Human-Robot Embodied Interaction in Hallway Settings: a Pilot User Study*

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***Abstract*— This paper explores the problem of embodied interaction between a service robot and a person in a hallway setting. For operation in environments with people that have limited experience with robots, a behaviour that signals awareness of the persons and safety of motion is essential. A control strategy based on human spatial behaviour studies is presented that adopts human-robot interaction patterns similar to those used in person-person encounters. The results of a pilot study with human subjects are presented in which the users have evaluated the acceptability of the robot behaviour patterns during passage with respect to three basic parameters: the robot speed, the signaling distance at which the robot starts the maneuver and the lateral distance from the person for safe passage. The study has shown a good overall user response and has provided some useful indications on how to design a hallway passage behaviour that could be most acceptable to human users.**

***Index Terms*— Embodied Interaction, User Study, Hallway Navigation**

I. Introduction

Robots are gradually entering the daily lives of people as household appliances, assistants to elderly and handicapped, office assistants, tour guides etc. These robots are in general referred to as service robots and have to interact with people as part of their normal operations. The actions of the robot are first and foremost related to achievement of task oriented objectives, but equally important is the behaviour of the robot when it encounters people as part of its operations. It has been observed by Severinson-Eklundh et al. [1] that the the design of the interaction strategy of a service robot should be grounded on the understanding of the social context in which the robot is operating which include primary and secondary users as well as bystanders. The interaction involves two aspects:

a) Instructing the robot to perform specific tasks, which might involve use of a GUI, speech, and/or gestures recognition.
b) Embodied actions by the robot in terms of its movements patterns when encountering people.

In particular for operation in environments with people that have limited experience with robots, it is essential that the motion behaviour of the robot is such that it signals safety to minimize distress of the people and to provide for smooth operation without undue disturbances from bystanders. In person-person interaction there are a number of rules determined by social conventions. One of the most commonly used models of interaction is the classification by Hall [2], referred to as *proxemics*. Other models include the F-formation model by Kendon [3]. 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. Consequently, the present paper considers the design of robot control actions that are based on social studies.

As part of human-robot interaction, the spatial interaction has been studied in a number of earlier efforts. Nakauchi and Simmons [4] have designed a system that stands in line, using the concept of personal space to model a line of people. Althaus et al. [5] considered robot navigation for group formation and maintenance among a robot and a number of people. Yoda and Shiota [6] considered control strategies for encountering people in a hallway scenario. However, few of these studies directly address the social conventions of encounters.

To fully appreciate the value of these methods and to fine-tune them to be socially acceptable there is a need for careful user studies. Butler and Agah [7] have reported about a survey with human subjects which investigated the psychological effects of robot motion patterns in three different tasks: person approach, person avoidance during passage and non interactive task. Among the factors evaluated in the user study, robot speed and robot distance from the user were considered to contribute significantly to the users perception of comfort.

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In the present study we consider the design of social patterns of spatial interaction for a robot that operates in hallway settings, based on the rules of proxemics (see Section II). In the design of these patterns a number of basic parameters must be considered, including: speed of travel, distance for early signaling and lateral distance for safe passage (as outlined in Section III). The basic experimental design is considered in Section IV. The present work has included a pilot user study in which participants were asked to rate the acceptability of the displayed behaviour. In Section V the user study is presented and in Section VI the overall results of the survey are discussed, prior to the summary and outlook in Section VII.

II. A Control Strategy based on Human Spatial Behaviour

Human spatial behaviour 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. Good overviews on proxemics literature can be found in Aiello [9] and Burgoon et al. [10]. In proxemics, the space around a person is divided into 4 distance zones:

1) 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.

2) 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.

3) 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.

4) 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.

It is important to realize that the personal space varies significantly with cultural and ethnic background. As an example, countries such as USA and the Netherlands have significantly larger distances that are to be respected in person-person interaction than Saudi Arabia and Japan. The passage/encounter among people does not only depend upon the interpersonal distance, but also the relative direction of motion. At the same time there are social conventions of passage that largely follow the patterns of traffic. So while in such countries as Japan, UK, Australia, the passage in a hallway is to the left of the objects, in most other countries it is to the right.

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. 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. 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. [11]).

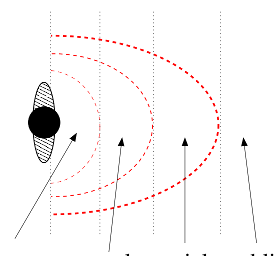

Fig. 1. Spatial distance zones for people moving through a hallway/corridor setting.

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". 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. In the event of significant clutter the robot should move to the side of the hallway and stop until the person(s) have passed, so as to give way. A number of basic rules for the robot behaviour 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 as far to the right as 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 behaviour 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. The strategy is relatively simple but at the same time it obeys the basic rules of proxemics.

III. The Passage Behaviour Parameters

Three parameters were considered as most significant when specifying the robot passage behaviour and will be evaluated in the user tests (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.

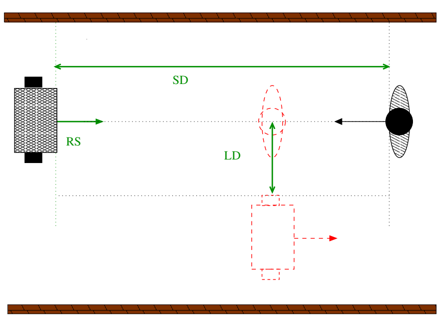

Fig. 2. Passage behaviour parameters.

It is of interest here to see how these parameters affect the users perception of the robot behaviour and how they are related with each other. The signaling and lateral distances are related with the personal space constraint and, as for the robot average speed during passing, it is interesting to know which speeds of the robot are comfortable for the users, and how the personal space dimensions are related to the robot speed.

IV. 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).

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

The system has an on-board Linux computer and uses the Player/Stage software (Vaughan et al. [12]) for interfacing the robot sensors and actuators. The four main components of the control system are (see Figure 4):

- A module for mapping of the local environment.
- A module for detection and tracking of people.
- A module for navigation in narrow spaces.
- A module for navigation among dynamically changing targets (persons).

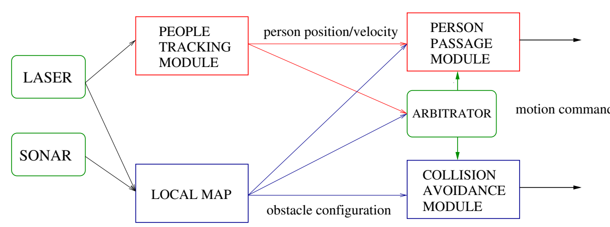

Fig. 4. The overall control system architecture.

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 people in the environment; it provides information about the current position of the people as well as their velocity. Both the magnitude and the direction of the velocity are important to decide when and how to react. A particle filter has been adopted, which can deal with the presence of multiple persons, similar to the one presented by Schulz et al. [13],

The navigation system relies on a local mapper that maintains a list of the closest obstacle points around the robot. Obstacle points are pruned away from the map when they are too far from the robot or when there is a closer obstacle in the same direction. The sonar data are processed through the Histogramic in Motion Mapping (HIMM) algorithm by Borenstein and Koren [14] before being added to the map.

The component for navigation in narrow spaces can deal with significant amount of clutter but it does not take the motion of the obstacles into account and it does not obey the rules of social interaction. The Nearness Diagram (ND) method by Minguez and Montano [15] has been chosen because it is well suited for motion among very close obstacles, a situation that can occur in a narrow corridor. The module for navigation among dynamically changing targets implements the Person Passage (PP) method and it is outlined in the next section. In our implementation, an arbitrator selects between the PP and the ND modes. The ND mode drives the robot safely along a corridor toward an externally defined goal, as long as no person is detected by the people tracker. As soon as the robot is approaching a person (i.e. the personal space of the person is about to be invaded) the control is handed over to the Person Passage module that ensues a passage maneuver that obeys the rules of social interaction. If the passage maneuver is not feasible (see Section IV-A), the robot stops until the user is at a safe distance, then the control is given back to the ND mode. Moreover, when in PP mode, if an obstacle is detected in a safety zone around the robot, the control falls back to the ND mode.

A. 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) determines the passage maneuver, and is computed as follows:

$$x_P^R = x_0^R + dX \quad (1)$$

$$y_P^R = y_0^R + dY \quad (2)$$

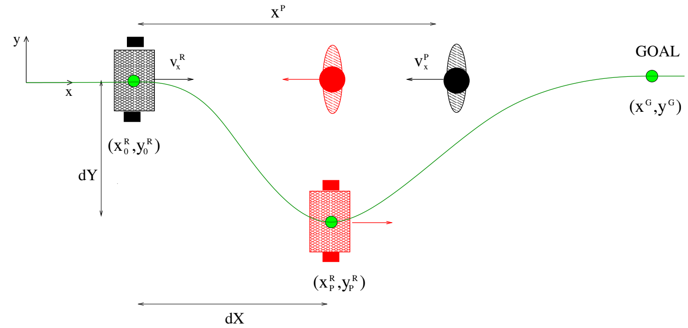

Fig. 5. Desired trajectory for the passage maneuver. The distance of the robot from the person is maximum when it is passing her/him (red).

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

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

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:

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

The trajectory speed depends on a maximum velocity parameter that changes the temporal parametrisation of the curve; the velocity along the curve is further reduced according to the curvature of the trajectory.

The robot starts the maneuver by clearly turning to the right to signal to the person its intent to pass on the right side, then 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.

The ability to adapt to the changes in speed of the person is crucial to establish a dynamic interaction between robot and person, and represents an important improvement with respect to the work of Yoda and Shiota [6], where separate conditions for a standing, walking and running person were considered.

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.

The trajectory following controller takes into account the differential drive kinematics of our robot to define the feed forward command (driving and steering velocity) (Oriolo et al. [16]):

$$v_D(t) = \sqrt{\dot{x_d}^2(t) + \dot{y_d}^2(t)} \tag{5}$$

$$v_S(t) = \frac{\ddot{y_d}(t)\dot{x_d}(t) - \ddot{x_d}(t)\dot{y_d}(t)}{\dot{x_d}^2(t) + \dot{y_d}^2(t)} \tag{6}$$

where $(x_d(t), y_d(t))$ is the reference trajectory. The controller includes also an error feedback in terms of a proportional and a derivative term.

V. The Pilot User Study

The implemented algorithm has been evaluated in a number of tests with human subjects. A family of passage behaviours has been tested according to different values of the chosen algorithm parameters. The psychological effects of the robot behaviour patterns have been analyzed to find the parameter configuration corresponding to the most acceptable passage behaviour.

The tests have been performed in the corridors of our institute (see Figure 6), which are relatively narrow (2 m wide or less). 4 people (2 males and 2 females) participated in the survey: a master student and three Ph.D. students. The subjects received a brief introduction about the purpose of the experiment and were then asked to walk along the corridor as naturally as possible. The robot passed the persons with the proposed approach, according to different values of the parameters that were set in each trial (see Section V-A). At the end of each trial the participants were asked to give feedback and to answer the survey questions.

Fig. 6. User study setting in one of the corridors of our lab.

A. The Parameter Setting

Two values for each parameter (speed, signaling and lateral distance) were set during the experiments (see Section VI for the real values): RS_1 and RS_2 ($RS_1 < RS_2$) for the desired robot forward speed, SD_1 and SD_2 for the desired signaling distance, $LD1$ and $LD2$ for the desired lateral distance, for a total of 8 behaviours tested for each user (see Table I). The order of execution of the trials was randomised, to compensate for the increasing familiarity (and the consequent comfort) of the user with the robot behaviour with the number of performed trials; besides, the parameters configuration in each trial was not known to the interviewers, to avoid any bias in posing the questions.

TABLE I

The behaviour parameters setting.

	Speed	Signaling Dist.	Lateral Dist.
Behaviour 1	RS_1	SD_1	LD_1
Behaviour 2	RS_1	SD_1	LD_2
Behaviour 3	RS_1	SD_2	LD_1
Behaviour 4	RS_1	SD_2	LD_2
Behaviour 5	RS_2	SD_1	LD_1
Behaviour 6	RS_2	SD_1	LD_2
Behaviour 7	RS_2	SD_2	LD_1
Behaviour 8	RS_2	SD_2	LD_2

B. The Survey

The participants were asked to report their feedback about the overall robot behaviour and about the individual factors (speed, signaling and lateral distances) for each trial. 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 behaviour and 5 that the user felt very comfortable.

There are some limitations in the survey that have to be considered in the interpretation of the results: the survey size is very small and all the subjects have a technical background with a certain degree of familiarity with robotics. A complete study should include a larger number of participants with a richer variety of backgrounds (including non-expert users). In spite of these limitations, we think that the work here presented can provide first indications on the factors that contribute to the user acceptability of the robot behaviour.

VI. Experimental Results

In the experiments, we set the value of the RS parameter controlling the maximum speed along the trajectory and the SD and LD parameters that define the shape of the curve (see Section IV-A). The values we set for each parameter (RS, SD and LD) are shown in Table II.

The results of the survey are presented in Table III (average ratings of the behaviours by the users) and Table IV (user ratings of the parameters). The overall response of the users

TABLE II

THE PARAMETER VALUES USED IN THE EXPERIMENTS.

Parameter	Value 1	Value 2
RS	0.5 m/s	0.6 m/s
SD	4.0 m	6.0 m
LD	0.3 m	0.4 m

to the experiments was good and in spite of the individuals differences in the evaluation, it has been possible to detect similar attitudes toward the single factors and the overall robot behaviours. It is important to underline nevertheless that, given the limited size and the characteristics of the user set (laboratory personnel), no strong conclusions can be inferred from the experiments but rather indications that we expect to be confirmed in an evaluation with a wider and more complete set of users.

TABLE III

SURVEY RESULTS: USER AVERAGE RATING OF THE BEHAVIOURS.

Behav.	Overall Behav.	Speed	Sign. Dist.	Lat. Dist.
Behav. 1	3.5	3.75	3.0	3.25
Behav. 2	3.5	3.75	3.5	3.5
Behav. 3	4.25	3.75	4.5	4.5
Behav. 4	4.0	3.75	4.5	3.75
Behav. 5	3.25	4.25	3.25	3.5
Behav. 6	4.0	4.0	4.0	3.5
Behav. 7	4.25	4.25	4.75	3.75
Behav. 8	4.75	4.25	5.0	5.0

TABLE IV

SURVEY RESULTS: USER PARAMETER RATING.

Parameter	User 1	User 2	User 3	User 4	Average
RS_1	3.5	5	2.25	3.25	3.5
RS_2	4.75	5	3.5	3.5	4.2
SD_1	3.25	3.5	3.75	3.25	3.44
SD_2	4.75	4.75	4.5	4.75	4.69
LD_1	3.5	4.67	3.25	4	3.85
LD_2	3.75	4.8	3.25	3.67	3.87

A. Robot Speed

The values (RS_1 and RS_2 in Table II) set for the robot maximum forward speed resulted in different values for the robot average forward velocity. Due to the trajectory parametrisation that reduces the robot speed according to the curvature radius of the trajectory in fact, the trials that used the smaller signaling distance SD_1 resulted in smaller average speeds. This however didn't affect the results as the two sets of average speeds achieved in the two cases RS_1 and RS_2 were considerably different, for each signaling distance value (SD_1, SD_2). The average forward speeds range from a minimum value of 0.25 m/s to a maximum value of 0.39 m/s. The reason for these relatively small values is that the average is computed in the time interval from the time when the robot starts to move to the side to the time in which the robot has reached the passing point, and that's when the robot trajectory is slowed down more. This speed has been considered appropriate, considering that the robot is maneuvering in a narrow corridor and at a close distance from the person. The average robot speed for the complete trajectory is higher: the robot starts at the maximum speed, then it slows down to pass the user and then resumes gradually the maximum speed.

It is clear from the users feedback (see Table IV) that higher speeds are preferred. An explanation for this result is that the robot moves faster to the side. Furthermore, the lower speeds were perceived as less safe or even annoying by the users. It is important to underline that the higher speeds during passage were still not higher than 0.4 m/s so they were never perceived as intimidating.

B. Signaling Distance

The values used for the signaling distance parameter are shown in Table II.

As shown in Table IV, the higher value of the signaling distance (SD_2) was highly preferred by all the subjects. To further confirm this result, the larger signaling distance was employed in the behaviour that was considered the best for all the users and in all the behaviours that received the lowest rate, the lower value for SD was used. Although not necessary to avoid the user, a large signaling distance is important for the robot behaviour to be clearly understood. An early maneuver allows the robot to signal its intent, so its behaviour is perceived as trustworthy by the user and it contributes to an effective interaction.

C. Lateral Distance

Because of the limited dimensions of the hallway in which we where operating, it was not possible to control the exact value of the lateral distance, as opposed to the SD parameter. So, the desired lateral distances set for each trials (see Table II) resulted in smaller values in each experiment according to the person's position with respect to the robot and the corridor walls. The actual lateral distances in the experiments range from a minimum of 0.099 m to a maximum of 0.430 m. For every couple of behaviour with the same value of RS and SD, we have chosen LD_1 as the one with the smallest LD value; the two values were always different enough to avoid any ambiguity.

The lateral distance evaluation is more complex than the previous parameters. No clear indication emerges in the tests about which value is to be preferred (see Table IV). An explanation for this is that, as long as the robot signals its passage intention early enough by moving to the side, the lateral distance value does not play an important role. This is especially true when the user reacts by moving to her/his right as well. On the other hand, if the user just proceeds straight during passage, a more appropriate value for the lateral distance would be necessary and some of the values used in the experiments could have been not high enough (due to the limited dimension of the corridor) to be perceived as safe from the users.

It is believed that the perception of this parameter is affected by the attitude of the user toward the robot. Two categories of users have emerged from the tests. The first one behaves as if the robot was a person and respects the social rules of passage: these users left space to the robot by moving to the side and had a positive evaluation of the lateral distance parameter. The second group of people consider the robot as a machine that has to give them way; often during the tests, these users walked straight to see how the robot reacted to their behaviour. They were often not completely satisfied with the LD parameter.

D. Overall Behaviour Evaluation

The best behaviour was, according to all the subjects, behaviour 8 (see Table III), i.e. the one with highest speed and largest signaling and lateral distances; it received the higher behaviour rate and the higher rates for all the parameters. This confirms that both the higher values of the robot speed and the signaling distance have to be considered in the definition of an acceptable passage behaviour. In this configuration the lateral distance received the highest rate too, to suggest that an higher value for it is to be preferred. Moreover, it emerges from the data that the lateral distance perception is affected by the overall parameters configuration and its evaluation has to be related to the behaviour configuration.

A few words need to be said on how these results could be affected by the special set of users involved in the experiments. All the user had a certain degree of familiarity with robotics and they were all comfortable in presence of the robot. This could explain both their positive attitude toward the higher speeds (as observed in Khan [17]) and the "less polite" attitude of some of them during passage. The attitude of users that have no experience with robots could be different. In particular for this category of users, it would be interesting to verify if the same speed values work as well and which kind of interaction the users establish with the robot. These issues should be investigated to achieve a more complete evaluation.

VII. Summary/Outlook

As part of human robot interaction there is a need to consider the spatial interaction. For operation in environments where users might not be familiar with robots this is particularly important as it will be assumed in general that the robot behaves in a manner similar to humans. There is thus a need to transfer the rules of human spatial behaviour into control laws that endow the robot with a "social" intelligence. In this paper the problem has been studied, in the case of person passage in a hallway and a control strategy has been presented, based on definitions borrowed from proxemics. Three basic parameters have been considered in the design of the interaction strategy: signaling and lateral distances and robot speed of travel.

The value of the approach has been evaluated in a pilot user study in a corridor of our building. Four persons belonging to the lab participated in the experiments. Some important indications have been achieved on the user acceptability of the method and on the behaviour parameters tuning. These results might not be immediately generalized, and should be verified in a complete study with an appropriate number of users including non-technically oriented subjects.

The hallway passage is merely one of several motion behaviours that a robot must be endowed with for operation in spaces populated by people. Human-robot spatial interaction in environments other than hallway settings pose more complex questions. The achievement of social skills in a complete set of environments is felt nonetheless necessary and it is an issue of current research.

Acknowledgments

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