Evaluation of Passing Distance for Social Robots

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Abstract— **Casual encounters with mobile robots for non-experts can be a challenge due to lack of an interaction model. The present work is based on the rules from proxemics which are used to design a passing strategy. In narrow corridors the lateral distance of passage is a key parameter to consider. An implemented system has been used in a small study to verify the basic parametric design for such a system. In total 10 subjects evaluated variations in proxemics for encounters with a robot in a corridor setting. The user feedback indicates that entering the intimate sphere of people is less comfortable, however a too significant avoidance is also considered unnecessary. Adequate signaling of avoidance is a behaviour that must be carefully tuned.**

I. INTRODUCTION

Robots are gradually entering into public spaces for assistance to humans in tasks such as logistic delivery of mail in office buildings, cleaning in supermarkets, material transportation in factories, professional service in hospitals, etc. As part of operation in such areas the robot will encounter people that have no or limited prior exposure to robots. In such encounters it is essential that the overall motion behaviour instills confidence and introduces a minimum of distress for these people. People should feel comfortable and the robot should operate in a manner that is experienced as safe. In person-person encounters there are social rules that dictate passage of each other in public places. As a minimum one might expect that a robot should have motion behaviour that obeys similar conventions.

Human spatial behavior has been widely studied in anthropology and psychology. Formal models of interaction go back to the 1960s when *personal space* was defined by Sommer [1] and the *proxemics* framework was presented by Hall [2]. 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 a robot should respect the same physical rules as we expect from other people, if the robot has to display some level of "social awareness". As part of human-robot interaction, the spatial interaction has been studied in a number of earlier efforts. Nakauchi and Simmons [3] have designed a system that stands in line, using the concept of personal space to model a line of people. Althaus et al. [4] considered robot navigation for group formation and maintenance among a robot and a number of people. Yoda and Shiota [5] considered control strategies for encountering people in a corridor 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 corridor setting and have presented an algorithm for person passing 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. The effort 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]).

The emphasis in this work is on evaluation of the social distance for passage in a corridor in terms of the lateral distance that the robot keeps form the person. The evaluation of this parameter has in fact proven the most critical in the pilot study. Our hypothesis is that people prefer the robot to stay out of their intimate zone. Some preliminary results of a user study with ten subjects are presented. In Section II 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 III together with the experimental results in Section IV. The results are discussed in Section V, the main observations (Section VI) and a summary (Section VII) conclude the paper.

II. SCENARIO

The operation of a robot in a corridor 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 more controlled conditions. In proxemics, the space around a person is divided into 4 distance zones:

- 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 here ranges 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. The personal space for a human in a corridor setting can be modelled 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. [8]).

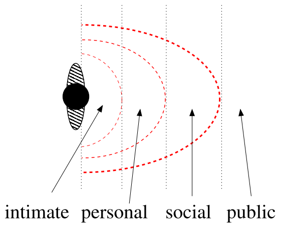

Fig. 1. Spatial distance zones for people moving through a corridor setting.

A. 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. At the same time there are social conventions of passage that follow the patterns of traffic, which need to be considered 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 while passing the person, if the layout of the corridor allows.
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.

The passing behavior is often constrained by 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.

B. The Passing Behavior Parameters

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

1. Robot speed (*RS*). This is the average forward speed of the robot during the passing 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 passing 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 passing point (dashed drawing in Figure 2), assuming that the person is walking straight along the corridor.

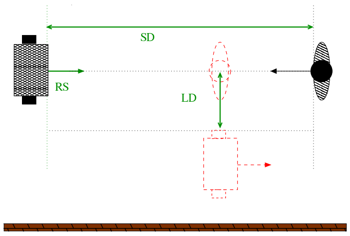

Fig. 2. Passing behavior parameters.

C. 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, pan-tilt camera and bumpers (see Figure 3). The system has an on-board Linux computer and uses the Player 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 local 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

Fig. 3. The PeopleBot system used in our studies.

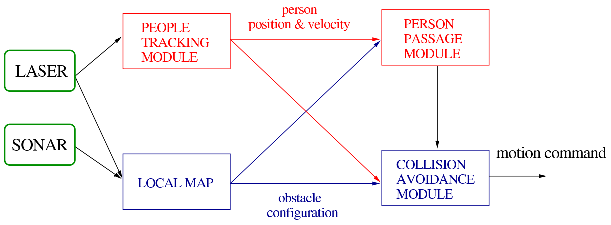

Fig. 4. The overall control system architecture.

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 [10] has been chosen because it is well suited for cluttered environments. The Person Passing module (PP) implements a method for navigating among dynamically changing targets and it is outlined in the next section. The system relies also on a localization module, based on the same main components that was used in [11] and is part of the CURE/toolbox software.[1] During normal operation the robot drives safely along the corridor toward an externally defined goal. The goal is fed to the collision avoidance module. 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.

D. Person Passing Method

The Person Passing module has been designed to perform a passing maneuver of a person, according to the previously defined proxemics rules (see Pacchierotti et al. [6] for a complete description). 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 to the right as possible to signal that it has seen the person 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 "passing" 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) determines the passing maneuver, and is computed as follows:

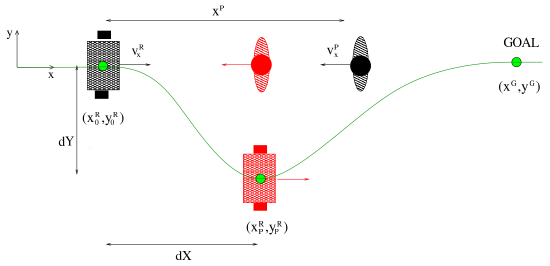

Fig. 5. Desired trajectory for the passing maneuver. The distance of the robot from the person is maximum when it is passing her/him (red).

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

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

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:

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

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.

III. USER STUDY DESIGN

Fig. 6. The corridor where the user study was performed.

In this study we were interested in evaluating the social distance for passing in a one-dimensional environment as a corridor. 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 and for the robot speed that showed highest preference in the user study have been adopted ($SD = 6.0m$, $RS = 0.6m/s$). The previous experience achieved with the pilot study showed also that the simultaneous evaluation of all the algorithm parameters may be critical because of their interaction and the high number of trials required. This study focused then on studying how the lateral distance parameter (LD) affects the overall user acceptance of the robot passing behavior. We decided to test a wider range of distances than in the pilot study (three values versus two values). The three values chosen were $LD_1 = 0.2m$, $LD_2 = 0.3m$, $LD_3 = 0.4m$ (see Figure 7). Each lateral distance value determined a different robot behavior that was evaluated in the study (Behavior 1, Behavior 2 and Behavior 3 in Table I). The tests have been carried out in a corridor of the main building of our institute (see Figure 6). The corridor is 2.5 meters wide and this

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[1] CURE stands for CAS Unified Robot Environment and the toolbox is a collection of tools to perform navigation, localization and mapping.

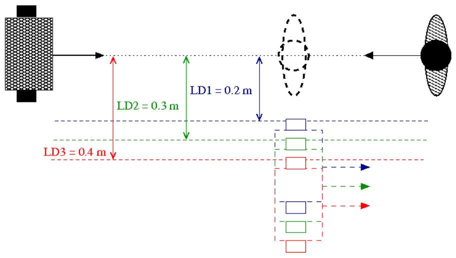

Fig. 7. User study design: 3 values of the lateral distance were tested.

TABLE I

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	$RS = 0.6 m/s$	$SD = 6.0 m$	$LD_3 = 0.4 m$

has allowed us to control the exact value of lateral distance parameter, as opposite to the previous study in which due to the limited width 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. The subjects were all affiliated with the university and their backgrounds were balanced between technical and non-technical. We were also interested in investigating if different attitudes towards the robot passing behavior could exist among persons with different backgrounds and experiences about robots. For this purpose the subjects have been associated to 2 groups of 5 people each. The subjects in the first group belonged to the fields of Robotics (2 subjects), Computer Vision (1 subject) and Human-Computer Interaction (2 subject). They either worked with robots or in the robotics lab or had participated in previous studies in human-robot interaction. The subjects in the second group belonged to the fields of Biochemistry (2 subjects), Administration (2 subjects) and Human Communication (1 subject). They had never worked with robots, two of them had never seen a robot before, all of them saw our robot Minnie for the first time.

The users were first introduced to the robot and to the experiment. They were told that they would encounter the robot in the corridor and that they were to pass each other. Then the subjects were asked to "walk along the corridor until the end of it". No further instructions 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 passing. Only the starting position for the subjects was fixed. A set of 3 trials was performed for each subject, in which the 3 behaviors 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 at the beginning of each session. 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. To measure the subject comfort during the interaction with the root, a closed-ended question survey was used with a 5-point Likert scale, 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.

IV. EXPERIMENTAL RESULTS

The results for the complete set of users are presented in Figures 8, 9 and 10. The average comfort evaluation of each behavior together with the standard deviation are shown for the overall set of 6 trials in Figure 8 and separately for the first and second set in Figure 9. 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 ($mean = 4.25$, $std = 0.72$) and the first and second set of trials separately ($mean = 4.2$, $std = 0.79$ in the first set, $mean = 4.3$, $std = 0.67$ in the second set). In Figure 10 the results for the non-technical and technical groups are compared and it is shown how the LD_3 value scored the highest average rate in the non-technical group ($mean = 4.4$, $std = 0.84$) while the the LD_2 value of the lateral distance scored the highest average rate in the technical group ($mean = 4.2$, $std = 0.63$), although the LD_3 value registered a close average comfort rate ($mean = 4.1$, $std = 0.57$). The results are discussed in the next section.

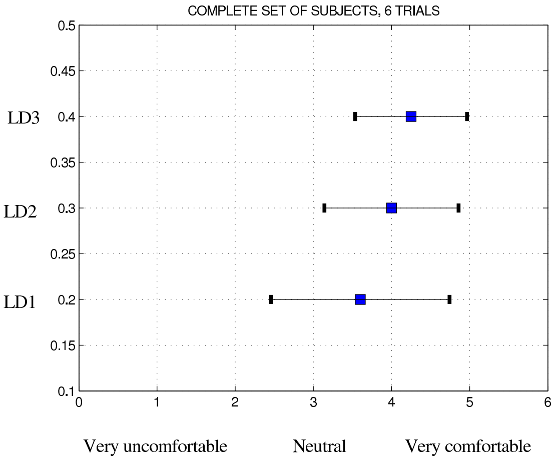

Fig. 8. Lateral distance evaluation (mean and standard deviation).

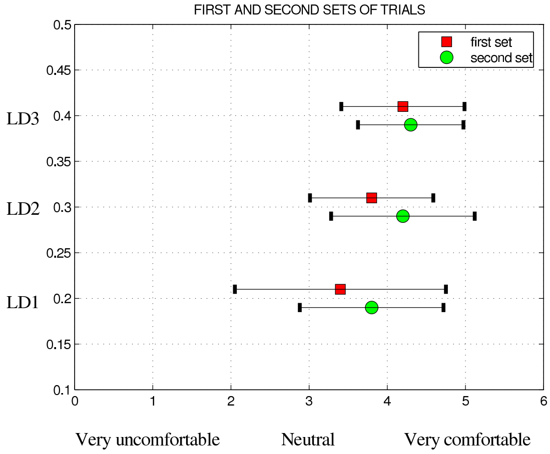

Fig. 9. Lateral distance evaluation (mean and standard deviation) for the first and second set of trials.

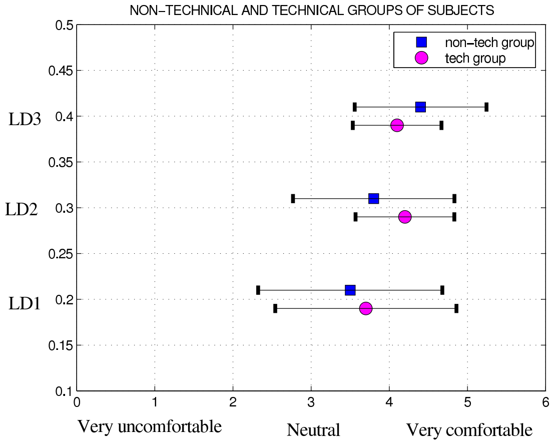

Fig. 10. Lateral distance evaluation (mean and standard deviation) for the technical and non-technical background groups.

V. EVALUATION

An indication of preference for the larger values of lateral distance (LD_2 and LD_3) has emerged from the experiments which seems to supports our hypothesis that people prefer robots to stay out of their intimate space when they pass each other in a corridor. However, high individual differences exist and the number of subjects involved in the study is not completely sufficient to get enough statistics to fully support the hypothesis. An influence of subjects' personality on individual proxemics preferences has been observed (Walters et al. [12], Gockley and Mataric [13]) that will require further investigation. In addition there were considerable variations in the subjects' walking speeds and trajectories in the user study trials that influenced the robot behavior and consequently the results, as it will be explained later on. Although the results are not entirely statistically significant, they can be used as indications of people's preferences to be confirmed in more complete studies. Similarly, the fact that people with a technical background accept smaller lateral distances need to be taken just as an indication, given the limited number of subjects (5) in each group. 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 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 II-B and Equation 3 in Section II-D) 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 passing 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" or "it didn't take me into consideration". On the contrary Behavior 3 was perceived as a "clear reaction" to the human presence.

VI. OTHER OBSERVATIONS

A learning and trust effect has been observed, 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 always started from the same initial configuration and it always turned to the right) contributed to increase the comfort level 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, as shown in Figure 9.

Some particular behaviors of the subjects were observed during the study that it is worth mentioning. Two subjects were very uncomfortable with the robot, they were walking at low speed, keeping a large distance from it. 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 also observed with some other subject 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 since 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). When the robot started to pass them on its right, they corrected their trajectory, moving back to their right as well. The emergence of this behavior from these subjects was not expected but we believe it was important to register it. 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's trajectory alone was enough to guarantee the respect of the lateral distance condition; in such situations the robot proceeded in ND mode towards the goal without signaling the human to have detected her/him. The feedback from the users has shown that this behavior was not acceptable because the robot was not signaling in any way its awareness of the human presence. The experiments have showed how important the signaling is for the humans to feel safe and we believe that the robot should always signal, even if the distance from the human is already large enough for passing.

VII. SUMMARY

In this work a study for the evaluation of the social distance for passage in a corridor environment has been presented. The proposed control strategy, based on the proxemics rules of human spatial behavior, has proven to be acceptable and some preliminary results about the preference of human users have been found. The subjects in general felt more comfortable in presence of the robot behaviors that were keeping the higher values of lateral distance. This fact indicates 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 felt the largest maneuvers of avoidance as uncomfortable and unnatural. This attitude has been observed with higher 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. However, there may be situations 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 situations seems desirable.

More generally it is felt desirable to continue with the work here presented to verify the achieved indications in studies with a higher number of subjects. It has also been noticed how conventional user study set-ups create artificial situations. To achieve a continuous experimentation in a more natural context, recent work has addressed the integration of the presented people passing control strategy in a framework of an office-guide robot. This will allow to study casual encounters of the robot with people walking in the corridors of our lab over extended periods of time.

VIII. ACKNOWLEDGMENTS

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