort in passenger vehicles. An omni-directional mobile wheelchair with an haptic joystick for operation considered user's comfort and safety in [13] as a man-machine system. In [14], grace motion for a robotic wheelchair was defined as safe, smooth, fast, and intuitive. In a later work, Gulati et. al. in [15], defined a measure of discomfort as a weighted sum of total travel time and time integrals. Their method searches for trajectories in static environments minimizing discomfort and satisfying pose, velocity and acceleration conditions. Later, a model for dynamic environments was proposed in [16] where navigation is defined as a continuous decision making process in the receding horizon. The model outputs a trajectory which satisfies a probabilistic cost function, however, a definition and an evaluation of comfort is not provided. In these three works, experimental results were based on computer simulation, the implementation on an autonomous vehicle was not realized and human subject comfort evaluation was not performed.

Car industry has addressed the comfort factor for passenger vehicles from the point of view of suspension stiffness, seats, interior temperature, spacing and looks. Nevertheless, research towards navigational comfort for passengers has not been studied, specially in the field of autonomous navigation. Traffic safety addresses safety parameters towards vehicles and pedestrians, whereas traffic comfort is considered to be achieved by having well maintained wide roads and sidewalks for the users [17].

The contributions of this paper are twofold: the proposal and creation of a Human-Comfort Factor Map ("HCoM") extracted from human preference and a framework to achieve human safe and comfortable navigation for passenger vehicles where navigation paths are computed from the HCoM. Experimental results confirm the advantage of the HCoM for computing comfortable paths which can not be created by standard geometric maps, moreover, an evaluation with human participants show their preference of HCoM computed paths in a comparison towards computed shortest paths.

## II. HUMAN-COMFORT AND COMFORT FACTOR FOR AUTONOMOUS NAVIGATION

This section explains a navigational framework for human comfortable navigation. First we define the concept of human-comfort and explain the factors involved in it. Then the robotic wheelchair used in this work is introduced.

Finally, navigation-comfort factor extraction is explained and a model for human comfort for navigation in an indoor corridor environment is proposed and explained.

### A. Human-Comfort and Comfortable Navigation

In this work, we define human-comfort as a state of ease; thus, human-comfortable navigation implies vehicle's motion that on top of being safe is free of anxiety and distress. The rest of the section explains what factors impact the human comfort and provides a model with numerical values extracted from people's preference.

### B. Navigation Comfort Factors

Fig. 1 shows a conceptual graph of the comfort state space which represents the different states achievable during navigation. The space is composed of unsafe, safe and comfort spaces. The unsafe space (blue) includes collision region and vehicle over specification regions. The safe space (blue to yellow) is the region where the vehicle is collision-free and encompasses the comfort and discomfort spaces. The comfort region (in yellow) represents the space where the human passenger feels safe and comfortable. The darker regions represent the space which is safe but not comfortable. The bottom left shows the discomfort of traveling very close to obstacles and the top left represents the "fear" of traveling close to obstacles at very high velocities. The region at the top right represents the discomfort of traveling at very high velocities and bottom right region is the discomfort or anxiety as the vehicle travels at very low velocities even without hazards around it. Fig. 1 shows that safe navigation without comfort is feasible, however, comfort without safety is not. It also shows that comfort space is not achievable by simply maximizing distance towards obstacles and minimizing time of travel (maximizing velocities and accelerations).

To build a HCoM and the comfortable navigation framework of this work we define the comfort factors listed below:

- $d_h$: euclidean distance towards obstacles: It is the distance from the center of mass of the human (wheelchair) to the closest object.
- $\dot{x}$: linear velocity of the wheelchair.
- $\dot{\theta}$: angular velocity of the wheelchair
- $\ddot{x}$: linear acceleration
- $\ddot{\theta}$: angular acceleration

### C. Robotic Wheelchair

In this work we use a differential drive robotic wheelchair from IMASEN (EMC-250) which is equipped with wheel encoders, two laser sensors (Hokuyo UTM-30LX) and an inertial measurement unit ($VG400$ from crossbow), see Fig. 2 for reference and Fig. 8 for data processing flow. The dimensions of the wheelchair are, width: $R_w = 0.66$ $m$, length: $R_l = 1.03$ $m$ and height: $R_h = 1.0$ $m$ and it can run at a maximum velocity of 1.6 $m/sec$. The laser sensors are used for map-building, localization, corridor wall detection and the IMU sensor to measure accurate linear accelerations and angular velocities and the wheel encoders to measure linear velocity and angular accelerations.

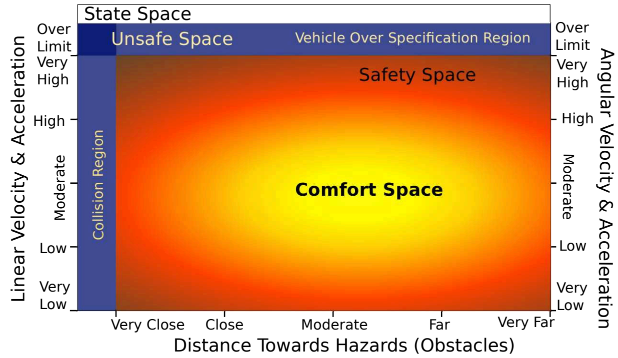



Fig. 1. Navigation space state is subdivided in unsafe, safe and comfort space. The unsafe space in blue includes the collision region and the vehicle over specifications region. The safe space includes the uncomfortable (orange) and comfortable (yellow) spaces. It is clear that there can be safe navigation without comfort but comfortable navigation without safety is not feasible.

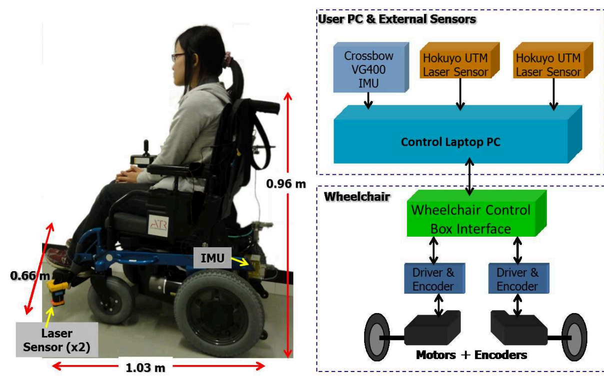



Fig. 2. Autonomous robotic wheelchair equipped with wheel encoders, three laser sensors, and an inertial measurement unit.

### D. Navigation Comfort Factor Extraction

To extract the numerical value of each comfort factor, we performed two experiments with human participants on an autonomous navigating wheelchair. The experiments had a within-subject design and 22 Japanese people (11 females and 11 males whose average age was 23.53) were paid for their participation. Participants were asked to sit down on the wheelchair while it autonomously drove itself in two different scenarios.

*1) Straight Corridor Environment Experiment:* We performed wheelchair navigation experiments in an indoor straight corridor (Fig. 3(a)) to extract comfortability preferred parameters related to linear velocity ($\dot{x}$) and distance towards corridor walls ($d_h$). The experiment involved the following steps:

a) The wheelchair drove in straight line (corridor line following) in nine different parameter combinations. With three different velocities ($\dot{x}$): Low (L) 0.8 $m/sec$, medium (M) 1.2 $m/sec$ and high (H) 1.6 $m/sec$ and three different distances ($d_h$): Close (C) 0.525 $m$, medium (M) 0.84 $m$ and far (F) 1.20 $m$ ; these distances represent the 20%, 35% and 50% of the width of the corridor.
The distance of the edge of the wheelchair ($d_e$) to the

wall is given by $d_e = d_h - \frac{R_w}{2}$

b) Every participant was given a questionnaire, and at the end of each run they evaluated how comfortable-uncomfortable it was from a scale from 5 to 1 with larger values being the most comfortable.

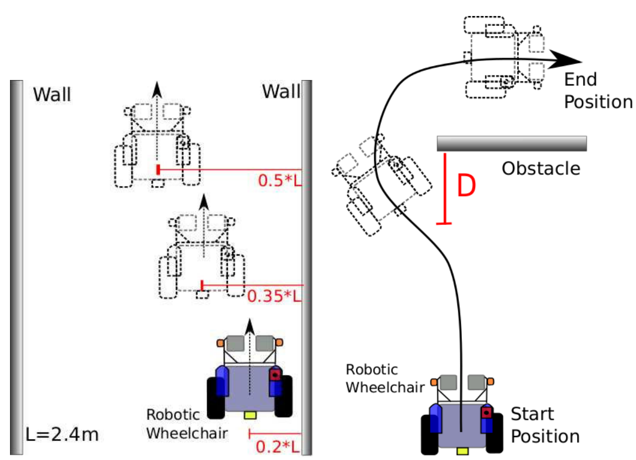
*2) Vehicle Turning Experiment:* In this second experiment we extracted parameters related to angular velocity ($\dot{\theta}$) and angular acceleration ($\ddot{\theta}$) while the wheelchair turned around an obstacle (Fig. 3(b)). The experiment involved the following steps:

a) The wheelchair drove autonomously while avoiding an obstacle in its path. To avoid factors due to imminent collision towards a harmful object, the obstacle was a small wall made of cardboard boxes.

b) The wheelchair navigated in nine different running sets at three different linear velocities: Low (L) 0.8 $m/sec$, medium (M) 1.2 $m/sec$ and high (H) 1.6 $m/sec$ and at three different distances (angular velocities) from the wall: Close (C) 0.2 $m$, medium (M) 0.5 $m$ and far (F) 0.8 $m$.

c) Finally, each participant evaluated the comfortability of each run from a scale of 1 to 5.

The experimental results are shown in Figures 4(a) and 4(b) and the preferred values extracted for each parameter are listed in Table I. An interesting result was that participants found the wheelchair running at 35% of the corridor (leaving half of it empty) was more comfortable than at the middle of it (peaks in figure 4(a)). After interviewing participants about this issue, they mentioned that it was more comfortable (even if riding a wheelchair) to leave half of the corridor empty so that they would not interfere in the case there were other people walking in the corridor.




(a) Extracting linear velocity and distance to wall in a corridor. (b) Extracting comfortable angular velocity.

Fig. 3. Experimental setup for human factor extraction.

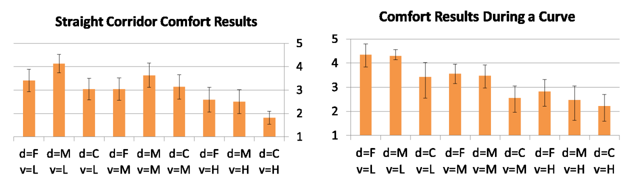
### E. Modeling Comfort

We model navigational comfort in a straight corridor environment in terms of distance from the wall and linear velocity by the energy expression (1):

TABLE I

COMFORTABILITY VALUES

| Parameter | Numerical value |
|---|---|
| $d_h$ | 0.84 $m$ (0.35 $*L$) |
| $\dot{x}_{comfortable}$ | 0.80 $m/sec$ |
| $\dot{\theta}_{comfortable}$ | 30.0 $deg/sec$ |
| $\ddot{x}_{comfortable}$ | 0.10 $m/sec^2$ |
| $\ddot{\theta}_{comfortable}$ | 10 $deg/sec^2$ |




(a) Wall following experimental results. (b) Box obstacle avoiding experimental results.

Fig. 4. Comfort factor extraction results.

$$U(d_h, \dot{x}) = 1 - \left(\frac{c_a \dot{x}}{d_h} + \frac{(\dot{x} - V_o)^2}{c_b^2} + \frac{(d_h - k_o L)^2}{c_c^2}\right) \quad (1)$$

This function has a maximum value (maximum comfort) in $V_o$ and $K_o L$ as it increases with velocities different from $V_o$ and distances different from $K_o L$. This comfort model takes into consideration velocity and distance to the wall as an extended version of pedestrian walking model proposed in [18]. Parameter $V_o$ is the preferred velocity, $K_o L$ is the preferred position within the corridor, $K_o$ is a percentage value and $L$ is the width of the corridor, $\dot{x}$ is the velocity variable, $d_h$ is the variable corresponding to the distance of the center of the human sitting on the wheelchair to the closest wall of the corridor. $d_h$ is constrained by $d_h > \frac{R_w}{2}$ where $R_w = 0.66\ m$ is the width of the robot. $d_h$ values smaller than $\frac{R_w}{2}$ (unsafe space) are non-feasible given that the wheelchair would be colliding to the wall. $c_a$ is the constant related to the trade off between velocity and distance and determine the minimum value, $c_b$ is the constant that determines the value of the weight of velocity and $c_c$ represent the weight of the position of the wheelchair within the corridor.

To model comfort we used the normalized values of table I and performed a regression analysis to determine the constants of expression (1) obtaining a the following values of $c_a = 0.040$, $c_b = 1.08$ and $c_c = 0.679$

The comfort is modeled as a convex function with a maximum at values of $V_o = 0.8$ and $K_o = 0.35$ which is at a distance of the human to the wall of $d = 0.84m$. This distance leaves half of the corridor free for other pedestrians or wheelchairs to pass by.

## III. BUILDING A COMFORT MAP

Comfort factors were added to a geometric map built by the robot sensory data where a global path is planned on a "comfort map" with a cost function that maximizes

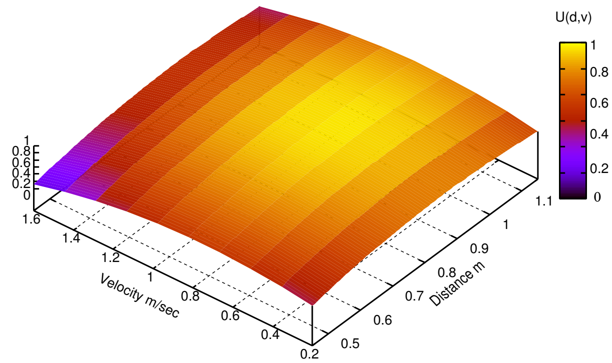



Fig. 5. Comfort model of an indoor straight corridor.

comfortability. The comfort map building is composed of two steps: the generation of a geometric map and the process to add human-comfort factor to the map and create a HCoM.

### A. Geometric Map Building

The geometric map of the environment is built via SLAM and stored as an occupancy grid map [19] where the cell resolution of the map is of 0.05 $m$ (Fig. 6). Each cell of the map has one of three states: occupied, free and un-explored.

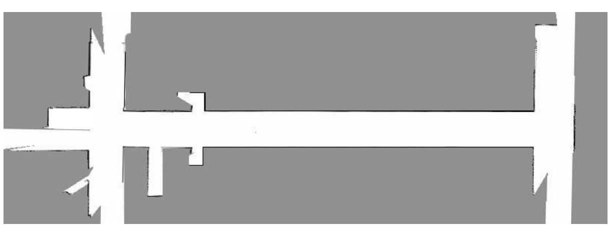


Fig. 6. Geometric grid map of an indoor corridor environment created via SLAM.

### B. Human Comfort Enhanced Map

This section explains the process to add comfort to the geometric map as the robot navigates the corridors of an environment.

To embed comfort factor in a geometric map, the velocity factor was not considered, and expression (1) is simplified to an energy function $U(d_h)$ with a single distance from the corridor variable as follows:

$$U(d_h) = 1 - \left(\frac{g_a}{d_h} + \frac{(d_h - k_o L)^2}{g_c^2}\right), \tag{2}$$

where: $d_h$ is the variable corresponding to the distance of the center of the human sitting on the wheelchair to the closest wall of the corridor. $d_h$ values smaller than $\frac{R_w}{2}$ mean that the wheelchair has collided to the wall (see the black color in Figures 7(a) and 7(b) for collision areas). Finally, the numerical value of the constants are $g_a = 0.009$ and $g_c = 0.363$. The steps to detect a straight corridor from laser data and the process to add human-comfort factor is described in Algorithm 1. Algorithm 1 can be applied on real time with a robot navigating in a straight corridor environment with a map of it. For the Straight corridor extraction is performed in local coordinates, then, it is converted into the global coordinate frame where corridor walls are matched with the map and comfortability is added in free cells according to expression 2. The algorithm can also be used off-line with a virtual agent running through the straight corridors in the map. We did not add the velocity parameter in the map and did not involve it in the path planning process, instead, we bounded the velocities of the wheelchair in the motion controller of Section IV-B.

The result of Algorithm 1 applied to Fig. 6 is shown in Fig. 7(a) as an enhanced comfort map. Fig. 7(b) shows the comfort map with an obstacle (light blue) 1.20 $m$ of length at 0.83 $m$ distance from the wall of the bottom.

**Algorithm 1** Adding comfort to a geometric grid map:

**Input:** Point cloud ($n_p$ points), grid map and global position
**Output:** Global HCoM

```
for all n_p points do
    group in n_c clusters neighboring points within 0.05 m
end for
for all n_c clusters do
    apply principal component analysis to detect n_l straight lines
end for
for all n_l lines do
    detect n_p pairs of parallel lines (corridor segments) whose distance is ≥ R_w (width of robot)
end for
for all n_p segments do
    vote into the grid map in n_f free cells
    occupied and unexplored cells are not considered
end for
for all n_f free cells do
    compute d_h(x) as the the distance from the cell x to the closest wall
    apply expression (2) to obtain comfort U(d_h(x))
    add comfort value U(d_h(x)) to free cell x
end for
return Comfort enhanced grid map
```

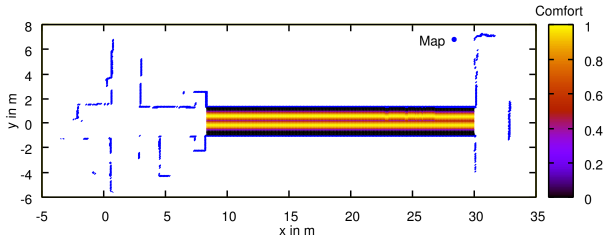
## IV. Comfortable Navigation Framework

### A. Global Path Planning Using $A^*$

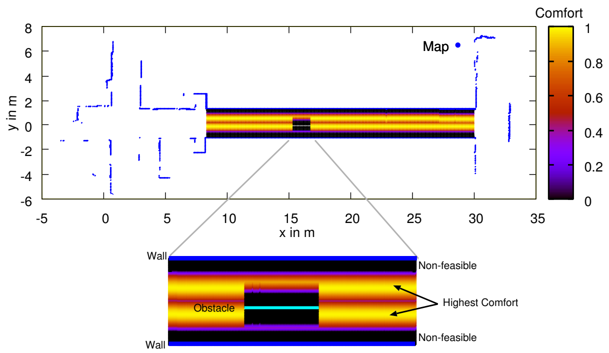
We use $A^*$ algorithm [20] to compute comfortable paths from a start to a goal location. The cost function of node $x$ is the sum of three functions given by the next equation:

$$f(x) = k_D(g(x) + h(x)) + (1 - k_D) m_{disc}(x) \tag{3}$$

where $g(x)$ is the distance of the starting node to current node $x$, $h(x)$ is the distance from node $x$ to the goal and $m_{disc}(x)$ is the discomfort cost of taking the path through node $x$ where $m_{disc}(x) = 1 - U(d_h(x))$ is the discomfort value of traversing through cell $x$. Parameter $k_D = 0.50$ is a weighting coefficient due to distance and discomfort. The path planner minimizes the cost function of equation 3, to compute short-comfortable paths for the wheelchair navigation.




(a) Comfort map of a straight corridor environment.




(b) Comfort map of a straight corridor environment with an obstacle.

Fig. 7. Human-comfort Map (HCoM). The darker colors (black and purple) show the areas with less comfortability and lighter colors show the regions with more comfortability (orange and yellow).

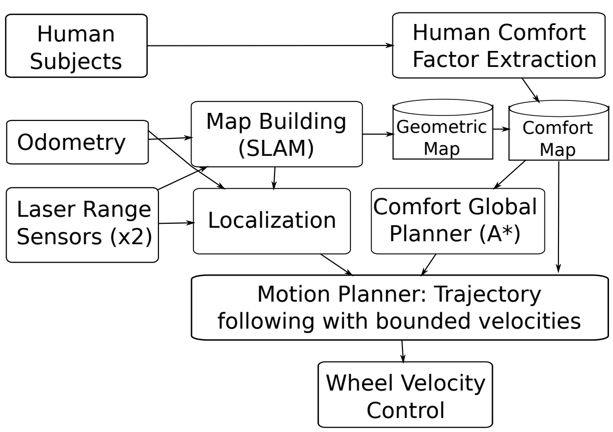



Fig. 8. Block diagram of the proposed comfortable navigation framework.

Fig. 9 shows a comparison of a path computed by a shortest distance based $A^*$ planner (gray bold dotted line) and the path computed by the $A^*$ on the HCoM proposed in this work (red bold dotted line). It can be seen that the shortest path produces a path which almost follows a straight line. Our proposed approach produces a path which goes around the obstacle in the corridor which is longer and more complicated to follow but "more comfortable". The evaluation of these paths is presented in Section V-C.

### B. Path Following Module with Bounded Velocities

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

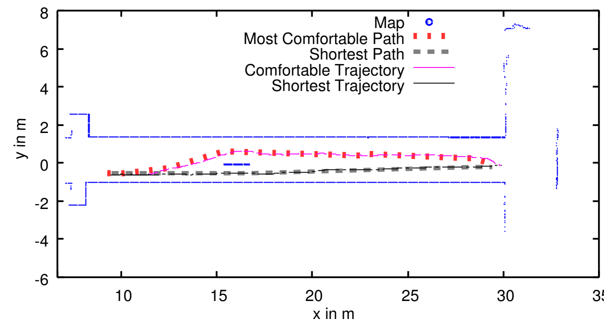



Fig. 9. Paths provided using an $A^*$ path planner in bold dotted lines and the trajectories followed by the wheelchair in thin solid lines. The gray line shows the path using only distance constraints and in red line is the path computed considering distance and comfort constraints. The black line shows the trajectory while following the shortest path and the magenta line shows the trajectory while following the comfortable path.

[21] (see Table I for comfortable parameters).

The linear velocity of the robotic wheelchair is given by:

$$\dot{x}(t+1) = \dot{x}_{ref} - c_1|\dot{\theta}(t)| \quad (4)$$

and the angular velocity $\dot{\theta}$ of the wheelchair is computed by:

$$\dot{\theta}(t+1) = \dot{\theta}(t) + \Delta t(-k_1\eta(t) - k_2\phi(t) - k_3\dot{\theta}(t)) \quad (5)$$

where $c_1$, $k_1$, $k_2$ and $k_3$ are constants and $\Delta t$ is the sampling time, $\eta(t)$ is the normal distance to the path to follow and $\psi(t)$ is the angle to the path to follow. The computed linear and angular velocities $\dot{x}(t+1)$ and $\dot{\theta}(t+1)$ are bounded by $\dot{x}_{comfortable} + \dot{x}_{comfortable} * 0.2$ and $\dot{\theta}_{comfortable} + \dot{\theta}_{comfortable} * 0.2$ respectively.

## V. System Evaluation

Experiments were held in an indoor straight corridor environment where the proposed approach was evaluated and compared towards a state of the art shortest path navigational approach.

### A. Hypothesis and Prediction

We conducted an evaluation experiment to confirm that the proposed navigation framework of Fig. 8 works as designed, and compared how would people find it towards a traditional approach.

Prediction: since the navigation framework proposed in this work outputs human comfortable paths, people on the wheelchair should find this navigation more suitable than navigation based on distance constrained paths.

### B. Experiment Design

Twenty nine Japanese people (15 females and 14 males whose average age was 21.8) were paid for their participation. We explained participants to sit down on the wheelchair while it autonomously navigated in an straight corridor environment with an obstacle (Fig. 10). from a start to a goal locations. Two approaches were evaluated: navigation by the proposed comfortable framework and navigation by the path resulting from a short distance constrained planner.

At the end, participants were asked to fill in a questionnaire to evaluate the two different presented approaches in a scale from 1 to 5 where the highest value corresponds to the most comfortable one.

### C. Results

The path the wheelchair navigated through the proposed framework resulted to be more suited for comfortable navigation in a straight indoor corridor environment with an higher average score of 3.9 compared to the shortest path framework with an average of 3.3. Average result values with confidence level interval bars are shown on Fig. 11. A t-test revealed that the higher score of the proposed framework had statistical significance ($p = 0.011$). Example of two of the trajectories of the wheelchair followed are shown in Fig. 9. Fig. 10(a) shows the wheelchair running through the narrow (and not comfortable) shortest path (black bold dotted line) and in Fig. 10(b) for the wider (more comfortable) path (magenta thin solid line).

Finally, at the end of the questionnaire we directly asked the 29 participants for their preference between the two paths. We found that only 2 of them (6.89%) found the shortest path more comfortable; on the other hand, 27 of them (93.10%) found the path computed on the HCoM using expression 3 was more comfortable. This confirms the hypothesis and prediction of Section V-A.

(a) Shortest path . (b) Most comfortable path.

Fig. 10. Real-time experiments with robotic wheelchair in an indoor corridor environment.

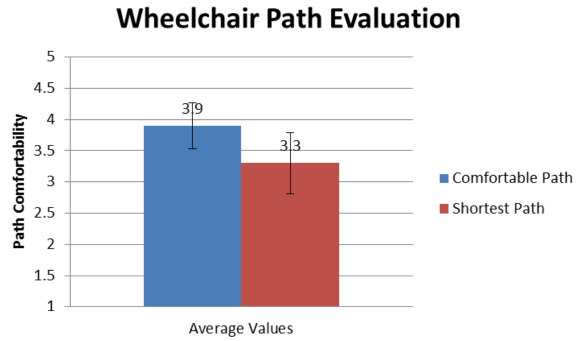



Fig. 11. Evaluation results for the two types of navigation.

## VI. Discussion and Future Works

To build the comfort model presented in this work, the comfort factors were extracted from human participants. Despite being a subjective evaluation, experiments were performed with several participants to cancel participant individual differences. While performing wheelchair experimentation, we noticed that participants fastly got used to the wheelchair speed and type of navigation. To avoid this effect we kept the number of runs low (nine) and counterbalanced experiment conditions.

Algorithm 1 can be used to detect straight corridors and to add comfort factor to straight segments on the fly, however, environment geometry for extraction and comfort computation for more complex environments such as paths with turns, curves and intersections is left for future work. Furthermore, the integration of a human-comfortable local planner is necessary for collision avoidance.

The path computed on the HCoM using expression 3 was confirmed to be more comfortable than the shortest path. This comfortable path can only be computed on the HCoM, i.e., minimizing distance, number of turns and decreasing amount of traveling time on a global planner would not output a “comfortable path” as depicted in this study. To avoid passing through narrow spaces, the system could be set to add width obstacles in the map, however, such “trick” would impede the robotic wheelchair to pass through doable paths such as doorways.

Future work is open for parameter extraction and evaluation with handicapped people in real environments. Finally, a more straight forward method to extract human comfort factors is needed to provide a robot system with real-time feedback. In on-going research we are performing experiments to find comfort-stress correlation with heart rate variability as well as the use of brain machine interfaces for providing human feedback to a robotic system.

## VII. Conclusions

This paper presented and defined the concept of human-comfort factor map (HCoM) for passenger vehicle navigation. The availability of this map allows the computation of comfortable paths for navigation that existing state of the art methods can not generate. The method to extract comfortability factors and build the HCoM was explained and a navigational framework for passenger vehicles to improve human comfortability was proposed and implemented. The comfort model parameters were extracted from 22 human participants and the navigation framework was implemented for a robotic wheelchair running in straight corridors. The evaluation was performed comparing paths followed by the wheelchair generated by an $A^*$ algorithm on the HCoM taking into consideration human comfort factor and a state of the art $A*$ on a geometric map. Finally, robotic wheelchair navigation evaluation with 29 participants showed that more than 90% of them preferred the proposed approach to a shortest distance based approach.

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