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Evaluating Group-Robot Interaction in Crowded Public Spaces: A Week-long Exploratory Study in the Wild with a Humanoid Robot Guiding Visitors through a Science Museum

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Abstract:	This paper describes an exploratory study on group interaction with a robot-guide in an open large-scale busy environment. For an entire week a humanoid robot was deployed in the popular Cosmocaixa Science Museum in Barcelona and guided hundreds of people through the museum facilities. The main goal of this experience is to study in the wild the episodes of the robot guiding visitors to a requested destination focusing on the group behavior during displacement. The walking behavior follow-me and the face to face communication in a populated environment are analyzed in terms guide-visitors interaction, grouping patterns and spatial formations. Results from observational data show that the space configurations spontaneously formed by the robot guide and visitors walking together did not always meet the robot communicative and navigational requirements for successful guidance. Therefore additional verbal and nonverbal prompts must be considered to regulate effectively the walking together and follow-me behaviors. Finally, we discuss lessons learned and recommendations for robot's spatial behavior in dense crowded scenarios.
Response to Reviewers:	See separate file

Dr.Ming Xie (Nanyang Technological University)
International Journal of Humanoid Robotics
Editorial Board Member

July 14, 2014

Manuscript Reference Number IJHR-D-13-00060. Cover Letter

Dear Dr. Ming,

Thank you very much for your kind response. We appreciate the opportunity to resubmit our manuscript (reference number IJHR-D-13-00060). Accompanying this letter, please find the revised version. Modifications and changes has been completed according to the reviewers' suggestions. We are providing below a point-by-point response to the reviews.

Response to Reviewer 1

Thanks a lot for your kind comments and helpful review. Response to the review:

"... The figure quality in the paper should be improve, and some pictures from recording camera should be explained and analysed more clearly. Fig.10 is redundant.,..."

According to your feedback, we have paid more attention to the quality and explanation of the images. It should be noted that certain figures (e.g. Figure 7) have been deliberately manipulated in order to protect the people's privacy. Figure 10 was omitted.

Response to Reviewer 2

We appreciate your detailed response. We have reviewed the manuscript and organized to follow your guidelines, which have helped to strengthen the scope of our work.

For your general comment, *"..what is unclear to me is what the actual contribution of this paper would be to the wider community. I don't believe enough has been done in this regard, either in terms of relating this to existing work, or to drawing out general lessons from the specifics of this study.."*

Exploratory work has been refocused to study interactions with groups in real environments using systematic observation techniques in general, focusing on the study of the composition of groups, size, spatial arrangement and interactive behaviors in particular. Under this improved scheme both related work and observational data analysis have been better explained and structured.

For your detailed comments,

"..Firstly, the paper in general seems to be overly introspective, reading more like a technical report. This makes it more difficult to see how to generalise the observations made in this paper to other work. .."

In our study we have performed a more comprehensive analysis of data, they have been better detailed, gathering information on its main components (e.g. for the size of the groups, rather than analyze them in groups from 1 to 9, we have classified them in couples, triples and larger groups), providing better statistical information and comparative results between them.

"..Secondly, while mention is made to other studies, these are only superficial and not particularly comprehensive, but also don't seem to have made much impact on the present study. In section 2 (which is quite short) for instance, there are a number of recommendations from other studies mentioned. For example (p4) one of these is that the robot can engage in some social behaviour to compensate for some shortfall/error in navigation. However, this very point was discussed as a future design requirement based on the observed results (section 6.2). Why was this not taken into account in the first place given that it was provided in the background to the work? .."

In our study, although the design of the robot behavior is very important in HRI, this is not the most important point of our work, but to analyze the group HRI in real environments using direct observation techniques.

"..In the introduction, the authors describe the various measurements that were taken throughout the study. These range from the two video cameras in the environment, to an on-board robot camera, and robot touchscreen interaction recordings. From these, the authors stated their intentions in terms of data analysis: characterising the interaction behaviours of visitors, and thereby identifying the key cognitive behaviours of the robot. These aims are very interesting, and providing analysis along these lines would have led to a paper with a good deal of interest to other researchers in the field, and indeed to practical applications. Unfortunately however, I feel that the results actually presented fall somewhat short of these expectations..."

This valuable comment has helped us to refocus our work to study group HRI in natural environments in the specific case of visitors walking with the robot (follow-me behavior). To characterize the behavior of groups, the observational data have been reclassified and detailed (with greater statistical rigor) in: groups description (both in composition (age) and size)(from external cameras), group spatial arrangement (from external cameras) and interactive behaviors(from the on-board robot camera).

"Given that a significant part of the study described is concerned with the spatial relationships between the robot and people, it seems a bit of an oversight that the literature on proxemics is not leveraged at all (of which there is a fair amount) in relation to the results obtained. While it is mentioned as something of interest to the study, there is no relationship to existing work in the area. Indeed, when it comes to spatial relationships between the robot and various groups of museum visitors, the authors provide very little objective analysis, stating instead that this work still needs to be carried out (section 7). It seems to me that this sort of analysis is precisely the sort of contribution that this manuscript should be

making (based on the expectations raised in the abstract/introduction), but does not. In this regard, section 5 seems inadequate since the results are primary presented in the form of a series of images, which says very little beyond the precise scenarios portrayed without additional analysis...."

As mentioned above, we emphasized on the objective analysis of the observed data, and we introduced more detailed information, statistically described, so that the information may be more useful to the HRI community.

"Regarding the results more generally, they seem to be descriptive in nature only, without any great analysis or interpretation of human interactive behaviours. For example, results tables 6, 7 and 8 provide only a course breakdown of observed aspects of phenomena, with the associated text only provides anecdotal information rather than objective analysis (e.g. section 5.3). While there is in my opinion certainly a useful role for such qualitative observations, I feel that this works best when used to contextualise a more formal treatment. For example, in section 5.2, there is a description of a few different types of human groupings when following the robot - but the significance of these is not explored, and indeed even a proper characterisation of these different groupings (and proportions of occurrence) is not proposed..."

The improvements allow us to present the results in a more objective way in the analysis of: the group's description (composition and size), the group spatial arrangement and the interactive behaviors.

"Finally, a comment on the primary authors goal to test the robot's robustness. Generally, this section is very introspective, which perhaps can be forgiven since it would necessarily be platform dependent. However, it also seems to be rather independent from the rest of the presented results, introducing observations that were not mentioned before. For example, in the description of situations where the emergency button was pressed, the authors infer that the people did so because they did not see the robot respond as expected. While such an issue would be very useful to know, there is no support given to this assertion, no evidence..."

This section has been omitted, since it does not fall within our new approach

Specific points

"– p2, the authors state that the difference between an information point and a robot guide s that the latter has to perform "social navigation in a dynamic scenario". In this context, how does social navigation differ from normal navigation? Does the fact that people are involved necessarily make it social, or are there other specifications that are required?."

After the statement, has added the following definition: "ie, that the social robot navigation design must consider the actions of people around them. "

"– p8, figure 4: a couple of questions: firstly, are all interactions with the robot started through the touchscreen, and if so, does this not detract from the robot social behaviour? Secondly, how are situations handled where the people change their mind or do not follow when the robot guides (the control paths for these situations are not shown)?"

1) That's right, the robot starts guiding through the touchscreen. It is not

clear that the use of such non-natural interfaces may affect the perception of the social behavior of the robot, in any case, this is an interesting research topic in the design of robot behavior that can be addressed in the future.

2) The robot behavior was not designed for these cases, so that the robot would continue its trajectory. Such cases were excluded from our analysis.

Given the dynamics of the natural environment for autonomous robot these two issues represent a huge challenge, out the scope of this research.

"– at the end of section 3.5, it is stated that the social robot was intentionally run in a busier period than the passive robot. Does this not provide a confound when analysing the results, since there are different numbers of people in each condition by design?"

As mentioned at the end of section social profiles: "The incompatible restrictions of keeping the experimental controlled conditions (social profiles schedule) vs. having a more realistic and social experience, entailed to consider the most social profile within this study, which is the *sociable* profile", only the social profile was taken into account.

"– p11: a ad-hoc coding scheme is mentioned - what sort of coding is used precisely? Is the coding manual available, and what coding tools were used (e.g. Anvil, Observer, etc...)? Table 5 shows the categories, but was the time period also recorded, and was the data second-coded?"

In this newer version the preparation of the video signals as well as the encoding scheme are better detailed(Study Design Section).

"– p13, table 6: does the result listed in the final line of the table imply that in only 5% of all cases did the follow-me episodes conform to the system design? What implications does this have? Conversely, does this table actually just highlight that a lot data is missing?"

5% corresponded to scenes where all the guidance states were observed. Yes, indeed several scenes of interaction were lost, but given that our study was focused on the guided state, from our point of view this does not represent a major problem. Since our study is focused on the guiding state, the table was not included in this new version.

"– while typically not detracting from the clarity of the paper, this manuscript would benefit from an improvement in the English used throughout (specifically, the use of commas is excessive)"

We have tried to to improve the wording of the article making a more detailed review of it.

Thanks again all the reviewers for their fruitful comments and positive feedback.

Sincerely,

Dr. Cecilio Angulo
Technical University of Catalonia -
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This paper describes an exploratory study on group interaction with a robot-guide in an open large-scale busy environment. For an entire week a humanoid robot was deployed in the popular Cosmocaixa Science Museum in Barcelona and guided hundreds of people through the museum facilities. The main goal of this experience is to study in the wild the episodes of the robot guiding visitors to a requested destination focusing on the group behavior during displacement. The walking behavior *follow-me* and the face to face communication in a populated environment are analyzed in terms guide-visitors interaction, grouping patterns and spatial formations. Results from observational data show that the space configurations spontaneously formed by the robot guide and visitors walking together did not always meet the robot communicative and navigational requirements for successful guidance. Therefore additional verbal and nonverbal prompts must be considered to regulate effectively the walking together and *follow-me* behaviors. Finally, we discuss lessons learned and recommendations for robot's spatial behavior in dense crowded scenarios.

Keywords: Group-robot interaction; Robotic-guide, Social navigation, Space management; Spatial formations; Group walking behavior; Crowd behavior.

1. Introduction

Service robots are increasingly taking part of people daily life activities interacting socially and sharing spaces with individual and groups in close proximity. For social robots featured with walk around functionality, key questions to be addressed for effective performance are how to move (i.e. speed, kind of movement, trajectories), where to perform (i.e. proximity management) and how to place (i.e. distance, position, stance and orientation) to be unobtrusive, effective and socially congruent.

Promising attempts to optimize social robots spatial management in different scenarios (e.g. assistive telepresence at home) have been done applying models and knowledge from social psychology (i.e. proxemics, space formations, group walking patterns and crowd dynamics). Guidance is one of the most useful services of robots in public spaces as museums, exhibitions, malls, and tourist sites. Assuming the role of guide the robot not only provides people with appropriate information to make the visit a more enjoyable experience but help them to reach intended destinations. The main difference between an informer or recommender robot and a robotic guide is that guidance in public spaces implies social navigation in a highly dynamic scenario; i.e., that the social robot navigation design must consider the actions of people around them.

Socially compliant navigation[1] implies planning and performing robot's trajectories and motion behavior taking into account the communicative function and social rules of space management in a shared location. Smart spatial behavior (e.g. interpersonal distance, orientation) according to social norms would not only enhance collocated user's safety and acceptance but also provide mobile robots with an intuitive rich nonverbal channel to communicate intentions (e.g. shift direction, initiate displacement) and to express emotional content[2].

To explore guide robot-visitors performance in open large-scale dense environments PAL Robotics' REEM robot was deployed during a week in the CosmoCaixa Science Museum informing, motivating, giving directions and walking groups of visitors to requested locations. The whole experience was video-recorded by two external general-view cameras and one on-board camera for observational data analyses. Our approach is to put the focus on the group spatial behavior rather than on individuals taken as independent agents. Therefore, in this paper group features (i.e. composition, size), and spatial and motion behavior (i.e. formations, trajectories) will be described and analyzed –based on the knowledge on group walking and crowd dynamics–, as well as communicative behavior towards the robot. Lessons learned from this long lasting experiment in the wild could also be considered for designing spatial behavior of mobile service robots in other contexts as receptions, leisure parks or hospitals.

In the next section findings from previous work on guide-robots in open large-scale environments and related knowledge from the fields of proxemics and group walk are reviewed. In Section 3, the experience at CosmoCaixa Science Museum Barcelona is described. Next, analysis of recorded human-robot social interaction data is detailed with special focus on the *follow-me* episodes. A discussion and recommendations for improved experience design follow in Section 6. Finally, some conclusions are provided and further research is pointed out.

2. Related Work

Mobile service robots may deploy their activity in close proximity to people either in closed (e.g. home[3], school[4], office, nursing home[5]) and open environments (e.g. exhibitions[6], museums, malls). In closed environments the occupants are known, and often belong to few homogeneous profiles (e.g. ages, familiarity to technology). On the other hand, in open public spaces occupants are unknown, diverse, variable and dynamic often including heterogeneous profiles (i.e. teenagers, staff, elderly). A frequent situation in large-scale open public environments is the configuration of dense crowds that the robot is supposed to travel through fulfilling safety (the primary requirement of a robot operating in a public space), reliability and social requirements at a time.

Moreover, robots with the “walk around” functionality get involved in spatial relationships with people[7,3]. Spatial relationships are a combination of distance, relative position and orientation that occur naturally whenever two or more people engage in an interaction[8] and convey significant and relevant social information (e.g. how each of them is involved) and also define an interpersonal space for developing activity.

Empirical studies in telepresence have identified the management of spatial relationships between people and robot as a main issue in order to improve the quality of interaction taking into account that interpersonal distances convey significant and relevant social information[7]. Based on Kendon’s model[9], the authors identify space formations or spatial patterns (e.g. vis-a-vis, side-by-side, L-shape, follow or ahead) related to the roles adopted by the robot, the activities and the spatial constrains, as well as individual variables such as familiarity with the agent. An interesting conclusion is that when physical constraints (e.g. narrow passages) in combination of navigational requirements unable the robot to maintain the convenient spatial behavior, it can compensate this situation with other interactive behaviors (e.g. verbally apologizing for an inappropriate distance or reducing the eye-contact) to maintain an overall degree of desired intimacy.

An open public scenario where autonomous mobile robots has been deployed are museums. Three aspects make the robot navigation in a museum specially difficult: the robot has to guide visitors through dense crowds, some elements of the physical space could be “invisible” to the robot (e.g. glass walls) and the configuration of the environment change frequently (e.g. pieces of furniture, fences). The robot guide in a museum faces two primary challenges: navigating safely, reliably and socially through crowds, and interact with people in a compelling and intuitive way[10].

Guidance is a demanding collaborative task that requires communicating intentions (i.e. robot offers the service, visitors select a destination and request the bring me there function, the robot head towards the destination) and social navigation (i.e. walk together to the target location). Walking along following the leader implies complex space regulations (i.e. distancing, spatial configurations) to allow guide and visitors group up and walk together effectively. These space relationships during guidance must be at a time socially meaningful and compatible with the robot's navigation specifications (i.e. collision avoidance performance).

To model the navigation through crowds of dynamic agents with uncertain trajectories some attempts has been done drawing inspiration from the pedestrians behaviors in dense environments, where people usually engage in "joint collision avoidance" (called the social forces model) and adapt their trajectories to each other to make room for navigation[11]. This model is proposed to overcome shortcomings of models based on anticipate trajectories taking each individual as independent agents that often lead when tested in the wild to ineffective overcautions robot behaviors and even to "freezing the robot" when people attracted by the robot surround it and once the environment surpasses a certain level of complexity, the planner decides that all forward paths are unsafe and freezes in place to avoid collisions. In the case of the "freezing problem", the focus on group collaborative behavior rationales can be more fruitful to design robot's ability to elicit the natural cooperative behavior of making room to create feasibly trajectories. Verbal and nonverbal cues as look at the intended direction or asking for permission could be enough to make room for safe navigation.

Communication between robot and users in this scenario is complex. According to its role, naturally the guide communicates with dynamic groups of different sizes, densities and composition often walking around in busy environments . Thus, the simpler models of one-to-one and face to face human-robot interaction are largely surpassed in this context. Moreover, in the social situation of visiting a museum (as an entertainment venue) people are likely to be curious, active and attracted by new appealing things as the robot itself. Exploration of the robot and of its limits [12] is a natural behavior that sometimes lead to malfunction (e.g. push the emergeny stop button) and even to damage the robot seriously. Malicious or vandalic are also observed, therefore the robustness of the robot and even resilience to physical abuse is a key specification for public robots design[13]. Several robotic museum guides as Minerva[14], Robovie[5], RoboX[6], Rhino[10], Chips, Sweetlips, Joe And Adam40-80[13] do quite well in addressing people and keeping their attention, however interaction between robots and humans is still limited due to the highly challenging environment. As far as we know, research on robotic guides has mainly focused on verbal and non-verbal communicative behaviors (i.e. dialog) to improve the visitor experience in static situations rather than on the spatial arrangements during guidance.

On the other hand, although there are several studies that evaluate the HRI by spatial relationships, these are framed only in the individual and in closed and non-natural environments[15,3,7,16,17,18]. An interesting approach related to spatial relationships, buy in crowds of pedestrians, were conducted by Bandini et.al.[19]. In this work, Bandini analyzes the behavior of groups such as the characteristics of the groups and their group spatial arrangement while walking in dynamic environments. From an empirical research, different patterns of group spatial arrangement (e.g. line- abreast, v-pattern and river-like) and its significance in relation to the social cohesion of the group were analyzed.

The present study focus on the description of *follow-me* group behavior from observational data gathered in naturalistic studies in the wild, applying models from group spatial management (i.e. proxemics, group walking[20] and crowd dynamics[19] in a qualitative approach.

3. The Experience at Cosmocaixa Museum

This section discusses general issues related to the design and development of the experience at CosmoCaixa Science Museum Barcelona: our main objective, the employed service robot, the working scenario in the museum, the task to be completed by the robot, and, finally, the social profiles defined in the robot.

3.1. *Objective*

The main goal of this experience was to study HRI in the context of a science museum. Our study focuses on the episodes of the robot guiding visitors to a requested destination in special on the group behavior during displacement. A field trial in an open, natural and very interactive environment as a science museum is a good option to deal with this goal.

This in-field approach is also interesting and very useful from the point of view of HRI. In the laboratory, most of the people tend to act as they think that the researchers would expect, thus experiences lead to biased results. The opportunity of having the robot REEM freely running at CosmoCaixa Museum allows to study visitor's behavior in front of such a robot, at this precise moment, when robots are still not very common in everyday environments. Additionally, this long-term natural-environment experience serves to observe robot acceptation in society nowadays, obtaining behavioral data, and allowing to propose some development guidelines and strategies for a near future.

3.2. *Humanoid robot*

REEM is a 1,65m high humanoid robot with 22 degrees of freedom. The upper part of the robot comprises of a torso with a touchscreen, two motorized arms, which give it a high degree of expression, and a head, which is also motorized, as shown in Figure 1. The robot has a mobile base with wheels, allowing it to move at 5 km/hour. It contains a small platform, which can be used to transport objects (e.g. a trolley). Finally the mobile base contains a lithium battery that lasts up to eight hours, allowing the robot to move around freely without the need of cables or human assistance. A complete range of sensors (cameras, ultrasonic, lasers) ensures the robot to find its way safely, avoiding obstacles and people. REEM is also equipped with several resources as verbal and nonverbal communication that facilitate human-robot social interaction (as shown in Table 2).

For safety reasons, some specifications about motion and navigation were set to very conservative values for this experience, as well as arms motion was very constrained to a limited space. The robot, even if monitored, was fully autonomously working and users' injuries must be absolutely avoided.

Fig. 1: REEM robot from PAL Robotics.

3.3. *Physical setting*

CosmoCaixa is a science museum located in Barcelona, Spain. The museum features a variety of exhibitions, permanent and temporary, that showcase the environment, nature, science, and space. A planetarium is also available at CosmoCaixa, as well as a number of exhibitions specially devoted to interaction, such as "touch and play" for small children. Around 800,000 people visited the Science Museum in 2012[21]. In 2006 CosmoCaixa Barcelona was awarded by the 'European Museum of the Year Award', an institution sponsored by the European Council, as the best science museum in Europe.

The field trial was scheduled from Tuesday, November 27th to Sunday, December 2nd, on the occasion of the European Robotics Week. This schedule includes a free entrance day (Sunday), so a high number of visitors was expected for this day. Most of the exhibitions, as well as the workshops with visits or performances aim at and are designed for all members of the family. The activities are divided in temporary and permanent exhibitions, as shown in Table 1.

Table 1: Types of activities at CosmoCaixa.

Activity	Exhibition type	Guide role?
"Clik"	permanent	Y
"Flash"	permanent	Y
"Touch-Touch!"	permanent	Y
"Bubble Planet"	permanent	Y
"Planetarium"	permanent	Y
"Flooded Forest"	permanent	N
"Robot workshop"	temporary	N
"Tecno-revolution"	temporary	N

The placement of the robot was the floor -2, along a corridor of about 5 meters wide and 40 meters long where the most of activities were held (see Figure 2). Activities "Planetarium" and "Flooded Forest" are represented by point A in the map, point B configures activities "Flash" and "Touch-Touch!", point C is for the activity " Clik", while point D is the information point where the robot was located, close to one of the main entrances.

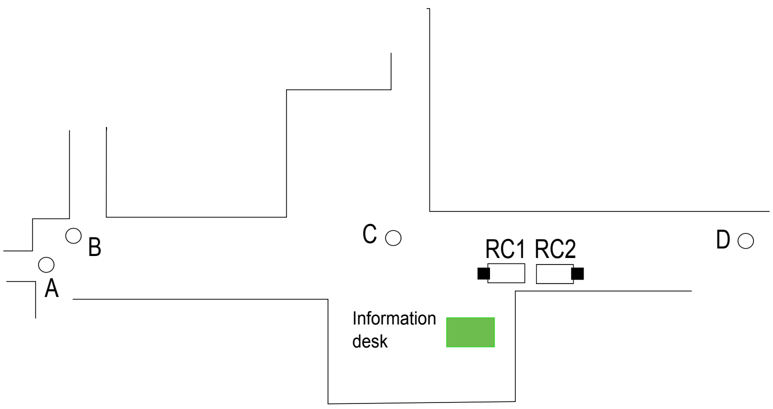


Fig. 2: Map for the robot placement at Cosmocaixa Science Museum Barcelona

In order to record the most of the interaction, but being non invasive in the experimentation, two commercial surveilllance recording cameras (RC1 and RC2 in Figure 2) were located in opposite directions at the center of the corridor (Figure 3), hidden in the roof, and a third camera (RC3) was used on-board the robot in order to obtain a subjective view of the interaction. The output images of each video camera were recorded and used to analyse the HRI.

(a) (b)

Fig. 3: External camera shots: (a) from recording camera 1 (RC1); and, (b) from recording camera 2 (RC2).

3.4. *Task*

The robot task for evaluating the proposed objective with the REEM robot at CosmoCaixa can be defined as "to provide information and facilitate people to get to a desired destination". Hence, the robot screens and movements were designed to provide information about Cosmocaixa, their activities, exhibitions and the robot manufacturing company.

If the user requires, the robot also serves as a guide towards a specific exhibition. So, the robot guide visitors from a starting point to the entrance of one of the planned activities. Once the robot has reached its destination, and depending on the pre-defined robot's social profile, it will either, stay in place or return to its initial base. Visitors freely interact with the robot and can quit anytime. For safety reasons, staff from the robotics company supervised the robot anytime from a distant place; thus, from the visitors perspective, assistance from technical staff is transparent.

An overview of the flow for the robot's guide role is summarized in Figure 4. Let's define each of the elements in this flow.

3.4.1. *Waiting state*

This state constitutes the starting point to initiate a user interaction. Depending on the social profile (operation mode) assigned, the robot can stay fixed in one spot or randomly move around. When the touch screen is pressed by the user, the robot changes from the wait state to the *screen interaction* state.

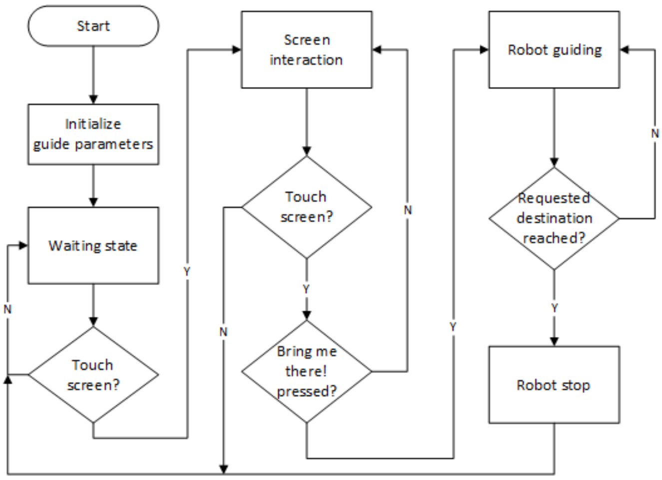


Fig. 4: Flow of robot's guide role.

3.4.2. *Screen interaction state*

In order to request a destination, the user must interact with the robot using the touchscreen in the screen interaction state. The feedback to the user is given through the screen, but also with voice commands. The exception is the passive mode. A diagram of the designed screens navigation is shown in Figure 5. This state ends either, when the robot does not detect any screen press event or when the *"bring me here!"* button has been pressed; in the latter case the robot will go to *robot guiding* state.

3.4.3. *Robot guiding state*

When the visitor selects the option *"bring me here!"*, the robot guiding process will take place. Depending on the selected point of interest (see Table 1) and robot social profile, the robot will execute navigation and guidance algorithms in order to reach the desired site. When obstacles are detected, it will dynamically look for an alternate route. As a safety measure, if along the way the robot detects any obstacle and it can not be avoided it will immediately stop, until it finds an alternate route.

We are interested in the exploratory study at this stage, especially in the *follow-me* behavior, referring to people who walk with the robot towards a target location.

3.4.4. *Robot stop state*

Once the robot reaches its target, the robot will stop to show that it has arrived to the desired site (*robot stop* state). Later, depending on its social profile, the robot would either, return to its initial point, stay in the same place, or moving around

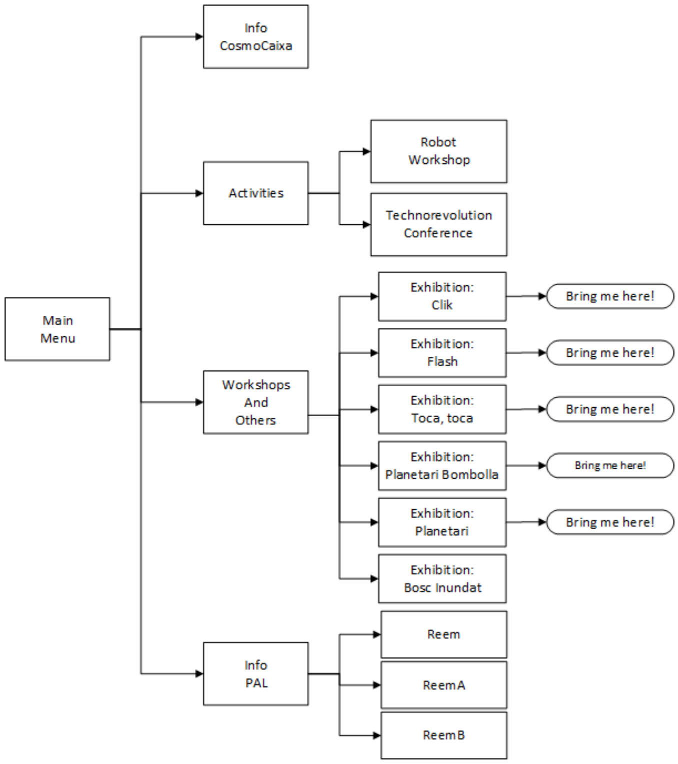


Fig. 5: Flowchart of the screen interaction.

waiting for a new interaction in the waiting state.

3.5. *Social profiles*

Several operation modes were established based on the resources of the robot to generate different interactive behaviors, as detailed in Table 2. Due to the real-life conditions of the experience, a number of limitations for safety reasons were considered. Specially, arms movements were heavily constrained, and avoiding obstacles during navigation was set to a wide safety space.

Hence, for the *standard* profile, the robot is able to show information about the museum activities through its screen, as well as through its voice; arm movements are forbidden; the 'follow faces' module is on; it offers the possibility to the user navigating to the room where the selected activity is being performed, otherwise, it holds in its current position, a predefined starting point; navigation is performed with a 'normal' speed.

Similar descriptions can be offered for the remaining behaviors: *passive*, *active*, and *sociable*. When arm movement is allowed, it raises up its forearms inside a

Table 2: Predefined social profiles.

Function / Mode	Talks	Arm move	Follow faces	Guide	Meet people	Return	Speed (km/h)	Reem Alive
Passive	N	N	N	N	N	N	0	N
Active	Y	Y	N	N	N	N	1	N
Standard	Y	N	Y	Y	N	Y	3	N
Sociable	Y	Y	Y	Y	Y	N	3	Y

circle no wider that its wheeled base, so movement is only for around 10cm. The 'meet people' module allows the robot to navigate in the environment looking for people and offering help. Finally, the 'Reem Alive' module implements some features like moving arms a little back and forward when navigating, or turning the head fifty degrees when navigating backwards. In this form, the robot behavior tries to simulate human movements for walking forward and walking backwards.

These social profiles were distributed among the six days of the experiment, as shown in Table 3. The different activities were divided between the defined operation modes of the robot, as well as a particular robotics workshop scheduled on the second day in the morning. The *passive* operation mode was scheduled only for two time slots in order to consider it as a baseline, because the robot avoids to use all its movement features and behaves like a static information point. The *sociable* profile was scheduled during the week-end, when entire families are usually coming to the museum.

The incompatible restrictions of keeping the experimental controlled conditions (social profiles schedule) vs. having a more realistic and social experience, entailed to consider the most social profile within this exploratory study, which is the *sociable* profile.

Table 3: Scheduling experience at Cosmocaixa.

Hour / Day	10:00 11:45	12:15 14:00	16:00 17:45	18:15 20:00
1	standard	passive	active	active
2	workshop	workshop	standard	standard
3	standard	active	standard	passive
4	standard	standard	active	active
5	sociable	sociable	sociable	sociable
6	sociable	sociable	sociable	sociable

4. Study design

This section covers the empirical studies to investigate the dynamics of HRI in a natural and open environment by using systematic observation. In particular, the study aims to explore the impact of group behavior and spatial arrangement in the dynamics of the human-robot interaction. The analysis is focused on: (i) the presence of groups and their composition, (ii) the spatial arrangement of the group, (iii) the interactive behavior of people around the robot. To increase reliability in the study, the manual encoding was carried out by two of the experimenters working together.

Due to the large amount of data, it was necessary to conduct a preliminary preprocessing of the videos. Thus, for (i) and (ii):

- Recordings from external cameras RC1 and RC2 (Figure 2) were initially used, with a total of 4828 minutes.
- Scenes without any kind of movement were eliminated using computer vision techniques. Upon completion of this phase, a Total of 3966 minutes of recorded video lasted.
- Video sequences where the robot and people were on the scene were selected. As a result, a total of 283 scenes, with approximately 825 minutes were selected.
- *follow-me* behavior scenes were selected at this stage. 91 episodes of the *follow-me* behavior were obtained for analysis, with approximately 96 minutes of recorded video.

Preprocessing for (iii) consisted of selecting scenes where the robot could see people (subjective robot view from camera RC3). Starting initially with a total of 83 min recorded, 14 scenes were pre-selected for a total of 47 min, approximately. In order to quantify the interactive behaviors, the 14 scenes were sampled considering 10 seconds every minute. Finally, a subset of 49 final scenes were selected with a total time of 8 minutes approximately.

4.1. *Group description*

An ad hoc coding scheme was built-up in order to carry out the analysis of the videotaped sequences to measure the occurrence on the group composition into the HRI.

The group description coding scheme is made up of 2 general criteria: composition and size (Table 4). Group composition corresponds to the age of the individuals within the group, such as children, youngster, adult; while group size corresponds to the number of people around the robot, such as single, couples, triples and larger groups.

Table 4: Group description

Category	Coding scheme
Composition	children, youth, adults, mixed groups
Size	single, couples, triples, larger groups

4.2. *Group spatial arrangement*

An ad hoc coding scheme was built-up in order to carry out the analysis of the videotaped sequences to measure the occurrence on the group spatial arrangement into the crowd HRI.

The group spatial arrangement coding scheme is made up of the spatial arrangement (Table 5), with the spatial formations as side-by-side, v-shape, leader-follower.

Table 5: Group spatial arrangement coding scheme

Categories	Coding scheme
Spatial arrangement	side-by-side, v-shape, leader-follower

4.3. *Interactive behavior*

An ad hoc coding scheme was built-up in order to carry out the analysis of the videotaped sequences to measure the occurrence on a predefined interactive behaviors.

The coding scheme is made up of 4 criteria: visual contact (look at each other), happiness (smiling), greeting gesture and mimic head movement (Table 6).

Table 6: Interactive behavior coding scheme

Categories	Coding scheme
Interactive behavior	visual contact (look at each other), ‘enjoyment’ (smiling), ‘waving’, mimic head movement

5. Results

5.1. *Platform*

The robot performance in the six day deployment can be summarized in Table 7. REEM operated for approximately 48 hours without any significant down-time (i.e., more than one hour).

Table 7: Summary of the robot's six-day deployment period

Hours of operation	48
Maximum speed	4 km/h
Number of incidences	5

To the best of our knowledge, during its 48 hours of operation REEM suffered a total of 5 incidences related to the shutdown of the robot through the emergency button.

5.2. *Group description*

To proceed with the quantitative analyses, the group description data were tabulated considering their coding scheme (Table 4) applied to the 91 *follow-me* episodes.

The identification of the groups in the streaming during the *follow-me* behavior was assessed on the basis of nonverbal communication among members: body orientation, gesticulation, and spatial cohesion among members. To more thoroughly evaluate all these indicators the coder was actually encouraged to rewind the video and take the necessary time to observe situations of simple local similar movements, due to the contextual situation, by different people from actual group situations. The whole 96 minutes of the 91 *follow-me* behavior episodes were analyzed (11.64% of the total videos where people and robot were detected in the scene).

Concerning the group composition, 1.10% of groups that interact with the robot were only children, 8.79% were only youth, 52.75% were only adults and 37.36% were mixed groups. From the mixed groups, 50% were formed by children and adults, 29.41% were formed by youth and adults, and 20.59% were formed by children, youth and adults.

Concerning the group size, 3.30% of the people walked alone with the robot, while the 96.70% arrived in groups: 10.99% of groups were couples, 14.29% triples and 71.43% larger groups.

The analysis of group size reveals that people who walked alone with the robot were 33.33% youth and 66.67% adults; couples were 10% youth, 80% adults and 10% children and adults; triples were formed by 15.38% youth, 61.54% adults, 7.69% children and adults, and 15.38% youth and adults. Larger groups were composed of 1.54% children, 6.15% youth, 46.15% adults, 23.08% children and adults, 12.31% youth and adults, and 10.77% children, youth and adults.

5.3. *Group spatial arrangement*

Results about group spatial arrangement with people walking together with robot in the *follow-me* behavior, showed that:

- 100% of guide-visitor couples (i.e. one person-one robot) was characterized by a leader (robot) - follower (person) spatial arrangement (as shown in Figure 6a);
- 90% of guide-visitors triples was characterized by the robot heading the group and followed by a dyad in an inverted V-like pattern (Figure 6b), and 10% by V-like pattern (Figure 6c) and,
- 100% of four-agents groups (i.e. three people-one robot) was characterized by the robot followed by a triad (Figure 6d).

We can show that 96.15% of the formations that were analyzed have a robot leader - person follower structure, indicating a weak social cohesion between the robot and people in almost all spatial arrangements.

5.4. *Interactive behavior*

From a total of 76 interactive behaviors observed in the 49 scenes, the results showed that:

- 55.26% of sequences corresponded to visual contact (Figure 7a),
- 31.58% corresponded to the tag of ‘enjoyment’ (smiling) (Figure 7b),
- 7.89% corresponded to ‘waving’ (Figures 7b–(d)), and
- 5.26% corresponded to mimic robot head movement (Figures 7e–(f)).

It is noteworthy that the observed behaviors are not mutually exclusive, i.e. that several behaviors may occur simultaneously. For example, of all waving behaviors, 66.67 % were performed simultaneously with the smiling behaviors (as shown in Figures 7c–(d)). Likewise, of all smiling behaviors, 83.33 % did so with visual contact behaviors (as seen in Figure 7b). This gives an idea that compound expressions can be very common in HRI.

6. Discussion

We believe that this field study provided us with many useful insights that we can apply to improve the evaluation of HRI in natural and crowded environments and therefore in the design of social robots. The humanoid robot autonomously interacted with people by using their verbal and non-verbal behavior in order to guide people in a science museum. The results suggest that the robot encourage people to be guided at the museum with its own special characteristics as the

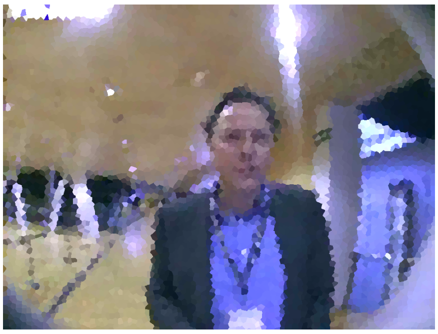
(a) (b) (c) (d)

Fig. 6: Group spatial arrangements: (a) guide-visitor couple with leader (robot)-follower (person) formation; (b) guide-visitors triple in a leader-follower spatial arrangement with robot heading the group followed by a dyad; (c) guide-visitors triple with V-like pattern; and, (d) four-agents with robot leader followed by a triad.

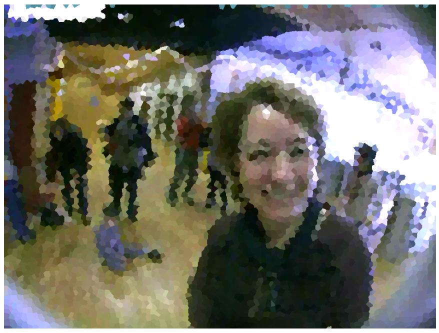
physical setting, the composition and size of the groups, and the robot- visitors spatial arrangements. Several contributions of this study and their limitations will be treated below.

6.1. *Contributions to the HRI Methodology*

Systematic observation is a common tool for study HRI in closed and non-natural contexts. In natural and crowded environments for the adoption of this technique is necessary to approach the study of the interactions of the robot with the group of people rather than with each of the individuals. In this case, the groups can be described in various ways, such as group's composition and size, and their spatial arrangement. The proposed approach is important since social interactions often take place in groups in dynamic and crowded environments.



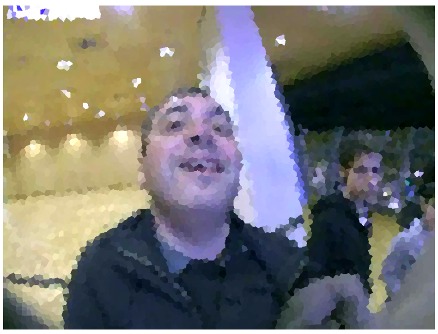
(a)



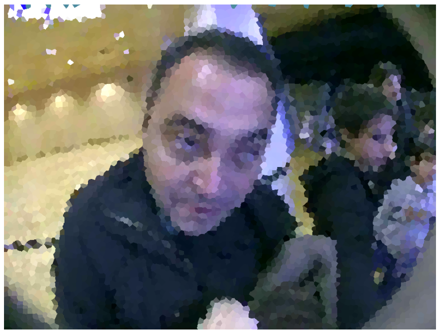
(b)

(c)

(d)



(e)



(f)

Fig. 7: Interactive behaviors: (a) visual contact; (b) smiling; (c)–(d) waving; (e)–(f) mimic head movement.

6.2. *Contributions to the Theory of HumanRobot Interaction*

Our exploratory study highlighted the important unsolved aspects of group human-robot interaction in a real social and crowded setting. In the specific context of a science museum and with the robot task of guiding people, the field study showed that adult and mixed groups were those who presented more interactions, the majority of interactions (96.70%) were made with groups (instead of only individuals) of which 71.43% were for groups larger than 3 people; that most spatial formations has a leader-follower structure showing a low social cohesion in the guide-visitor interaction; and interactive behaviors, which are not mutually exclusive, were in greater proportion eye contact and smiling expressions.

The low percentage of people interacting alone with the robot supports the observations made by Kanda[4] in a field trial in a school setting which indicates that children who interacted with the robot, did it almost always accompanied by their friends.

6.3. *Limitations*

Unlike laboratory experiments where working conditions are quite controlled, studies *in the wild* have several challenges.

In our study the space robot interaction with people has been delimited to exhibits displayed by the robot. As this area is greater, the greater the number of cameras to make the observations. In the study of HRI in open and natural environments where there is the difficulty to place cameras on the outside, an arrangement of on-board cameras around the robot can provide an omnidirectional or spherical view of robot's scene and facilitate the use of systematic observation.

Due to technical problems in the recording of video from the onboard camera (RC3), the videos were limited to about 83 minutes.

The use of automatic processing techniques, such as computer vision, can be useful tools for studying HRI through systematic observation; however, their use still represents great challenges of reliability and robustness for use in real environments.

7. Conclusions and Future Work

An exploratory study on group-robot interaction was carried out during a week in an open and natural environment to observe visitor's spatial behavior and communication with the guide robot Reem.

Differently from previous works on mobile service robots that evaluate navigation and HRI as separate functions, we address spatial behavior analyses focusing on its social meaning, not only as a prerequisite for effective communication (i.e. orientation, positioning) but as potential communicative acts (i.e. express intent and emotions).

The analysis is focused on visitor's groups rather than individual. Groups were described according to their composition, size, spatial formations and interactive behavior with the robot during guidance. Observational methods applied to evaluate the group-robot interaction provide fruitful insight to understand the relationship between robot positioning and efficient communication (i.e. walking side-by-side) and between robot motion cues (e.g. gaze behavior, body orientation) and collaborative walking together behavior through populated environments. Although there is no common consensus on the metrics to evaluate HRI in natural and crowded environments, we hope that this paper has brought light to some of the issues relevant to the this research area.

Further work will extend the analysis of the groups by gender and by physical group characteristics such as dispersion, density and velocity, using techniques that allow automatic analysis as computer vision.

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