We could use our framework to test various navigation strategies to reveal the most appropriate navigation mechanism; in fact, we explored the navigation strategy of the robot using this same simulator, and the results of our analysis will be reported elsewhere [17]. In this paper we report only the most suitable strategy we found.

The idea underlying the navigation mechanism is to use a strategy similar to that used by pedestrians, to obtain human-like collision avoidance in the robot. To this end we used the social force model [8] with the human-robot parameter values. In concrete, given the local destination to obtain the preferred velocity, the system computes the robot's desired next position on x-y coordinates using the “collision prediction” (CP-SFM) social force model of eq. (1), and converts it into a polar coordinates velocity command ($vp,\ \omega p$). However, we needed to consider the discrepancies between the "ideal" simulation world and the real one as, for example, slow acceleration, the inability of our differential drive robot to move aside, the noise in the human tracking system and the computation delays; discrepancies that cause the robot’s trajectory to diverge from that determined by the “ideal” model. To compensate this difference, we further calibrated the pedestrian model parameters to fit the real world behavior (see section 4.1). The polar coordinates ($vp,\ \omega p$) velocity command is finally examined through a safety-check mechanism, a time varying dynamic window method [19] using a 1.5 sec window time by considering maximum speed and acceleration of our robot, which is long enough to stop the robot.

3.5 Simulator

The simulator is used to test the robot navigation, reproducing people's walking behavior around the robot. The simulator has three sub-modules: pedestrian simulator, noise/delay simulator, and the robot's motion simulator.

The pedestrian simulator computes pedestrians’ positions every 100ms, on the basis of the pedestrian model [8]. The noise/delay simulator simulates the noise in sensing, modeled as a Gaussian noise, and delay in observation and computation. The parameters of the noise simulator were decided on the basis of data collected in the target environment (section 4.1). The robot's motion simulator simulates the movements of the robot by using the robot controller taking also in account the dynamics of its two-wheeled mobile base.

Fig. 6 shows the trajectories of the robot (red ellipse) and of a pedestrian (black ellipse) that got closer and stopped around the robot before directing to his goal. As the pedestrian approached the robot, the latter deviated to the right and was able to avoid him, even if the pedestrian approached and stopped around the robot.

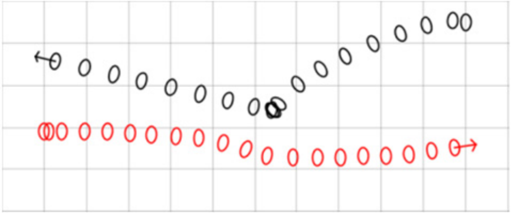

Fig. 6. Trajectories in simulation

4 Simulation

4.1 Overview

The simulation was conducted in a 10 x 20 m virtual corridor. The simulator sets people's initial positions and goals to opposite sides of the corridor, along with their arrival time to the environment and preferred velocity (average and S.D are 1.4m/sec and 1.33, based on the data collection in Section 3.3.1). The ratio of HRI type behaviors is set as the same as the one observed in data collection (section 3.3.1). We also measured the delay of the system in the laboratory, which resulted to be 350msec, and defined the noise of the sensing system as 0.06m, as reported in [7]. The initial position and goal of the robot are set as for the pedestrians.

By using delay and noise information, we further calibrated the values of the pedestrian model parameters to obtain in the real robot system trajectories as similar as possible to the "ideal" ones (i.e. obtained using the HRI model with no noise or delay). As a result, the parameters for the real robot were increased to Ar= 0.93, Br =1.61, showing that the collision-avoiding interaction has to be strengthened to cope with the robot's motion limitations.

4.2 Measurement

We propose two performance measures:

Ratio of collision: we defined a collision initiated by the robot as a situation in which the distance between a center of person and the center of robot gets smaller than 30cm, and the ratio of collision was computed as the number of collisions per the number of people who entered within a 5m distance from the robot. In this evaluation, we did not count collisions caused by a pedestrian, defined as either a) a pedestrian collided with the robot while it was stopped, or b) a pedestrian collided with the robot from behind. Note that in the real world collisions might not happen even if this distance is attained, as humans may rotate their body to avoid the collision; nevertheless this is a valid measure of the safety of the robot's behavior.

Efficiency: defined as: "time to reach the goal" over "time to reach the goal going straight at preferred speed". Deviations due to collision avoiding reduce efficiency.

4.3 Results

To confirm the safety capability of robot navigation in various situations, we conducted simulations by increasing density from 0.01 to 0.05 people/m^2 with 0.01 intervals. In each density setting, we conducted 1000 simulations.

Fig. 7 shows *efficiency* and *ratio of collision* in each density setting. We had *ratio of collision* 0% until density 0.03, while the robot caused 0.01% and 0.02% collisions at density 0.04 and 0.05, respectively. The *efficiency* at density 0.01 was 79%, and it decreases with increased density (65% at density 0.05).

The final publication is available at
http://www.springer.com/gp/book/9783642343261?wt_mc=GoogleBooks.GoogleBooks.3.EN&token=gbgen#otherversion=9783642343278

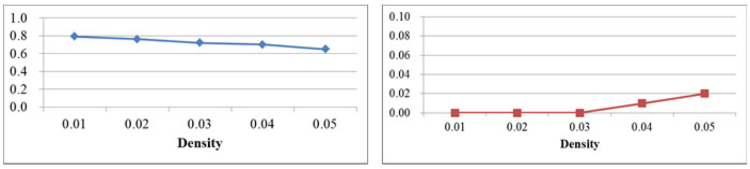

Fig. 7. Efficiency (left) and ratio of collision (right) in simulations

5 Field Trial

5.1 Overview

According to the results of simulations, our robot has enough safe capability in real environments provided that the density is not higher than 0.03. To confirm this prediction, we conducted a field trial in a real environment with characteristics similar to the simulated one. Fig. 8 shows the corridor of a shopping mall in which we performed the field trial, an area of size 10 x 20 m, in which people walk with an average speed of 1.32m/sec (s.d. 1.33) at a density up to 0.03 people/ m^2. The purpose of the field trial is to test (a) whether the robot safely navigates as predicted by simulations, and (b) whether the efficiency trend is reproduced as predicted.

The robot was fully autonomously operated, except for the start signal sent by an operator to trigger it to move. After receiving the signal, the robot moved from points A/B to B/A (we defined a single movement between these points as one trial).

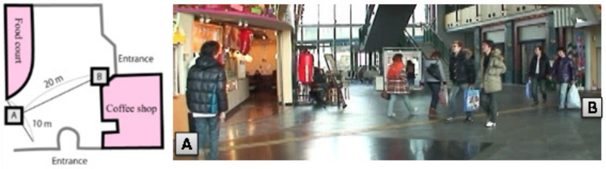

Fig. 8. Map and image of the field trial site

5.2 Measurements

To confirm whether the robot could navigate safely in a real environment, we measured *efficiency* and coded whether the robot's behavior caused any problems in terms of safety, i.e., for each person who walked within 5 m from the robot, we asked *coders* to determine whether the situation was safe, using the following criteria:

Unsafe: due to the presence or motion of the robot, the pedestrian had to make a quick change in his/her moving direction to avoid colliding with the robot.

Otherwise, the person's situation was coded as **safe**.

5.3 Results

In the field trial, we conducted a two-hour test consisting of 27 trials. Two coders classified the interactions between the robot and the 160 pedestrians that walked within a 5 m distance from it as safe or unsafe by observing the recorded videos. Cohen's kappa coefficient was 0.89, indicating high consistence. Moreover, for consistent analysis, the coders discussed and reached a consensus on all the observed situations.

Fig. 9 shows *efficiency* and *unsafe situation* in the field trial. As shown in the figure, no *unsafe situation* was found, confirming that our system safely navigates the robot in both simulated and real environments. The *efficiency* was 59%, 58% and 51 % for density 0.01, 0.02 and 0.03, respectively. These values are lower than the simulated ones, possibly due to the more complex behavior of actual pedestrians (the models reproduce only average pedestrian behaviors; introducing stochasticity in pedestrian decisions could thus reduce the gap between simulations and the real world). However, the results showed a trend similar to the simulated one (an increase in density caused a decrease of efficiency). These results suggest that our simulation system reproduces properly the interaction between the robot and a pedestrian crowd.

Fig. 10 shows a scene in which the robot successfully navigated in a many-people setting. The robot initially changed its moving direction to avoid a group of people, just to meet another incoming group (Fig. 10-a). As a result the robot slightly deviated to slip through the groups (Fig. 10-b). After avoiding the two groups, the robot tried to reach its goal, but another pedestrian was coming from the goal direction (Fig. 10-c). Therefore, the robot deviated again to avoid the pedestrian and eventually headed toward its goal (Fig. 10-d).

The robot was equally able to deal with pedestrians that tried to approach it, as predicted by our HRI type behaviors. In Fig. 11 we analyze one of these situations. While heading to its goal, the robot met a group of pedestrians coming from the opposite side (Fig. 11-a). After noticing the robot, a pedestrian deviated suddenly to approach it, and the robot changed its moving direction in order to avoid him (Fig. 11-b). The pedestrian continued to approach the robot despite this avoiding maneuver (Fig. 11-c), but the robot could safely cope with the pedestrian's motion (Fig. 11-d). These examples illustrate that the robot is able to navigate safely in the real environment as well as in the simulated environment.

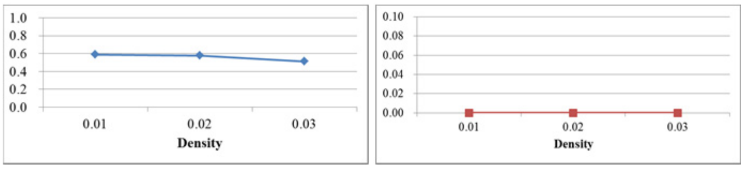

Fig. 9. Efficiency (left) and unsafe situations (right) in the field trial

(a) (b) (c) (d)

Fig. 10. The robot safely navigates through pedestrians in the mall

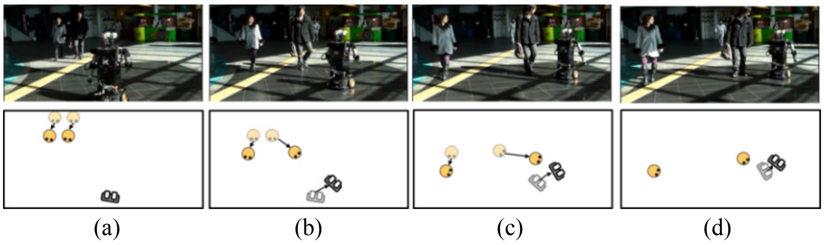

Fig. 11. The robot safely avoids an approaching pedestrian

6 Conclusion

We report our framework to deploy robots in a real shopping mall environment. We used a pedestrian simulator in order to develop and estimate the safety of the robot navigation system among a human crowd. In the simulator we employed a particular specification of the Social Force pedestrian model that has been developed to describe the relatively low-density settings occurring in shopping malls and the like [8]. We further addressed the diverse behavior of pedestrians toward the robot, i.e. we gathered data from a real environment and built a "HRI behavior model" for people slowing down to look at the robot, or approaching and stopping for curiosity, and included such a model in our simulator.

We first tested the developed robot, which is navigated using the same collision avoidance model used for simulated pedestrians, in a simulation to confirm its safety. The results showed that the robot safely navigated among people with reasonable efficiency. Given that the simulation yielded safe navigation for densities up to 0.03 people/m^2, we estimated that we could deploy it in a real world environment with a similar density. To confirm this estimation, we conducted a field trial in a real shopping mall, and the results of this trial demonstrated that the robot can navigate safely among people even when facing complex situations.

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