Study on the comfort of people in spatial interactions with a social robot

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Abstract. *In this work, it was verified how spatial interaction affects human comfort through experiments in simulated and real environments with 20 volunteers in everyday situations. Interactions were observed taking into account a non-social and a social behavior of the robot. Metrics were used to assess task completeness, occurrence of collisions, invasion of interaction space, spatial and temporal coefficients in robot navigation, in addition to respect for proxemics, verification of movement smoothness and questionnaires to assess the comfort of the volunteers. The study concludes that the social navigation proposed in this work manages to deal with social interactions in a satisfactory way for humans and aspects such as noise produced by the robot and familiarity with the robot's behavior have great influence on user comfort.*

Keywords: Human-Robot Interaction (HRI), Spacial interaction, Social navigation, Comfort.

1. Introduction

Human comfort has been a topic studied for several years in the field of human-robot interaction (IHR) and social navigation [Kruse et al. 2013, Truong and Ngo 2017b] In this work presents the results of a research on the comfort of people in spatial interactions with a social robot. The focus of this study is on understanding comfort related to spatial interactions within the area known as social navigation. This work also assesses the issues of physical and emotional safety of people, as well as the spatial and temporal efficiency of the robot in environments shared with people. Comfort, as it is a subjective measure, is evaluated in questionnaires presented to the volunteers and reveals important characteristics that affect human comfort, such as the appearance of the robot, the presence of noise, familiarity with the robot and its functional capabilities, and finally, generation and maintenance of expectations in human beings as an impacting factor in comfort.

The theory on which this study is based is seen in the section 2. In the section 3 the materials and methods used to carry out the experiments are seen. In the section 4 the results of this work are presented. In the section 5 the discussions of the results are presented. Finally, the section 6 presents the conclusions and future work.

2. Theory

A mobile robot must be able to freely navigate in a environment with obstacles. However, the coexistence of robots and humans in the same environment adds some new dimensions to mobility, such as comfort and sociability. People are not common obstacles, because they have a set of social and cultural rules that dictate how people should move.

To [Breazeal 2002], a sociable robot is able to communicate and interact with humans, understand and even relate to us, in a personal way. This robot must also be able to understand us and itself in social terms. For a sociable robot to establish and maintain relationships with individual humans, the robot must understand people, and people must be able to intuitively understand the robot.

The proxemic theory proposed in [Hall 1910] is the study of the dynamic manipulation and interpretation of the human social behavior that are controlled by sociocultural rules in social encounters. This study defines cultural rules and privacy zone, personal zone, social zone and public zone. To enable socially accepted human-robot interaction, a robot need the ability to understand and respect this concept. Proxemics is concerned with the interpretation, manipulation and dynamics of spatial behavior in social encounters and takes into account physical representations [Mead and Matarić 2016]. According to [Truong and Ngo 2018], proxemics can be extended to a dynamic social space that is a space for interaction between two humans, group of humans, or human and object of interest, and can be generalized as a potential field that allows the robot does not approach human beings within this zone or cause them discomfort. This zone is incorporated into the route planning system, ensuring comfort and physical and psychological safety.

According to [Kruse et al. 2013], the challenges of social navigation involve naturalness, comfort and sociability. Naturalness is related to the similarities between robots and humans in the low-level behavior pattern; sociability deals with the robot's adaptation to high-level sociocultural standards; while comfort refers to the suppression of annoyance or stress for the human in interactions with the robot.

Among the highly relevant articles in the literature, the author Truong *et al.* [Truong and Ngo 2018, Truong and Ngo 2016, Truong et al. 2017, Truong and Ngo 2017a] was the most collaborative in developing a social navigation model. Truong proposes a generic and unified model to handle social navigation with a person or group of people standing or moving in different situations. It presents some social navigation problems observed in other works. Physical and psychological safety measures are used, as well as socially accepted behaviors of robots with humans. Tests are performed in a simulated environment with gazebo and ROS and real environment. The unified structure presented is built on conventional navigation and can be divided into two parts: (1) conventional navigation and (2) extension for social navigation.

The work entitled ”The Marathon 2: A Navigation System” [Macenski et al. 2020] presents the current trends in robotics to create a new navigation system based on the experiences of researchers working with the ROS framework. Among the new features are the Spatio-Temporal Voxel Layer (STVL), the Timed Elastic Band (TEB) controller and a structure for sensor fusion.

In [Lu et al. 2014], the authors develop and implement a map of semantic layers. The authors claim that it is not enough for the robot to avoid obstacles just to prevent collisions. It is necessary to treat obstacles differently depending on the nature of each obstacle. There are several scenarios that take personal human space into consideration, where the shortest path is not always the best. The work divides the cost map layers into classes.This layered cost map approach allows for a wide variety of representations of robotic behavior related to social rules.

In the [Pimentel and Aquino-Jr 2021], an exhaustive simulated experiments were carried out with different environments, types of obstacles, statically and dynamically simulated people, interacting with other people and objects, also varying local and global planning algorithms and cost maps. Safety and accuracy aspects in terms of estimated time and space, natural navigation and respect for personal space were observed.

3. Material and methods

3.1. Materials

3.1.1. Hardware

To carry out the simulated experiments, a DELL XPS 8500 *desktop* computer with 8 intel® Core^{TM} i7-3770 CPU @ 3.40GHz, 12GB of RAM and NVIDEA GeForce GT640 graphics card was used.

To carry out the experiments in a real environment, the HERA (Home Environment Robot Assistant)[1] platform developed at Centro Universitário FEI was used.

3.1.2. Software

The main softwares tools used throughout the work were Gazebo, a robotic simulator used in the simulated experiments, and ROS for the development of robot modules and the robot's internal communication. The ROS packages implemented for the development of this research are presented below [2]:

- **social_worlds** - Simulation environments modeled on Gazebo used to explore the performance capabilities of a social robot in different scenarios.
- **social_move_base** - A package that runs on move_base[3] , present in the ROS navigation stack, its function is to receive navigation commands with a higher level of complexity and translate to move_base thus serving as an interface layer between the social robot and the move_base. Instead of the social robot sending a destination pose, requested by move_base, the robot sends the name of the destination, the packet then identifies if the destination is a known place or person and determines the most suitable destination pose for the robot must address.
- **social_layers** - It defines the social navigation layers used to build the robot trajectory plan, is built on top of the ROS costmap_2D[4] and is based on the work of [Lu et al. 2014].
- **social_reasoning** - Builds and publishes the knowledge representation needed for social interactions. It uses information about people, objects and places, storing the information in a database.

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[1] `https://github.com/Home-Environment-Robot-Assistant`

[2] `https://github.com/orgs/Social-Droids`

[3] `http://wiki.ros.org/move_base`

[4] `http://wiki.ros.org/costmap_2d`

- **social_msgs** - Has the set of messages used by previous packages.

Next, each of the environments used for the development of this study are presented. The simulated environments (implemented in the package social_worlds) and the representation of the environment where the real experiments with the volunteers.

The following environments were used for the simulated experiments:

- **Static Individual (SI)**: Environment with several people standing without interacting with each other between the starting and ending point of the robot trajectory (Figure 1.a)
- **Object Interaction (OI)**: Environment with several people standing and interacting with an object (a frame on the wall) between the starting and ending point of the robot's trajectory (Figure 1.b)
- **Face-to-Face Group (FG)**: Environment with different groups of people in face-to-face interaction between the starting and ending point of the robot's trajectory (Figure 1.c)
- **Group in circular formation (CG)**: Environment with several groups of people in circular interaction formation between the starting and ending point of the robot trajectory (Figure 1.d)
- **Marathon (M)** Environment that mixes all previous scenarios (Figure 1.e).

The experiments with volunteers were carried out in an internal space measuring 10 by 11 meters (Figure 2). Both the robot and the volunteers had enough space to move freely.

The following environments were used in the real experiments: Static Individual (IE) seen in figure 2.a, Object Interaction (IO) seen in figure 2.b and Face-to-face group (FG) seen in figure 2.c.

3.2. Methods

The development methodology of this research aims to evaluate social, safety and precision criteria in navigation planning methods using different configurations. The work here was to select a navigation that was as natural, social and comfortable as possible for human beings. The experiment ran a script that follows the following steps for the simulation (the code for reproducing these experiments can be found on GitHub [5]): (1) Receives input data with a set of settings that will be used in the experiment; (2) A set of regions ($R = [CR_0, ..., CR_{nr}]$) that have nr regions is extracted from the environment. This represents the regions the robot must pass through during the experiment, here called ChechRegions ($CR = [P_0, ..., P_{ncr}]$). Each CR has ncr points ($P = [x, y]$). For every CR, one P is randomly selected. It will compose the path the robot will take during the experiment ($CP = [P_0, ..., P_{nr}]$). Then a global planner is used to calculate the shortest distance passing through every P in CP; (3) The environment and robot are reset to their initial settings; (4) The experiment is started by passing the list of CP to the navigation system. The experiment is ended when the robot reaches its final destination or a navigation failure occurs; (5) Finally, the experiment data is saved for future analysis.

The comparative study between the simulated and real environment is one of the objectives of implementing social navigation in a social robot, which aims to improve the

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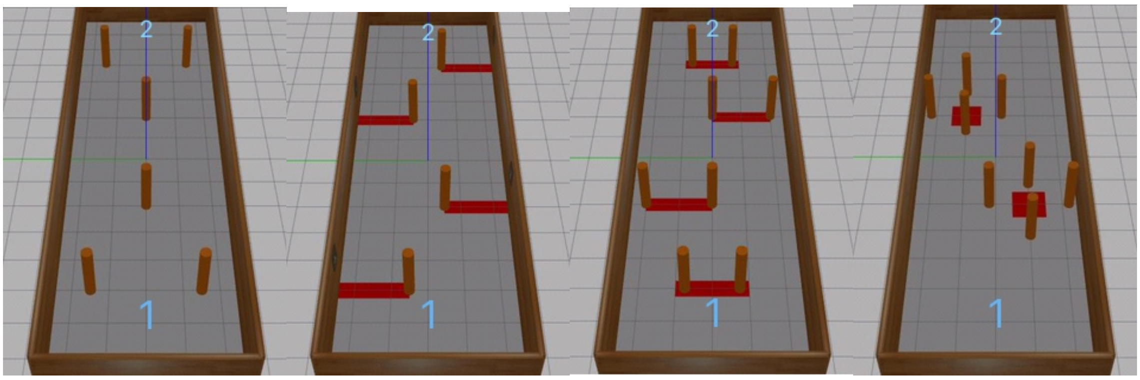
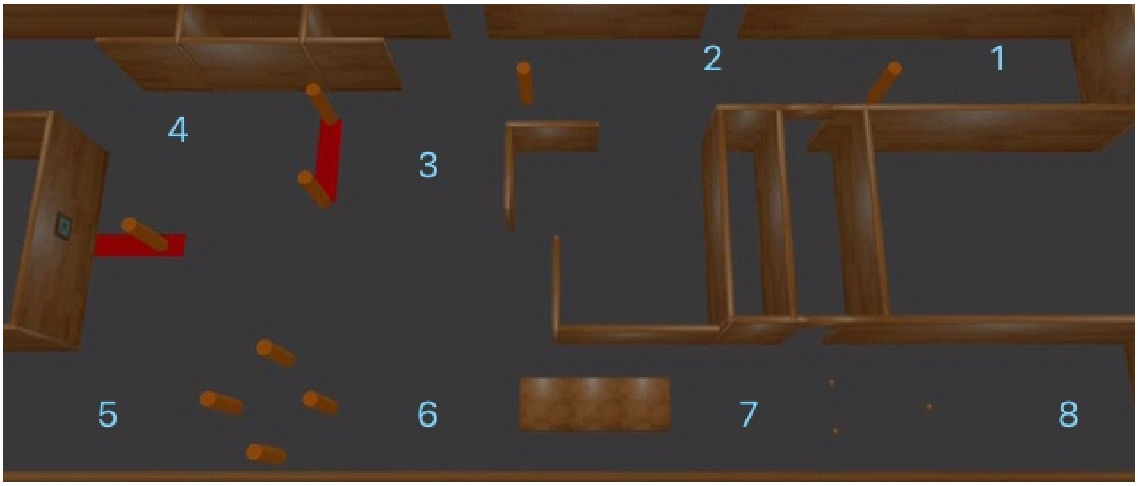
[5] `https://github.com/fagnerpimentel/phd`



(a) IE **(b)** IO **(c)** GF **(d)** GC



(e) Marathon

Figure 1. Simulated environments. The orange cylinders are representations of the humans that cause collision error if the robot touches, the red areas are prohibited areas, and the numbers are the checkpoints of the robot's trajectory.

behavior of naturalness in the robot's movement regardless of the sensors or environment in which it is operating. For the real experiments, two types of spatial interaction between people and the robot were applied. In the first type, the robot navigated through the environment passing through some specific points. Between each point there were people performing a certain action (stopping, moving, interacting with other people or objects). In the second type, the robot approached a person or a group of people in a certain location. For some of the volunteers, sharing an environment and interacting with a robot are almost everyday tasks, as they work directly with this type of scenario, where a robot is present. However, for other volunteers, interacting or just sharing the same environment with a robot, these experiences would be unprecedented. In this sense, for such volunteers, the simple presence of the robot is something that draws attention, and can directly influence the comfort of these people. We tried to prevent the robot from attracting the volunteer's attention unnecessarily. For this, we selected tasks that kept the volunteer busy, such as using the cell phone when he was alone, and we established an informal conversation when interacting with other people or objects.

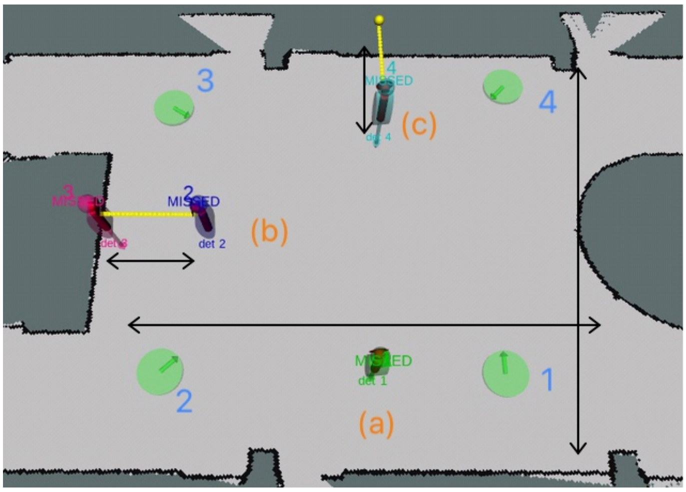


Figure 2. Representation of the environment where the real experiments were carried out. The numbers are the checkpoints of the robot's trajectory. The letters represent the interactions: (a) Static Individual, (b) Face-to-face Group, (c) Individual with Object.

The main benefit of carrying out these experiments is the promotion of a study that will be able to observe how people's comfort is changed with the presence of the robot and thus improve the behavior of the social robot so that it presents a more acceptable behavior in society.

We chose to do all tasks in sequence to minimize the discomfort volunteers might feel from performing repetitive tasks. A smaller number of experiments were carried out in the real environment, so as not to overwhelm the humans involved in the experiment.

During the performance of the tasks, all the security protocols required by the government regarding the new coronavirus pandemic (Covid-19) were followed.

3.3. Metrics

These metrics aim to select optimal planners in the robot's current navigation so that it becomes safer, more natural and comfortable for humans, since these characteristics are the main pillars for social navigation according to [Kruse et al. 2013]. The following variables will be analyzed in this study:

- Success rate (SR): Determines the percentage number of experiments where navigation was completed successfully. It is given by: $SR = s/ex_{max} * 100$ where s is the number of experiments completed successfully and ex_{max} is the maximum number of experiments performed.
- Fail rates (FR): Determines the percentage number of experiments where navigation failed. There are five types and they are given by the following formulas:
  - Space exceeded (FR_SE): $f_1/ex_{max} * 100$ where f_1 is the number of experiments that failed due to space exceeded.
  - Time exceeded (FR_TE): $f_2/ex_{max} * 100$ where f_2 is the number of experiments that failed due to timeout.
  - Abortion (FR_A): $f_3/ex_{max} * 100$ where f_3 is the number of experiments that failed due to abortion.

  - Collision (FR_C): $f_4/ex_{max} * 100$ where f_4 is the number of experiments that failed by collision.
  - Invasion (FR_I): $f_5/ex_{max} * 100$ where f_5 is the number of experiments that failed due to invasion of personal space.
- Spatial Coefficient (SPC): Determines how close the traveled distance the robot is to the planned navigation distance, given by: $SPC = 1 - (s_e - s_{min})/(s_{max} - s_{min})$ where s_e is the space traversed by the robot, s_{min} is the minimum space between the start position and the end position, s_{max} is the maximum space the robot can navigate in this experiment. The result ranges from 0 to 1, where 1 means that the path traveled is the same as the planned path.
- Temporal Coefficient (TEC): Determines how close the robot's execution time is to the estimated time to perform the navigation, given by: $TEC = 1 - (t_e - t_{min})/(t_{max} - t_{min})$ where t_e is the time used by the robot in the experiment, t_{min} is the minimum time required for the robot to move from the starting point to the end in a straight line, given the speed robot maximum, t_{max} is the maximum time the robot can navigate this experiment. The result ranges from 0 to 1, where 1 means that the elapsed time equals the planned time.
- Smooth Coefficient (SMC): Determines how smooth the trajectory performed by the local planner is. It is used as a measure to assess the naturalness of the robot. which is given by averaging the differences in the angles of each line that creates the trajectory. The result ranges from 0 to 1, where 1 means the navigation is smoother.
- Proxemic Coefficient (PRC): Determines the amount of trajectory performed by the robot in relation to the proxemics in the environment with people. This metric tries to represent the average comfort degree of the person closest to the robot in the experiment. The result ranges from 0 to 1, where 1 means that the navigation respects the proxemic rules.
- Individual Social Index (SII) [Truong and Ngo 2017b]: Uses proxemics as a basis for measuring individuals' social distance. $SII = \max_{i=1:N} \exp\left(-\left(\frac{x_r - x_i^p}{\sqrt{2}\sigma_i^{px}})\right)^2 + \left(\frac{y_r - y_i^p}{\sqrt{2}\sigma_i^{py}}\right)^2\right)$, where N is the number of people close to the robot, (x_r, y_r) is the position of the robot, (x_i^p, y_i^p) is the position of the ith person , and $(\sigma_i^{px}, \sigma_i^{py})$ is the standard deviation of people's positions in x and y.

4. Results

4.1. Results of simulated environment

In the simulated environment, it was possible to carry out an implementation and evaluation of several elements that make up a navigation system for mobile social robots. 1000 experiments were performed for each set of environments, types of interaction and types of navigation. 18 different combinations were performed, totaling 18,000 experiments.

In the experiments, the main cause of failure was the invasion of interaction spaces, with the exception of environments with static individuals, where there is no interaction area that could be invaded, all other environments presented this failure for common navigation and the best results are presented for environments that had social navigation.

Regarding the spatial coefficient (SPC), it was observed that all environments with common navigation, the values are equal to 1. This means that the robot does not deviate from its trajectory compared to the planning performed. In environments with social navigation, a drop in these SPC values is observed. This drop is due to a change in the trajectory in capacity with the planning. In this case, the robot takes a longer trajectory than planned to avoid passing too close to the humans or avoiding passing in places of interaction.

Regarding the temporal coefficient (TEC), all experiments have values close to 1, without much difference. The values indicate that the robot is following the plan in relation to time. A slight increase in values is observed in experiments with active spatial interactions, this increase occurs because the robot plans to go to the point where the person is but stops its movement before, to avoid space invasion of interaction or even a collision.

Regarding the smoothness coefficient (SMC), this metric presents excellent values for passive spatial interactions (above 0.91). These values indicate that the trajectory was smooth, with few curves.

Regarding the proxemics coefficient (PRC), there is a difference between the experiments with common navigation and social navigation. It is possible to observe that social navigation manages to respect the social distances of people with values very close to or equal to 1 in all experiments.

4.2. Results of Real environment

In real experiments, volunteers performed everyday tasks such as using a cell phone, interacting with other people and interacting with objects. Meanwhile, the social robot performed tasks that involved spatial interaction, such as moving through the environment, being able or not to pass close to the participant (implicit interaction) or approaching him at some point (explicit interaction). The robot could present a socially accepted behavior or not while the volunteer's reaction was observed.

In these experiments, 20 people of different ages and familiarity with a social robot were invited to interact with the robotic platform HERA. Each experiment has different combinations totaling 120 different experiments.

In these experiments, 50% were performed with common navigation while the other 50% were performed with social navigation.The type of navigation was randomly selected for each volunteer, until completing the requirement of fifty-fifty between common and social.

The volunteers concepts in social navigation are presented below.

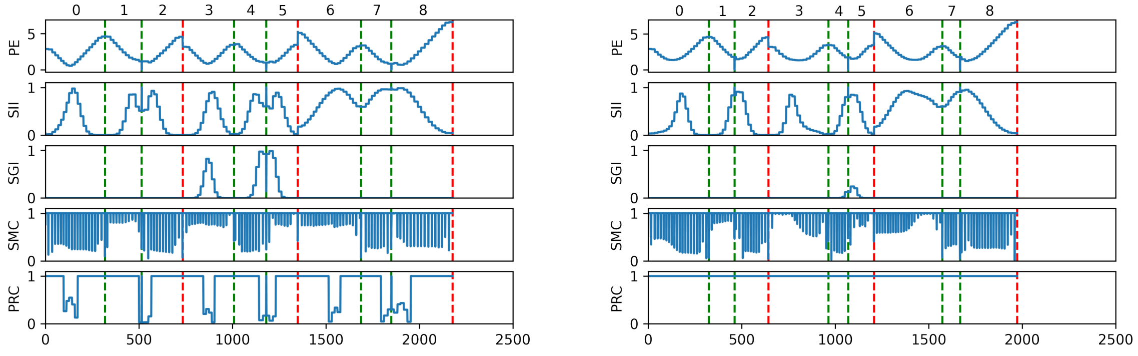
- **Physical security:** Volunteers define it as the simple fact that the robot does not hurt the person, such as not passing the wheel over the person's foot and avoiding physical contact unless there is some interaction that requires such contact. To avoid physical contact, the robot must respect the person's space, maintain a safe distance, and avoid approaching the person unless it is going to interact with a person.
- **Naturality:** For the robot to be natural, physical safety must also be respected. Therefore, the robot cannot bump into anyone, not get too close and restrict human

space. Two points stand out when volunteers try to define the naturalness of the robot. The first is that naturalness is closely linked to the shape and purpose of the robot. Therefore, if the robot has a humanoid shape or anthropomorphic features, then naturalness will be linked to human-likeness. However, for some volunteers, the robot's appearance may not be too close to that of a human either. In this scenario, where the robot looks more like a human, it needs to walk moderately, not make a robot movement and not do something that the human being cannot do because the person interacting could feel threatened or inferior to the robot. Some features in addition to spatial interaction are also important in naturalness such as greeting the person. The second point observed in the naturalness is the familiarity of the movements.

- **Sociability:** Regarding sociability, volunteers frequently mention two points. The first is related to verbal interactions, for them, sociability is related to the robot communicating properly, asking if the human being wants something, establishing some kind of speech relationship and expressing their intentions through verbal interaction with the human being. The second point is related to the robot's behavior in spatial interactions. The robot must respect the human being's space, approach it in a light way and avoid any type of collision, respecting its social area, as well as not interfering with other interactions that the human being is carrying out. The robot must also have an adjustable behavior for humans and avoid making unnecessary noises.
- **Readability:** Regarding readability, three points are noted. The first about robot movement: This movement needs to have a speed compatible with the environment, always start with slow movements and be changed gradually when reducing and reducing speed around people. The second point is the signage. The robot must indicate at all times what it is doing, what it is going to do and where it is going, for this it can use verbal interaction such as speech, or text on some panel and non-verbal ones such as gestures, expressions, and arrows that indicate the movement. Finally, the third point is familiarity. At this point, the robot needs to present a behavior similar to something similar that the human being knows, if for a robot with humanoid appearance, the ideal is that it has movements similar to the human being. If the robot performs any specific activity, it must have an appearance and behavior that indicates that activity. This helps humans to find patterns and know what to expect from the robot.
- **Comfort:** Regarding comfort, the volunteers went through several points to try to define this concept: (1) respect for spatial interactions, avoiding being invasive in people's space, respecting distances. At this point, the robot's speed was cited as an important characteristic, keeping the movement fluid, without sudden changes; (2) maintenance of a verbal interaction that is courteous with the human being; (3) the familiarity that appears again as an important point for the human being to be able to deduce the robot's intentions; and (4) appearance of the robot that needs to be nice to the human being that

The figure 3 presents the values of the PRC and SMC metrics, and in addition to these two, the PE is also presented, which is the distance from the robot to the closest person (used as a basic measure of proxemics) and SII, which also uses PE as a base.

The experiments with common navigation present similar behavior to each other



(a) Volunteer 3: Common Navigation **(b)** Volunteer 1: Social Navigation

Figure 3. SII, SMC and PRC metrics in experiments with volunteers.

and the same occurs between the experiments of social navigation, only one experiment of each type of navigation was selected to be analyzed: the volunteer experiment 3 (common navigation) and the volunteer experiment 1 (social navigation). In these graphs, the x-axis represents the points of the trajectory executed by the robot and the y-axis, the value of each metric. The graphs are divided into bands that represent each moment of the experiment.

Among the graphs presented, the PRC and the SMC are the most representative when comparing common and social navigation. By the PRC it is possible to observe with clarity the moments when the robot gets too close to the human being in common navigation experiments, while in social navigation experiments the robot respects the distance at all times. By the SMC we can see the moments when the robot performs smooth movements (close to 1) and not so smooth (close to 0).

5. Discussion

During this study, it was possible to evaluate objective metrics on the robot's behavior and to verify the level of comfort of the volunteers based on the perception and observation of these volunteers to propose improvements in the robot. It was also possible to compare common and social navigation approaches in a simulated environment and in a real environment with volunteers having different degrees of familiarity with social robots. In each situation, it was observed that navigation that does not follow social rules causes greater discomfort for people and that the noise of the wheels on the HERA platform was the main reason for discomfort for the volunteers.

The main difficulties encountered were in keeping the volunteers' focus on the elements of spatial interaction. It was observed that other elements of human-robot interaction stand out in relation to the elements of spatial interaction. In this direction, it was noticed that the robot's appearance and design elements are the first to call the volunteer's attention, especially when this volunteer is not familiar with the robot, then the ability of verbal interaction is what attracts the most attention, followed by the gestural interaction capacity and finally, the spatial interaction capacity. We believe that the shape of the robot also influences the behavior that human beings expect from this robot because it is linked to a previous experience or idea that the participant has of the robot's capabilities. The fact that the robot has the ability to interact verbally and through gestures encourages the volunteer to create expectations in relation to a behavior that suits these abilities, and the lack of this behavior ends up generating frustration and, consequently, discomfort, it is possible that in robots that do not have devices for verbal and gestural interaction, the discomfort is smaller when these interactions do not occur.

In the context of sharing an environment with a robot, ideally, the person must to forgets that the robot is in the scene unless it actively calls their attention. In this direction, any action that unnecessarily draws attention as an unexpected movement is a potential discomfort for the human being. Given this difficulty, it was necessary to make some changes in the way the experiment was carried out, as explained at the beginning of this report.

Volunteers in general had little discomfort with the robot. During common navigation, discomforts were observed when the robot interrupted social interactions. In social navigation, the robot respected social interactions and was more accepted.

The main reason for discomfort pointed out by the volunteers was the noise that the robot's wheels make when navigating the environment. Noise appears as an impact factor because in the social context it is little or non-existent, being seen as a nuisance by people when it happens, as people who work directly with the robot are not bothered by the noise as they are already familiar with it, but admit that it can be a problem after being asked about it.

The volunteer's previous familiarity with the robot had a great influence on comfort by facilitating the legibility of the robot's movements. This familiarity can be from prior face-to-face interaction, fictional observations, or media observations. It was observed that comfort is linked to the familiarity that the volunteer has with the robot and the knowledge that the volunteer has about what the robot can do. Consequently, many discomforts are caused by the performance of an unexpected behavior by the robot.

It is observed that, both in the simulator and in real environments, the SMC registers a low performance in environments with several checkpoint points where they need to make several curves. This metric still needs to be improved, however, it already gives us signs of improvement points to smooth the robot's trajectory. Two improvements need to be done to the SMC metric: better accepting movements where turns are needed and penalizing more on axis turns.

This study was limited to spatial interactions only, however it was possible to observe the influence of other types of interactions, such as verbal and gestural, on human comfort and how these interactions or the lack of them influence the comfort related to spatial iterations.

6. Conclusions

The paper presented a study on the comfort of people in environments with social robots. 18000 experiments were carried out in a simulated environment and 20 volunteers were invited to carry out experiments in a real environment.

The concludes that elements such as appearance of the robot and noise produced by the robot stand out in comparison with elements of spatial interaction causing discomfort in human beings. It was observed that the volunteer's previous experience influences the way in which social norms are accepted. Volunteers with previous experience of the robot's capabilities usually reveal some discomfort points such as appearance, noise and even sudden interventions in people's interactions. Thus, it was observed that the existence of previous experience in people with the robot's capabilities has a great influence on the comfort of these people.

In future works, experiments will be carried out with dynamic people and larger groups. In these future experiments we will focus more on the comfort elements that attracted the most attention in this work, such as noise reduction performed by the robot.

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