Evaluation of Distance for Passage for a Social Robot

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ABSTRACT

In this work a study for the evaluation of the social distance for passage in a one-dimensional environment is presented. The proposed control strategy is based on the proxemics rules of human spatial behavior. The results of a user study with ten subjects are presented. Our hypothesis is that people prefer the robot to stay out of their intimate zone. The subjects felt in general more comfortable in presence of the robot behaviors that were keeping the higher values of lateral distance and this fact seems to clearly confirm our hypothesis. Some users have felt nonetheless the largest maneuvers of avoidance as not comfortable and natural; a possible correlation between the subjects background and the preferred lateral distance values has been investigated.

1. INTRODUCTION

For operation in environments with people that have limited experience with robots, it is essential that the motion behavior of the robot signals safety to minimize distress of the people and to provide for smooth operation without undue disturbances from bystanders. Person-person interactions are regulated by a number of rules determined by social conventions. As a starting point it might be considered that robots ought to follow interaction patterns that are similar to those used in person-person encounters.

Human spatial behavior has been widely studied in anthropology and psychology. Formal models of interaction are recent and go back to the 1960s when the *personal space* term was defined by Sommer [8] and the *proxemics* framework was presented by Hall ([3]). Given that proxemics plays an important role in person-person interaction, it is of interest to study if similar rules apply for the interaction between people and robots operating in public spaces. It would be natural to assume that the robot respects the same physical boundaries as we expect from other people, if the robot has to display some level of "social intelligence".

As part of human-robot interaction, the spatial interaction has been studied in a number of earlier efforts. Nakauchi and Simmons [5] have designed a system that stands in line, using the concept of personal space to model a line of people. Althaus et al. [1] considered robot navigation for group formation and maintenance among a robot and a number of people. Yoda and Shiota [11] considered control strategies for encountering people in a hallway scenario. However, few of these studies directly address the social conventions of encounters.

The authors have previously addressed the problem of social interaction of a robot with people in a hallway setting and have presented an algorithm for person passage in which the proxemics rules were used to define the interaction strategy (Pacchierotti et al. [6]). In the design of the patterns of interaction a number of basic parameters have been considered that includes: speed of travel, distance for early signaling and lateral distance for safe passage. An earlier work has included a pilot user study in which participants were asked to rate the acceptability of the displayed behavior with respect to the three parameters (Pacchierotti et al. [7]).

It has been found that the distances preferred by humans when approaching a robot or being approached by a robot are comparable to those respected when a human approaches another human (Walters et al. [10]). In this work we are interested in evaluating the social distance for passage in a hallway. Our hypothesis is that people prefer the robot to stay out of their intimate zone. The results of a user study with ten subjects are presented; a clear indication of preference for passage outside the intimate zone has been observed. In Section 2 the scenario is described, including Hall's proxemics rules and a sketch of the control strategy. The design of the user study is presented in Section 3 together with the experimental results in Section 4. The results are discussed in Section 5, the main observations (Section 6) and a summary (Section 7) conclude the paper.

2. SCENARIO

The operation of a robot in a hallway scenario is presented here; spatial interaction in a hallway progresses typically along a single dimension and has allowed us to study the problem of spatial interaction under simplified conditions.

In proxemics, the space around a person is divided into 4 distance zones:

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- Intimate distance. This ranges up to 45 cm from the body and interaction within this space might include physical contact. The interaction is either directly physical such as embracing or private interaction such as whispering.

- Personal distance. This ranges from 0.45 m to 1.2 m and is used for interaction with family and friends or for highly organized interaction such as waiting in line.
- Social distance. The interaction ranges here from 1.2 m to 3.5 m and this distance is used for formal and businesslike transactions, interaction among casual acquaintances and as a separation distance in public spaces such as beaches, bus stops, shops, etc.
- Public distance. It extends beyond 3.5 m and is used for no interaction or in one-way interaction such as the one between an audience and a speaker.

Personal space varies significantly with cultural and ethnic background. One could model the personal space for a human in a hallway setting as a set of elliptic regions around a person as shown in Figure 1. Video studies of humans in hallways seem to indicate that such a model for our spatial zones might be correct (Chen et al. [2]).

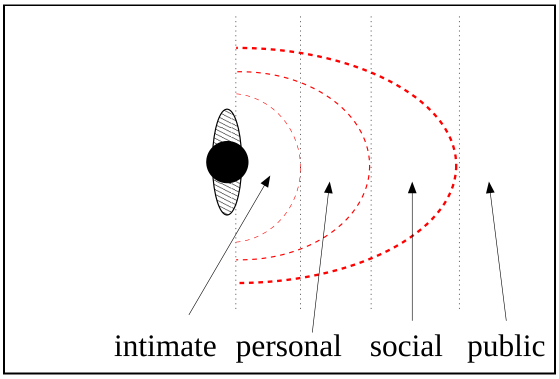

Figure 1: Spatial distance zones for people moving through a hallway/corridor setting.

2.1 Control Strategy

Informally one would expect a robot to give way to a person when an encounter is detected. Normal human walking speed is 1-2 m/s which implies that the avoidance must be initiated early enough to signal that the robot has detected the presence of a person and to indicate its intention to provide safe passage for her/him. At the same time there are social conventions of passage that follow the patterns of traffic. We believe the robot should follow these rules too. A number of basic rules for the robot behavior may thus be defined:

1. upon entering the social space of the person initiate a move to the right (wrt. to the robot reference frame) to signal the person that has been detected.
2. move clearly to the right if the layout of the hallway allows, while passing the person.
3. await a return to normal operation (e.g. navigation toward a goal) until the person has passed. A too early return to normal operation might introduce uncertainty in the interaction.

Using the rules of proxemics previously outlined, one would expect the robot to initiate avoidance when the distance is about 3.5 meters to the person. Given a need for reliable detection, limited dynamics and early warning however, a longer distance seems to be desirable. The passage behavior is subject to the spatial layout of environment. If the layout is too narrow to enable passage outside of the personal space of the user, as in the case of a corridor, it is considered sufficient for the robot to move to the right as much as it is possible, respecting a safety distance from the walls. This simple strategy obeys the basic rules of proxemics.

2.2 The Passage Behavior Parameters

Three parameters were considered as most significant when specifying the robot passage behavior (see Figure 2):

1. Robot speed (RS). This is the average forward speed of the robot during the passage maneuver.
2. Signaling Distance (SD). This is the distance of the robot from the person along the robot direction of motion (i.e. along the corridor direction) at which the robot starts the maneuver of passage and thus signals detection.
3. Lateral Distance (LD). This is the distance along the direction perpendicular to the corridor direction that the robot keeps from the person at the passage point (dashed drawing in Figure 2), assuming that the person is walking straight along the corridor.

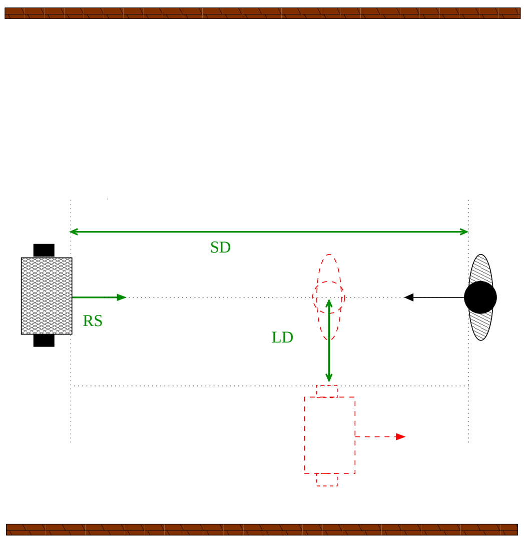

Figure 2: Passage behavior parameters.

The signaling and lateral distances are related with the personal space constraint.

2.3 Implementation

The strategies outlined above have been implemented on a Performance PeopleBot (Minnie) in our laboratory. Minnie is equipped with a SICK laser scanner, sonar sensors and bumpers (see Figure 3). The system has an on-board Linux

Figure 3: The PeopleBot system used in our studies.

computer and uses the Player/Stage software (Vaughan et al. [9]) for interfacing the robot sensors and actuators.
The four main components of the control system are shown in Figure 4. The laser and sonar data are fed into a lo-

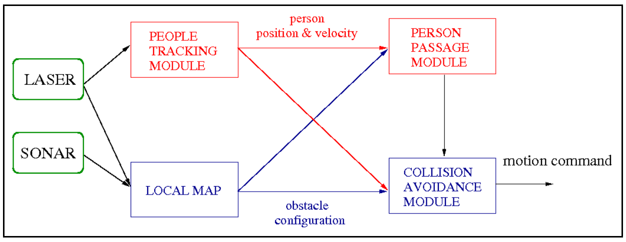

Figure 4: The overall control system architecture.

cal mapping system for obstacle avoidance. In addition the laser scanner is fed into a person detection/tracking system. All the software runs in real-time at a rate of 10 Hz. The serial line interface to the SICK scanner runs at a rate of 5 Hz.
The tracking module detects and tracks people in the environment; it provides information about the current position of the people as well as their velocity.
The navigation system relies on a local mapper that maintains a list of the closest obstacle points around the robot. The collision avoidance module can deal with significant amount of clutter but it does not take the motion of the obstacles into account as part of its planning and it does not obey the rules of social interaction. The Nearness Diagrams (ND) method by [4] has been chosen because it is well suited for cluttered environments. The Person Passage module (PP) implements a method for navigating among dynamically changing targets and it is outlined in the next Section.
During normal operation the robot drives safely along the corridor toward an externally defined goal. The goal is fed to the collision avoidance module. The person tracker runs in parallel to detect the potential appearance of a person. If a person is detected by the people tracker both the PP and the ND modules are notified. The PP module generates a strategy to pass the person and if a passage maneuver is feasible, the generated motion commands are filtered through to the robot.

2.4 Person Passage Method

The Person Passage module has been designed to perform a passage maneuver of a person, according to the previously defined proxemics rules. It operates as follows: as soon as a person is detected in front of the robot and closer than SD, the robot is steered to the right to maintain a desired lateral distance LD from the user. If there is not enough space, as might be the case for a narrow corridor, the robot is commanded to move as much as possible to the right to signal to the user that it has seen her/him and lets her/him pass.
A desired trajectory is determined, that depends on the relative position and speed of the person and the environment configuration encoded in the local map. The desired trajectory is computed via a cubic spline interpolation. The control points are the current robot configuration (x_0^R, y_0^R), the desired "passage" configuration (x_P^R, y_P^R), and the final goal configuration (x^G, y^G) in the corridor frame of reference, where the x axis is aligned with the main direction of the corridor (see Figure 5). The control point (x_P^R, y_P^R) de-

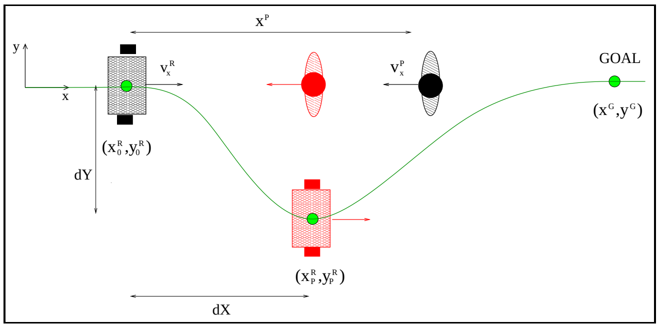

Figure 5: Desired trajectory for the passage maneuver. The distance of the robot from the person is maximum when it is passing her/him (red).

termines the passage maneuver, and is computed as follows:

$$x_P^R = x_0^R + dX \tag{1}$$

$$y_P^R = y_0^R + dY \tag{2}$$

The value of dY depends on the lateral distance parameter (LD) that the robot has to keep from the person:

$$dY = LD + w_R/2 - (y^P - y_0^R) \tag{3}$$

where w_R is the robot's width and y^P is the person's y coordinate in the corridor frame. The value of dY may be limited by the free space on the robot right. dX is computed so that the robot maintains the maximum distance from the person when it is passing her/him, according to Equation 4:

$$dX = v_x^R/(v_x^R - v_x^P) \times (x^P - x_0^R) \tag{4}$$

The maneuver is updated according to the person's current position in the corridor's frame x^P and velocity v_x^P, until the person has been completely passed, at which point the robot returns to its original path. A maneuver is considered feasible if there is enough space to the right of the robot to keep the desired lateral distance from the user; the tracker and local map information is used for this purpose. If a maneuver is not feasible, or at any instant the robot is too close to the person (i.e. it is about to invade her/his intimate space), the robot is commanded to stop. The robot operation is resumed in ND mode as soon as the person has walked far enough away from the robot.

3. USER STUDY DESIGN

Figure 6: The corridor where the user study was performed.

In this study we were interested in evaluating the social distance for passage in a one-dimensional environment as a hallway. The main hypothesis of the study is that people prefer robots to stay out of their intimate space when they pass each other.
Indications achieved through a previous pilot study (Pacchierotti et al. [7]) have been followed in the design; in particular the values for the signaling distance as well as the value for the robot speed that showed highest preference in the user study have been adopted (SD = 6.0 m, RS = 0.6 m/s) . The focus in this study is then on the evaluation of the most acceptable lateral distance for passage (parameter LD). We decided to test a wider range of distances than in the pilot study (three values versus two values); the three values chosen were LD_1 = 0.2 m, LD_2 = 0.3 m, LD_3 = 0.4 m (see Figure 7). Each lateral distance value determined a different robot behavior that was evaluated in the study (see Table 1). The tests have been

Table 1: The behavior parameters setting.

	Speed	Sign. Dist.	Lateral Dist.
Behav. 1	$RS = 0.6$ m/s	$SD = 6.0$ m	$LD_1 = 0.2$ m
Behav. 2	$RS = 0.6$ m/s	$SD = 6.0$ m	$LD_2 = 0.3$ m
Behav. 3	$RS = 0.6$ m/s	$SD = 6.0$ m	$LD_3 = 0.4$ m

carried out in a hallway of the main building of our institute (see Figure 6). The corridor is 2.5 meters wide and this has allowed us to control the exact value of lateral distance parameter, as opposite to the previous study in which due to

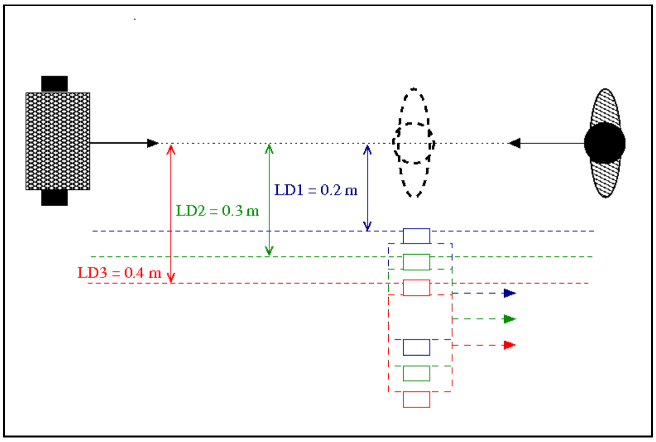

Figure 7: User study design: 3 values of the lateral distance were tested.

the limited lateral dimension of the corridor (2 meters wide or less), the desired lateral distance resulted in a smaller value, according to person's position relative to the robot and the corridor walls.
10 adult volunteers participated in the study, they were balanced in gender (5 males, 5 females) and age (see Figure 8). The subjects were all affiliated with university

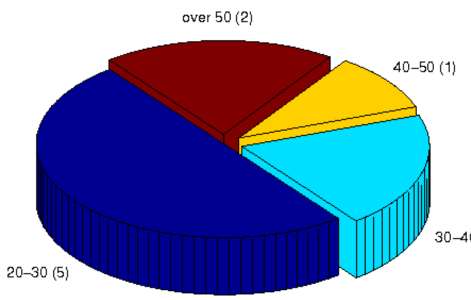

Figure 8: Age distribution of survey population.

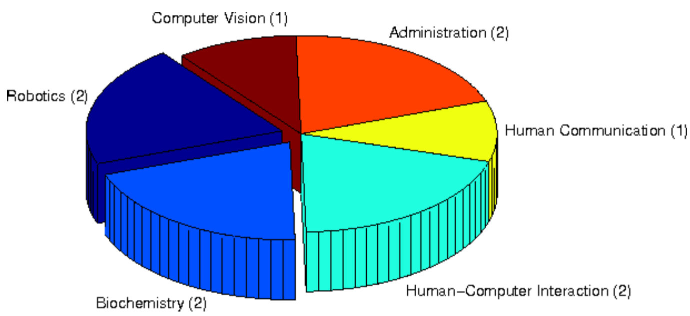

Figure 9: Background distribution of survey population.

and their backgrounds were balanced between technical and non-technical (see Figure 9).
We were also interested in investigating if different behaviors and psychological reactions from users with different backgrounds (i.e. technical background versus non-technical background) could exist. For this purpose the subjects have

been associated to 2 groups of 5 people each. The subjects in the technical group either worked with robots or in the robotics lab or had participated to previous studies in human-robot interaction. The subjects in the non-technical group had never worked with robots, 2 had never seen a robot before, all of them saw our robot Minnie for the first time. In Table 2 the occupation of the subjects and the number of subjects belonging to each group are shown.
The users were first introduced to the robot and the experiment and then asked to "walk along the corridor until the end of it". No further indications were given to the participants on how to walk during the tests. The subjects were left free to choose their own walking speed, the position in the corridor and consequently the distance from the robot as we were actually interested in observing the dynamics of robot-human interaction during passage.

Table 2: Technical and non-technical groups.

Technical (5)	Robotics (2)
	Human-Computer Interaction (2)
	Computer Vision (1)
Non-Tech. (5)	Biochemistry (2)
	Administration (2)
	Human Communication (1)

A set of 3 trials was performed for each subject, in which the behaviors (Behavior 1, Behavior 2 and Behavior 3) were executed in random order. The experiment was then repeated as a consistency check, for a total of 6 trials for each subject. A mark on the floor guaranteed the robot's initial position and orientation to be the same during all the sessions. Moreover a localization module that relies on odometry and laser scan data made the system insensitive to wheel slippage and other odometry errors.
The participants were asked to report their feedback after each set of 3 trials. A closed-ended question survey was used with a scale for rating from 1 to 5, where 1 meant that the user felt very uncomfortable with the robot behavior and 5 that the user felt very comfortable. Subjects comments about their feelings about the robot behavior were also noted, after each set of 3 trials. Finally, video records of each session were acquired, for later evaluation of subjects behavior (walking speed and trajectory performed) during the experiments.

4. EXPERIMENTAL RESULTS

The results for the complete set of users are presented in Figures 10, 11 and 12. The average user evaluation of each behavior together with the standard deviation are shown for the overall set of 6 trials and separately for the first and second set, respectively. The larger value of the lateral distance parameter LD_3 scored the higher average comfort rate and the smallest variance both considering the complete set of trials ($mean = 4.25$, $std = 0.7164$) and the first and second set of trials separately ($mean = 4.2$, $std = 0.7888$ in the first set, $mean = 4.3$, $std = 0.6749$ in the second set). Significant individual differences are present that explain the high standard deviation values, they are discussed in the next Section.

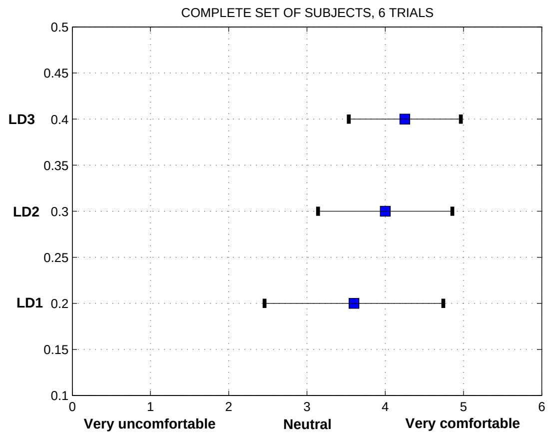

Figure 10: Lateral distance evaluation (mean and standard deviation).

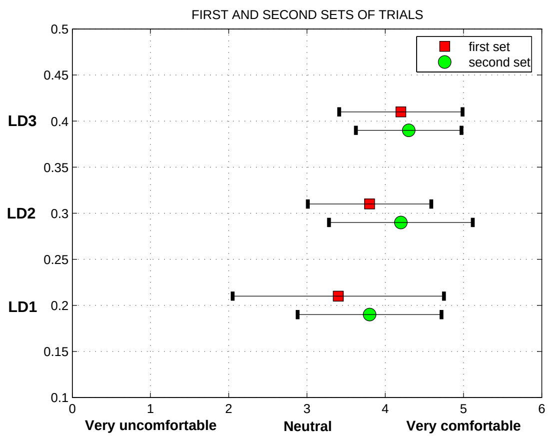

Figure 11: Lateral distance evaluation (mean and standard deviation) for the first and second set of trials.

In Figure 12 the results for the non-technical and technical groups are presented and it is shown how the LD_3 value scored the highest average rate in the non-technical group ($mean = 4.4$, $std = 0.8433$) while the subjects in technical group felt most comfortable with the LD_2 value of the lateral distance ($mean = 4.2$, $std = 0.6325$), although the LD_3 value registered a close average comfort rate ($mean = 4.1$, $std = 0.5676$). These results are commented in the next Section.

5. EVALUATION

A clear indication of preference for the larger values of lateral distance (LD_2 and LD_3) has emerged from the experiments; this confirms our hypothesis that people prefer robots to stay out of their intimate space when they pass each other in a corridor.
Significant individual differences are present in the data set; it is clear from the data that different people have subjective preferences and in addition there are variations in walking

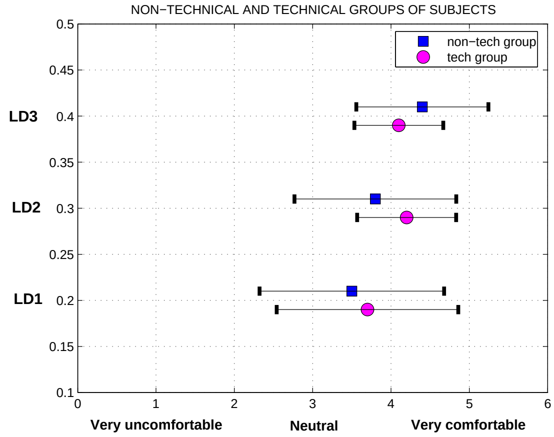

Figure 12: Lateral distance evaluation (mean and standard deviation) for the technical and non-technical background groups.

speed and trajectories that influence the results.
It is important to point out that the fact that people with a technical background better accept smaller lateral distances need to be taken as an indication rather than a conclusion, given the high individual differences in the user evaluation of the robot behaviors and the limited number of participants (10) involved in the experiments. Nonetheless this indication seems to have been confirmed through a direct inspection of the subjects behaviors (through the video record) and their evaluations/comments reported in the survey forms.
In the technical group of subjects a tendency of walking faster and at a smaller lateral distance to the robot has been observed with respect to the non-technical group. This could explain the preference given to the intermediate lateral distance value LD_2 with respect to the largest one LD_3. The LD_3 value in fact determines a larger turning maneuver of the robot and increases the time that it takes to the robot to pass the person. Given that the maximum average speed of the robot is limited to 0.6 m/s, the maneuver that results was perceived as too slow for fast-walking users. Some users felt that the maneuver was larger than it was really necessary. One user said that "the robot was paying too much attention to him". The robot behaviors that deployed the smaller values of lateral distance, instead were preferred because "the robot just let the user through" and the reaction of the robot was perceived as "early and comfortable".
As for the non-technical group of users, the tendency to walk at larger lateral distances from the robot could explain the preference for LD_3. It is important to underline that in our definition of the LD parameter (see Section 2.2 and Equation 3 in Section 2.4) both the robot and the person displacements contribute to the same extent, so the larger distance the person keeps from the robot, the smaller is the maneuver that the robot has to perform. Given the relative large width of the corridor, the subjects had a certain amount of freedom in choosing their trajectory and in some cases their own avoidance maneuver was enough to guarantee that the desired lateral distance condition was actually respected. When using the lower values of lateral distance then, in several cases either the robot did not need to perform a passage maneuver at all but just proceeded in Collision Avoidance (ND) mode or it just performed a small maneuver that was not perceived as clear enough from the users. Some subjects commented the robot behavior saying that "it was not reacting to my presence but just going its way" and "it didn't take me into consideration". On the contrary Behavior 3 was perceived as a "clear reaction" to the human presence.

6. OTHER OBSERVATIONS

In the evaluation of the experimental results, it is not possible to ignore the presence of a learning and trust effect due to the within-subjects experimental design in which 6 behaviors of the robot were presented to each person. The consistency of the robot behavior (i.e. the robot started always from the same initial configuration in every trials and it always turned to the right) contributed to increase the level of comfort of the subjects with the number of tests performed and the second set of trials recorded a higher user comfort rate with respect to the first one for all the 3 behaviors (Behavior 1, Behavior 2, Behavior 3), as shown in Figure 11.
Some particular behaviors of the subjects were observed during the study that it is worth mentioning. Two subjects were significantly uncomfortable with the robot, they were walking at low speed and keeping a large distance from the robot; during the first trial they said that they were scared because "they did not know what to expect from the robot".
A tendency to experiment with the robot was observed in the subjects which can also be due to the within-subjects design. One subject made a fast jump to see "how the robot would have reacted". In this case the subject was explicitly told not to challenge the robot. Otherwise we preferred not to give instructions to users on how to behave because we were interested in observing the dynamics of the interaction in as natural conditions as possible. Three subjects moved to the left side of the corridor imagining a situation in which they had to cross the corridor to reach an office on the left side (offices were situated on the left side of the corridor). The emergence of this behavior from these subjects was not expected but we believe it was important to have been able to registered it and it could not have been observed if the users had been explicitly told how to walk along the corridor.
As described in the previous Section, some cases have been observed in which the person trajectory alone was enough to guarantee the respect of the lateral distance condition; in such situations the robot proceed in ND mode towards the goal without signaling the human to have detected her/him. We think that this behavior should be corrected and that a signaling maneuver of the robot is always desirable regardless of the fact that the robot is invading or not the personal space of the person.

7. SUMMARY

In this work a study for the evaluation of the social distance for passage in a one-dimensional environment has been presented. The proposed control strategy, based on the proxemics rules of human spatial behavior, has proven to be acceptable and indications about the preference of human users have been achieved. The subjects felt in general more comfortable in presence of the robot behaviors that were keeping the higher values of lateral distance. This fact seems to clearly indicate that there is a preference for the passage

of the robot outside the intimate space of the person. In the pursuing of the most acceptable behavior of the robot, it has emerged nonetheless that the definition of an optimal maneuver of avoidance could be somehow critical. Some users have felt the largest maneuvers of avoidance as not comfortable and natural; this attitude has been observed with more frequency in the group of subjects with a technical background and could be related to a higher familiarity with technology.
A tendency of the subjects to pass the robot from the left side has also emerged, in few trials. The working hypothesis of our approach is that people follow the social conventions of traffic, so the robot was not entitled to pass persons on the left side. There may be situations, nonetheless, in which a person has to go to the left to reach a specific location, in this case the behavior of robot is felt as unnatural. A more explicit experimental evaluation of the rules of passage in such a situation seems desirable.
Future work should involve the integration with a context-based control based on a more complete set of information (global knowledge of the environment and user intention model) to deal with situations in which a higher level behavior is required. The generalization of the passage behavior to other kinds of environment is also felt particularly desirable.

8. ACKNOWLEDGMENTS

The present research has been sponsored by the Swedish Foundation for Strategic Research (SSF) through its Centre for Autonomous Systems (CAS) and the EU as part of the Integrated Project "CoSy" (FP6-004150-IP).
The authors thank H. Hüttenrauch and K. Severinson-Eklundh for participating in the discussion on the interaction strategy and D. Jönsson for the assistance provided during the user study experiments.

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