Modeling of Human Velocity Habituation for a Robotic Wheelchair

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Abstract—This work proposes a model for human habituation while riding a robotic wheelchair. We present and describe the concept of human navigational habituation which we define as the human habituation to repetitively riding a robotic wheelchair. The approach models habituation in terms of preferred linear velocity based on the experience of riding a wheelchair. We argue that preferred velocity changes as the human gets used to riding on the wheelchair. Inexperienced users initially prefer to ride at a slow moderate pace, however the longer they ride they prefer to speed up to a certain comfort level and find initial slower velocities to be tediously “too slow” for their experience level. The proposed habituation model provides passenger preferred velocity based on experience. Human biological measurements, galvanic skin conductance, and participant feedback demonstrate the preference for habituation velocity control over fixed velocity control. To our knowledge habituation modeling is new in the field of autonomous navigation and robotics.

I. INTRODUCTION

Recently, human factors are starting to be considered as an important topic for autonomous vehicles and passenger transport [1]. However, this field of research is small due to its recent development, and there are many topics that need to be explored. Vehicle comfort is measured in terms of ergonomics, quality of shock absorbers, and temperature control capabilities [2]. However, the human perception of navigational comfort needs to be addressed in order to develop autonomous vehicles that people would be willing to use. We consider autonomous passenger vehicle “safety” in two ways; safety of everyone in terms of a physical process (i.e.: avoiding collisions, vehicle vibrations/temperature/noise, passenger body position) and comfort (safety) of the passenger in terms of an internal/emotional process (i.e.: moving at a speed and/or taking a path that causes the passenger to feel at ease). This paper focuses on the latter interpretation of comfort as an internal/emotional process that can be measured and modeled using behavioral and biological information.

The process of feeling comfortable is dynamic, changes over time, and is linked to the speed and direction of the wheelchair [3]. We define our navigational model in terms of habituation, instead of sensory adaptation, because one remains fully aware of sensing and moving during the process of navigating a vehicle. Additionally, human navigational behavior is likely to be different for each situation, habituated responses are shown to be applicable for each stimulus situation. In this paper we introduce the concept of human navigational habituation when people ride a robotic wheelchair. We argue that habituation occurred when participants temporarily increased their speed to a certain plateau (maximum comfort speed), while controlling the wheelchair in which they were seated in. Once participants reached their preferred comfortable speed the variance of their navigating path decreased.

In addition, the concept of habituation/comfort is demonstrated for the case in which participants are passively being driven via autonomous navigation. We show the occurrence of habituation using skin conductance, a biological measure, by capturing changes in human arousal. Many cognitive psychology studies show that changes in skin response (temperature and/or conductance) are directly linked to psychological processes such as emotion, stress, decision making, and pain [4]–[6]. Emotional responses can be induced by visual, auditory, and tactile/smell stimuli [7].

II. RELATED WORKS

A. Human Comfortable Navigation

There are works in which the robot considers a human partner. Navigation in the presence of humans was presented in which a planner computes human-compatible paths [8]. Also, there are works regarding geometric reasoning frameworks in which the human spatial perspective is considered in order to understand shared workspaces [9], [10]. In these works the human is considered as an external agent, therefore, the robot performs its actions based on the cost functions it has to satisfy. Differently from these works, the proposal of this paper is the consideration of the human on a robotic passenger vehicle where the robot has to perform its actions based on human comfort.

Other than cars, research on autonomous navigation on passenger vehicles has been discussed in the form of robotic wheelchairs [11]–[14]. Comfortable motion and path planning with robotic wheelchairs have been presented where paths are computed in order to satisfy a comfort cost function [15], [16]. There are works in human-robot dialogues for providing route instruction tasks to robotic wheelchairs where semantics for instruction communication are used [17]–[19]. Regarding human direct control and interaction with robotic wheelchairs there are works on basic research for brain controlled systems in which the human passenger...
motor imagery is read from a brain computer interface cap to control the vehicle [3], [20], [21]. In other works, vehicle physical comfort factors have been taken into consideration and classified into dynamic (vibrations, shocks), ambient (thermal, noise) and ergonomic (passenger’s position) [2]. In a work to consider human navigational comfort a human-comfort factor map was proposed in where distance and velocity comfort factors in a straight corridor were extracted from human participants and added to a geometric map to compute comfortable paths [3]. In the approach presented in this paper and differently from previous works, we propose a model of human navigational habituation when riding a robotic wheelchair. We discuss the importance of velocity habituation when riding a wheelchair "how used is a person to it" in order to select the appropriate velocity of the wheelchair.

III. HABITUATION MODEL

This section provides the general definition of habituation and presents our proposal of habituation in terms of navigation. Finally, the observations that led to the necessity of modeling habituation are presented.

A. Definition

Habituation is defined as a behavioral response decrement that results from repeated exposure to a stimulus [22], [23]. In this work we define human navigational habituation as the decrease in response to stimulus while riding a vehicle after repeated presentations. The approach concentrates in modeling the preferred velocity of the wheelchair in terms of user experience. We assume that the human preferred velocity is comfortable for them. The objective of this velocity habituation model is to provide the preferred velocities of human passengers as they get experienced to the wheelchair.

B. Observations

In previous work we extracted human preferred velocity when riding an autonomous robotic wheelchair during autonomous navigation [3]. In these experiments the linear velocity of the wheelchair was fixed and participants were given only three runs each to avoid habituation effects. During experimentation with human participants we found out that humans’ comfortable velocity region changes as they get more habituated (more experienced) with the wheelchair. Usually novice passengers prefer slow velocities and as they get experienced most of them tend to find faster velocities as more comfortable. The increase of velocity will gradually happen until the preferred velocity level is achieved.

This increase of velocity can be modeled as an asymptotic function in which the horizontal axis represents the human experience and the vertical axis represents the element to be habituated. Figure 1 shows the habituation asymptotic curve in terms of velocity. The model in this work concentrates in the preferred linear velocity of the wheelchair in terms of distance. Habituation concept is illustrated in Figure 1 in terms of user experience. When the human on the vehicle is not experienced he tends to ride the wheelchair at a low velocity, as he becomes more experienced the velocity tends to converge to a comfortable velocity region. Exact comfortable velocity depends on each individual. The figure illustrates a couple of habituation examples. Fast habituation (riding the wheelchair faster) at the top of the comfort region and slow habituation (riding the wheelchair slower) at the bottom of the comfort region. In this work distance was used instead of time to represent the user experience because it is constant for all the experimental set. Time varies from each experimental run because it depends on the velocity in which the wheelchair was driven.

In short, preferred velocity (or comfortable velocity) varies with experience. For most people what was comfortable at the beginning feels to be slow as experience accumulates and what was perceived to be fast at the beginning gradually becomes more acceptable or comfortable.

IV. METHODS

This section presents two different navigation experiments with human participants. In the first experiment the wheelchair traveled along an indoor corridor loop via two types of navigation sessions: active and passive. First thirty external participants were asked to drive the wheelchair as their driving path and velocities were recorded and then replayed in autonomous mode while their galvanic skin response (GSR) was logged. Based on the acquired data while participants drove, a velocity habituation model is proposed and the parameters of the model were computed through regression analysis for all the participant data sets. In a second experiment the habituation velocity model while the wheelchair drove autonomously in straight line was evaluated with fifteen participants.

A. Hardware

The robotic wheelchair (IMASEN EMC-250) used in this work has two powered rear wheels (differential drive configuration) and two free casters at the front with a maximum velocity of 1.6 m/sec. It is equipped with wheel encoders and two laser sensors (Hokuyo UTM-30LX). The laser sensors were used for map building and localization.

In autonomous navigation experiments, participants wore a mobile skin conductance measuring device called eSense.
by Mindfield/Germany (http://www.mindfield.de/en/). Figure 2 shows the eSense sensor, it applies a small, safe, and unnoticeable electrical voltage to the skin.

B. Active and passive wheelchair navigation for habituation modeling

For the first experiment, thirty healthy external participants (payed for their evaluation) with normal corrected vision [mean age, 22 ± 14 (SD) years; males =15, females =15] performed both active and passive wheelchair navigation on a predefined route in two opposing directions. The experimental environment is shown in Figure 4 in blue dotted lines where the total length of the loop is around 130 m. All participants gave informed consent approved by the Ethics Committee at ATR. Twenty five of the thirty participants were right handed and the remaining five participants were left handed. As shown on the left side in Figure 3 each participant was administered the active navigation first, the direction of counter clockwise (CCW) and clockwise (CW) was randomly selected to control for behavioral biases due to experimental order. During active navigation, participants were instructed to drive the wheelchair through the corridor loop route as best as they could four times consecutively for each direction. Immediately following the active navigation session, participants were asked to remain seated on the wheelchair for two additional passive trials.

During passive navigation, speed and direction in which the wheelchair automatically drove the participant through the predefined route changed each trial. The two speed settings were self and expert, the self speed was the same in which the participant drove the wheelchair during the active session (recorded from the wheelchair localization system) and the expert speed was a speed preferred by volunteers who had spent more than 30 hours driving the wheelchair. Similarly to the active session, the direction and speed order was randomly selected for each participant.

C. Data acquisition

Participants sat on the wheelchair in a moderately lighted hallway. During the active session, in the first experiment, participants used their right hand to manipulate a standard styled joystick that was attached to the wheelchair. The joystick had position based control, such that the direction in which it was deflected corresponded to the same direction in which the chair traveled. Similarly, the amount of deflection corresponded to the speed of the chair, where less deflection corresponded to a slow speed and more deflection corresponded to a fast speed. Wheelchair driving trajectories and velocities were recorded. During passive sessions, skin conductance and wheelchair position and velocity were recorded simultaneously while participants sat idle on the wheelchair holding an emergency stop button in their right hand.

D. Analysis methods

1) Modeling velocity habituation: Following discussion of Section III and using collected data from active experiments of Section IV-C, we propose and build a linear velocity model based on traveled distance of the wheelchair.

First, the velocity of the robotic wheelchair is limited by the maximum velocity \( v_{\text{max}} \) of its wheels. The relation between the linear velocity \( v(t) \) and the angular velocity \( w(t) \) is given by

\[
\begin{bmatrix}
v(t) \\
w(t)
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{2} & -\frac{1}{2}
\end{bmatrix}
\begin{bmatrix}
v_R(t) \\
v_L(t)
\end{bmatrix}
\]

(1)
where \( b \) is the length of the wheelbase and \( v_R(t) \) and \( v_L(t) \) are the linear velocities of the right and left wheels. By taking the inverse of the matrix in Eq.(1), the following relation

\[
v(t) + \frac{b}{2}w(t) = v_R(t)
\]

implies that the linear velocity of the wheelchair has to decrease when the angular velocity is such that \( v_R(t) \) reaches \( v_{\text{max}} \). Namely, the linear velocity decreases when the wheelchair takes a turn.

Since the linear and the angular velocities are dependent, the velocity habituation was modeled using only the linear velocity. In order to take into account the variations of velocity controlled by the user and not the ones induced by the limiting behavior in Eq.(2), the linear velocity is only considered when the angular velocity is below the threshold \( \epsilon_a = 3 \, \text{deg/s} \).

Figure 5, describes this selection procedure. The linear and absolute angular velocities were averaged for all the participants and the threshold \( \epsilon_a = 3 \, \text{deg/s} \) was applied to the averaged absolute angular velocity (bottom). Then only the averaged linear velocities (blue points in the top) corresponding to the low angular velocities were used. Note that these curves are a function of the distance \( d \) driven by the participants.

This selection procedure was applied to the data of the two active experiments. Then the selected points were used to estimate the parameters of the habituation model given by

\[
C = A(1 - e^{\alpha d})
\]

The result of this data fitting is represented in figure 6.

The controller used during the second experiment is shown in equation (3), such that \( A \) and \( \alpha \) denote the habituation speed and rate respectively. The population average that was obtained for \( A \) during the first and second active experiments were 1.37142 and 1.43735, respectively. Similarly, the population average obtained for \( \alpha \) during the first and second active experiments were -0.28411 and -0.50974, respectively. \( d \) refers to the distance traveled or duration of exposure on the wheelchair. The results are presented on table I.

### E. Autonomous wheelchair navigation for velocity evaluation

A habituation velocity controller was constructed from expression 3 of Section IV-D.1 and evaluated towards different static velocities. The experiment was performed on a group of fifteen participants (from our laboratory) with normal corrected vision [males =8, females =7]. The wheelchair velocity was isolated to determine subject preference of the wheelchair controller during passive navigation. Each participant remained seated on the wheelchair for three passive trials in alternating directions, as represented in the right side of Figure 3. The three passive trials corresponded to three different control conditions for the wheelchair; moderate velocity (\( v_{\text{mod}} = 0.6 \, \text{m/sec} \)), maximum velocity (\( v_{\text{max}} = 1.6 \, \text{m/sec} \)), and velocity provided by the habituation velocity model (expression 3). Participants were administered each of the three trials in randomized order. For habituation velocities, expression 3 was used with parameters of Table I; self parameters for first run trials and non-self parameters for second and third trials. The path of the experiment was a straight line of 46.3 m in length which is shown in the bottom of Figure 4 in red. After each run participants were given a questionnaire where we evaluated three points in a scale from 1 to 7:

- Comfort: how uncomfortable (1) or comfortable (7).
- Feeling of ease: how stressed (1) or non-stressed (7).
- Perception of velocity: how slow (1) or fast (7).

### V. EXPERIMENTAL RESULTS AND DISCUSSION

This section presents the experimental results and a discussion of the model limitations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First Run (self)</th>
<th>Second Run (non-self)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>1.37</td>
<td>1.43</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>-0.28</td>
<td>-0.50</td>
</tr>
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</table>
uli. Phasic skin conductance can be described a noticeable recovery time. Tonic skin conductance is the baseline level of three events on the GSR curve; tonic, phasic rise time, half-time recovery does not occur for the CW direction. We interpret recovery occurs briefly at 18 m. The rise time of the phasic GSR occurs from 18 m until peak response at 45 m, and half-time recovery occurs at 88 m and thereafter. For the expert speed condition, the latency period before the phasic GSR occurs 0 – 15 m. The rise time of the phasic GSR occurs from 15 m until peak response at 45 m, and half-time recovery occurs at 88 m and thereafter. For the expert speed condition, the latency period before the phasic GSR occurs 0 – 18 m. The rise time of the phasic GSR occurs from 18 m until peak response at 64 m, and half-time recovery occurs briefly at 102 m for CCW. Half-time recovery does not occur for the CW direction. We interpret the return to baseline as an indicator that the participants became familiar with or habituated to the experimental con-

A. Autonomous Navigation Evaluation Habituation

Questionnaire results corresponding to autonomous wheelchair velocity evaluation of Section IV-E are presented in Figure 7. The graphs show evaluation results for the moderate, habituation model, and maximum velocity conditions regarding ride comfort, perceived sense of ease and velocity of the wheelchair.

The run with velocity computed with the habituation model received overall better scores in measured comfort and feeling of ease than moderate and fast velocities. The left side shows that for user comfort all three runs received similar scores without significant difference. For feeling of ease, moderate and habituation were ranked higher than fast velocity, however, moderate was rated as too slow regarding the velocity perception. Habituation and fast were rated as slightly fast. Users found the fast mode to be not relaxing compared with its counterparts. Moderate was found relaxing, but too slow (which at some point could produce uneasiness and discomfort if traversed path had to be longer). In this sense, habituation was found free from stress and comfortable without being too slow. Similarly, for the habituation condition there was a significant correlation with how content participant’s were with the speed and their perception of comfort (Spearman correlation, $\rho = .64, p < .001$). For example, the higher participants rated their contentment with the speed the higher they rated their sense of comfort. However, no such correlation was present for the moderate or fast condition.

We tried to make a fair comparison between our habituation model and fixed velocities. We selected a moderate velocity of $0.6 m/sec$ because it resembles average walking speed for hospital-like settings, where it is commonplace to walk side-by-side with a wheelchair for longer distances. After 40 m participants regarded this speed as slow, therefore we believe that slower fixed velocity speeds would have resulted in an unfair comparison.

B. Galvanic Skin Response

In general, skin conductance is evaluated by identifying three events on the GSR curve; tonic, phasic rise time, half-recovery time. Tonic skin conductance is the baseline level of skin conductance in the absence of any external stimuli. Phasic skin conductance can be described a noticeable change from baseline when discrete environmental stimuli are presented, such as a visual cue, sound, and smell. A change in skin conductance due to stimulus exposure is called phasic rise time; it is the time between the onset of the event-related GSR and the peak of the response. Half-time recovery time is the interval between the time of the peak of the response and the moment the skin conductance level is equal to half of the peak amplitude.

GSR mean was shown to directly relate to the level of comfort felt by participants [6]. Skin conductance measures show that participants were sufficiently stimulated during both experiments because GSR values remain significantly greater than the resting baseline throughout the session. GSR measurements were normalized for each subject and trial, using the maximum phasic value of each trial. Therefore, the absolute amplitude of GSR measurements are interpreted in terms of relative value [24]. Normalized GSR measurements were interpolated, in terms of distance, so that the length of each trial or condition for all participants would be equivalent. Within the first and second experiments, the population average across trials and conditions were obtained by respectively averaging 26 of the 30 and 12 of the 15 participant measurements. Participant measurements that were excluded were inaccurate due to measurement error.

In the first experiment (Section IV-B), the baseline/tonic value for participants sitting stationary (resting) was 0.58 ± 0.26, and the new tonic value for participants passively riding on the autonomous wheelchair was 0.80 ± 0.22. For the second experiment, the resting baseline was 0.85 ± 0.13 and the passive riding baseline was 0.94 ± 0.06. One-way ANOVA analysis of the GSR measurements, regardless of speed condition, showed that the CW direction resulted in a significantly ($p < 0.05$) greater mean than the CCW direction; the CW direction had an additional location where participants could not visually see where they were going such as a 90 degree corner turn [25]. Participants may not clearly know what is ahead and/or around a corner, therefore they may feel more aroused in terms of stress. In addition, one-way ANOVA of the GSR measurement, regardless of direction condition, revealed that the expert speed condition resulted in a significantly ($p < 0.05$) greater mean than the self speed condition. Figure 8 shows the mean and within-subject standard error during passive riding for the expert speed condition in both CW and CCW direction, gray line denote corners. Similarly, Figure 9 shows the mean and within-subject standard error during passive riding for the self speed condition in both CW and CCW direction. For the self speed condition, the latency period before the phasic GSR occurs 0 – 15 m. The rise time of the phasic GSR occurs from 15 m until peak response at 45 m, and half-time recovery occurs at 88 m and thereafter. For the expert speed condition, the latency period before the phasic GSR occurs 0 – 18 m. The rise time of the phasic GSR occurs from 18 m until peak response at 64 m, and half-time recovery occurs briefly at 102 m for CCW. Half-time recovery does not occur for the CW direction. We interpret the return to baseline as an indicator that the participants became familiar with or habituated to the experimental con-
Fig. 8. Average of 26 participant GSR measurements during the expert speed condition for both CW and CCW directions during passive wheelchair navigation. GSR measurements for CW and CCW show that participants remained simulated due to the speed and could not recovery to the initial baseline after exposure to being on the wheelchair.

Fig. 9. Average of 26 participant GSR measurements during the self speed condition for both CW and CCW directions during passive wheelchair navigation. GSR measurements for CW and CCW demonstrate a recovery to baseline after exposure to being on the wheelchair; recovery to baseline is defined by a statistically similar mean value during the start and end of the experiment.

Fig. 10. Average of 12 participant GSR measurements during the second experiment for three speed conditions, fast, moderate, and habituated. Fast and moderate speed conditions induce typical event-related GSR such that a latency, rise time, and recovery time is identified. Habituation speed condition does not induce event-related GSR, therefore participants felt similarly comfortable while being driven.

The condition expert CW and expert CCW show participants starting at a tonic value and ending at a significantly higher value. For these two cases, participants were unable to become comfortable/habituated to the experimental conditions within the given time (one-way ANOVA comparing latency period with recovery period: \( p < 0.05 \)). In addition, these results show that participants were more sensitive to changes in speed than route selection. In particular, participants were unable to adapt to speeds in which they would not actively choose to use for themselves (expert condition). When participants were driven at speeds that they actively choose to use (self condition) they were able to adapt/habituate and thus remain comfortable.

Figure 10 shows the normalized within-subject GSR average for all three speed conditions, moderate, fast, and habituated of experiments of Section IV-E. We selected a shorter driving length of 43.6 m because we only needed to observe a peak response before or at 40 m. Figure 10 shows the expected peak response for the moderate condition at 37.6 m where upon a decrease occurs afterward. Additionally, the fast condition is similar to the expert condition within the first experiment such that the peak is observed at 25.2 m and the response remains elevated. The habituation condition does not have a rise time due to the stimulus, therefore we interpret these results such that participants felt the same during the entire task. Participants felt comfortable during the start of the task and therefore remained comfortable while being driven using the habituated model. These results demonstrate a way to passively drive participants such that they feel comfortable and account for the human psychological response due to exposure to stimuli. However, a longer experiment where the complete GSR can be measured using more subjects is needed to confirm the reliably of the habituation model.

C. Discussion and Model Limitations

The habituation model presented in this work is applicable to indoor environments and is intended to provide human comfortable velocities. We think that the model could be extended to other similar environments and navigational factors. For instance, the acceleration or distance between objects can be similarly controlled to induce a feeling of comfort for passengers. For both extensions there would be a time period where people would adapt their preferences, therefore a controller that can describe asymptotic behavior, like the velocity habituation model, would be expected.

The model parameters were fitted using a data base of 30 participants. In order to improve the model and have a more personalized model we would require a data base composed of large number of users and that could find an appropriate user profile to find appropriate habituation parameters.

A limitation of the model is that currently we do not
have on-line automatic methods to measure or extract user experience, therefore, it is not possible to have a reasonable estimation of human expertise. One possible approach could be to measure humans biological state to estimate the level of habituation.

Skin conductance is an accurate measure of human stress, however the time needed to determine the nature of one’s response to a stimuli can be lengthy and difficult to determine if many stimuli are presented simultaneously. Other methods as heart rate, eye movements, and breathing can be used to assist with determining humans’ level of stress.

VI. CONCLUSIONS AND FUTURE WORKS

This paper presented a human habituation model in terms of linear velocity for a robotic wheelchair. The proposed function models the change of driving style of humans when they get more experienced to the wheelchair. Based on human driver style analysis and supported by skin conductance measurements we observed that humans tend to increase their driving velocity and feel less stressed as they become experienced drivers. The model is based on the driving style of 30 participants while they drove the wheelchair in an indoor corridor environment and we used their driving velocity profile to fit the habituation model. Finally the model was tested in an autonomous navigation experiment by 15 participants and was compared to two different constant driving velocities. Experimental results showed that the habituation model was perceived more comfortable and less stressful than its two counterparts while not being perceived as slow.

In future work we plan to extend the linear velocity habituation model by investigating the suitability of non-linear models. In addition, we hope to generalize the model to various spatial areas, instead of a corridor, and better characterize the relationship between linear and angular velocity during habituation. Finally, we intend to make use of multiple biological measurements such as electroencephalograph (EEG), electromyography (EMG), skin conductance, heart rate, and blink rate to ensure reliable characterization of the user’s stress state.

REFERENCES


