International Journal of Social Robotics (SORO), Volume 5, Issue 4, Page 549-561,
Special Issue on Emotional Expression and Its Applications, Springer, 2013.

# Human-like Interaction Skills for the Mobile Communication Robot Robotinho

**Matthias Nieuwenhuisen · Sven Behnke**

Received: date / Accepted: date

**Abstract** The operation of robotic tour guides in public museums leads to a variety of interactions of these complex technical systems with humans of all ages and with different technical backgrounds. Interacting with a robot is a new experience for many visitors. An intuitive user interface, preferable one that resembles the interaction between human tour guides and visitors, simplifies the communication between robot and visitors. To allow for supportive behavior of the guided persons, predictable robot behavior is necessary. Humanoid robots are able to resemble human motions and behaviors and look familiar to human users that have not interacted with robots so far. Hence, they are particularly well suited for this purpose.

In this work, we present our anthropomorphic mobile communication robot Robotinho. It is equipped with an expressive communication head to display emotions. Its multimodal dialog system incorporates gestures, facial expression, body language, and speech. We describe the behaviors that we developed for interaction with inexperienced users in a museum tour guide scenario. In contrast to prior work, Robotinho communicated with the guided persons during navigation between exhibits, not only while explaining an exhibit. We report qualitative and quantitative results from evaluations of Robotinho in RoboCup@Home competitions and in a science museum.

**Fig. 1** Robotinho explains our soccer robot Dynaped to a group of visitors during a tour given at the *Deutsches Museum Bonn*. Persons surround the tour guide robot while listening to its explanations and block its path to the next destination. For successful navigation Robotinho articulates its desired motion direction clearly.

**Keywords** Multimodal Communication · Tour Guide Robot · Human-Robot Interaction

Matthias Nieuwenhuisen
E-mail: nieuwenh@ais.uni-bonn.de
Tel.: +49-228-73-4434

Sven Behnke
E-mail: behnke@cs.uni-bonn.de
Tel.: +49-228-73-4116

Autonomous Intelligent Systems Group
Institute for Computer Science VI
University of Bonn
Friedrich-Ebert-Allee 144
53113 Bonn, Germany

## 1 Introduction

For many years, the research in the field of robotics was mainly focused on the core functionalities needed for autonomous operation of robot systems. Consequently, skills like safe navigation, localization, motion planning, and reliable perception of the environment have been improved tremendously. These advances make it possible to develop flexible service robots suitable for non-industrial applications. In contrast to the application in research and industry, where only few specialists interact with the robots, user interfaces for these personal robots have to be easy to understand and use. Hence, designing human-like robots and human-robot interaction have become active research areas.

Up to now, most people have never interacted with robots and are not used to robots operating in their vicinity. Robots deployed as tour guides in a museum might interact with persons of all ages, including children and elderly people, and with different technical backgrounds. A museum constitutes a highly dynamic environment, but the domain is restricted. The interactions with the robot are usually short. This prohibits lengthy instructions on how to control the robot. Finally, the robot itself can be seen as an exhibit. Hence, a museum is a good testbed for gathering experience in human-robot interaction.

Figure 1 shows our anthropomorphic communication robot Robotinho. Robotinho's human-like appearance facilitates users to predict its motions and behaviors. An expressive communication head enables the robot to display different moods and to gaze at people in a natural way.

Museum visitors in the vicinity of the robot can be startled by sudden movements. Our robot avoids this by implicit or explicit communication of its intents, either verbally or non-verbally.

Additional to intuitively communicating with the visitors, another essential skill for a tour guide robot is to navigate safely and reliably in dynamic environments. We are convinced that the interaction with visitors attending the tour and the attraction of visitors strolling around in the proximity of the tour are important skills.

The evaluation of service robots is difficult. Basic skills, like collision-free navigation, accurate localization, and path planning, may be evaluated in a laboratory using objective and comparable metrics. Evaluating factors like the appearance to and interaction with people not familiar with robots requires operating the robots in public environments. We evaluated Robotinho in different scenarios before:

- Extensive body language was required while conducting cellists of the Berlin Philharmonic [4].
- Robotinho explained exhibits in a static scenario using its multimodal interaction skills [3].
- In a tour guide scenario at the University of Freiburg Robotinho guided visitors in a corridor. Robotinho was used as a walking tour guide [2].
- In the @Home competition at RoboCup 2009, Robotinho assisted our service robot Dynamaid with its communication skills [1].

Details of the previous evaluations are given in [18] and [34]. In order to extend our prior work, we analyzed the navigation in the vicinity of visitor groups and developed behaviors to make the navigation more predictable and to keep the visitors feeling attended during the navigation between exhibits. In this article, we describe our robot and its dialog system, detailing our approach to mobile interaction. We also report our experiences made in a science museum and present quantitative results from questionnaires.

## 2 Related Work

The idea of enhancing the museum experience by the use of mobile robots has been pursued by several research groups. Notable examples of wheeled robots operating as tour guides in museums or guiding people on large fairs include [35, 44, 49, 14]. In these deployments, the researchers did not focus on natural interaction with the visitors, but on skills like collision-free navigation. Nevertheless, first challenges in the interaction between humans and robots could be identified.

The robot Hermes [10] is a humanoid robot with an upper body equipped with an arm mounted on a wheeled base. It was installed for a long-term experiment in a museum. The human-like appearance enabled the robot to realize more human-like interaction. In contrast to Robotinho, Hermes has limited multimodal interaction capabilities and has no animated face to show emotional expressions.

How a robot should approach a person and navigate in the presence of humans was evaluated by Dautenhahn *et al.* [16]. A robot should be visible to the person most of the time and approach an individual from the front. This avoids uncomfortable feelings on the human side. In our work, we focus on predictive behavior by clearly articulating the robot's intents.

Shiomi *et al.* [43] studied if tour guide robots should drive forward or backward, facing the visitors, during navigation to keep them interested in the tour. In contrast, we focus on the gaze direction of the robot.

The tracking of persons using laser-range sensors and cameras has been investigated, e.g. by Cui *et al.* [15], Schulz [41], and Spinello *et al.* [45]. In contrast to these works, our approach uses laser-range finders (LRFs) at two heights to detect legs and trunks of persons and also utilizes a static map of the environment to reject false positive hypotheses.

Hristoskova *et al.* [25] present a museum tour guide system of collaborative robots with heterogeneous knowledge. Tours are personalized using techniques developed for the semantic web. The personalization is based on individual persons' interests and the knowledge of currently available robots. Robots can exchange guided persons to provide tours that cover most of the interests. We use a single robot in a smaller museum. Hence, Robotinho let the user select between several predefined tours. We focus on keeping the guided visitors interested in the tour by communicating with them.

Yousuf *et al.* [56] developed a robot that resembles behaviors of human tour guides. Human tour guides build an *F-formation* with the visitors, the exhibit and themselves. Their robot checks whether this formation is satisfied before explaining an exhibit or tries to obtain this formation otherwise. We allow for more loose formations. Robotinho asks persons to come closer and arranges itself such that it can attend the visitors adequately while explaining an exhibit.

The importance of gestures along with speech is evaluated in [39]. For example, a Honda Asimo robot explained to a human assistant where to place kitchen items. Pointing gestures—even if sometimes wrong—lead to a more positive reception of the robot than just announcing the places. In contrast to this static scenario, we present a dynamic tour guide scenario in our work.

Kismet [12] is a robot head with multiple cameras that has been developed for studying human-robot social interaction. It does not recognize the spoken words, but it analyzes low-level speech features to infer the affective intent of the human. Kismet displays its emotional state through various facial expressions, vocalizations, and movements. It can make eye contact and can direct its attention to salient objects. A more complex communication robot is Leonardo, developed by Breazeal *et al.* [13]. It has 65 degrees of freedom to animate the eyes, facial expressions, the ears, and to move its head and arms. Another humanoid upper body for studying human-robot interaction is ROMAN [30]. ROMAN, Leonardo and Kismet are mounted on a static platform. Mobile robots used for communication include PaPeRo [42], Qrio [6], and Maggie [21].

When designing robots for human-robot interaction, one must consider the uncanny valley effect, described by Mori [32]. Humans are no longer attracted to robots, if they appear too human-like. Photo-realistic android and gynoid robots, such as Repliee Q2 [29], are at first sight indistinguishable from real humans, but the illusion breaks down as soon as the robots start moving. For this reason, our robot does not have a photo-realistic human-like appearance, but we emphasize the facial features of its heads using distinct colors.

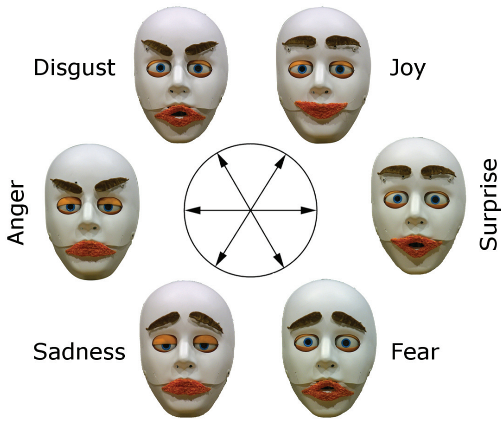


**Fig. 2** Robotinho generates facial expressions by a weighted mixture of the six depicted basic expressions.

Another expressive communication head has been developed by Kędzierski *et al.* [27]. It uses the same basic facial expressions as Robotinho, but with less degrees of freedom. In contrast to our head, it is very distinctive from a human head due to its basic shape and the division into three parts.

Probo [38] is another robot capable of generating facial expressions. It is designed to study human-robot interaction with the goal to employ it in robot aided therapy (RAT). In contrast to our robot, Probo is modelled as an animal to avoid the uncanny valley effect. It looks like an elephant and can express emotions by movements of its trunk.

A recent study shows that people interpret body language of artificial agents similar to humans [7]. The strength of the perceived emotion depends on the realism of the agent. Experiments were conducted using animated agents and the Aldebaran Nao robot by Gouaillier *et al.* [22].

The importance of multimodal communication capabilities for human-robot interaction was evaluated by Schillaci *et al.* [40]. Head and arm movements increased the perceived interactiveness of the robot. This work backs our claim that multimodel interaction is key to successfull interaction with humans.

Our main contribution is a communication robot that combines human-like interaction skills and an expressive communication head with mobility. Furthermore, it attends and interacts with persons while guiding them towards their destination.

## 3 Robot Design

Robotinho's hardware design is focused on low weight, dexterity, and an appealing appearance ([18],[34]). We are convinced, that these features are important for a robot that interacts closely with people. For example, the low weight makes our robot inherently safer than more heavy-weight robots, as only limited actuator power is required. The robot's joints are actuated by light-weight Dynamixel servo motors. Furthermore, we used light-weight materials to build the robot. Its skeleton is made mainly from aluminum and its hull is made from carbon composite materials and plastics. This yields a total weight of about 20 kg—an order of magnitude lower than other service robots of comparable size (e.g. [11],[54]).

Robotinho is fully autonomous. It is powered by high-current Lithium-polymer rechargeable batteries and has its computing power on-board.

Robotinho's anthropomorphic appearance supports human-like multimodal communication. For use as a communication robot, we equipped Robotinho with an expressive head with 15 degrees of freedom, depicted in Fig. 2. To generate facial expressions, it actuates eyebrows and eyelids, mouth, and jaw. The eyes are movable USB cameras. One camera is equipped with a wide-angle lens to yield a larger field-of-view.

For verbal communication in noisy environments, Robotinho has a directional microphone, which our robot aims towards the person it is paying attention to, and a loudspeaker in the base.

In prior work, Robotinho walked while guiding persons. To ensure faster and safer movement in dynamic environments, we placed it on a wheeled base with the capability to move omnidirectionally. We equipped the base with four steerable differential drives. To measure the heading direction of each drive, they are attached to the base by passive Dynamixel actuators. Another advantage of the base is that Robotinho's total height is now about 160 cm, which simplifies the face-to-face communication with adults (Fig. 3).

Our robot is equipped with two laser range finders (LRF). A Hokuyo URG-04LX LRF in Robotinho's neck is mainly used to detect and track people. For navigation purposes and to support the tracking of persons, the base is equipped with a SICK S300 LRF.

Robotinho was originally designed to operate independently from its base. Thus, we distributed the control system to two computers connected over Ethernet. This is still advantageous, as tasks like speech recognition, vision, and localization require substantial computational power. The majority of Robotinho's dialog system runs on one PC, including speech, vision, and the robot's behaviors. The other PC is dedicated to localization and navigation using the robotic framework Player [20]. This ensures safe navigation independent from the high-level behavior control system.


**Fig. 3** Robotinho is placed on an omnidirectional wheeled base for fast and safe navigation. The total height of 160 cm simplifies face-to-face communication with adults.

## 4 Navigation

Guiding people around requires the robot to safely navigate in its environment. For this purpose, it must be able to estimate its pose in a given map, to plan obstacle-free paths in the map, and to drive safely along the path despite dynamic obstacles. Finally, the robot needs the ability to acquire a map in a previously unknown environment with its sensors.

To acquire maps of unknown environments, we apply an implementation [23] of the FastSLAM [31] approach to Simultaneous Localization and Mapping (SLAM). Once the robot obtained a map of the environment through SLAM, it can use this map for localization. We apply a variant of the adaptive Monte Carlo Localization [19] to estimate the robot's pose in a given map from measurements of the base LRF.

For navigation in its environment, the robot needs the ability to plan paths from its estimated pose in the map to target locations. We find short obstacle-avoiding paths in the grid map through A* search [24]. Our algorithm finds obstacle-free paths that trade-off shortness and distance to obstacles.

The path planning module only considers obstacles represented in the map. To navigate in partially dynamic environments, we implemented a module for local path planning and obstacle avoidance. It considers the recent scans of the LRFs at the base and neck. The local path planner is based on the vector field histogram algorithm [50].

The movements of dynamic obstacles cannot be well predicted. Hence, larger margins around dynamic obstacles are useful during path planning to reduce the need for replanning or stops due to persons violating the safety space around the robot. For this purpose, we use the tracked positions of persons to influence the repulsive forces of obstacles in our local path planner. If possible, the path planning algorithm avoids the area around dynamic obstacles by passing static obstacles more closely.

## 5 Multimodal Interaction

### 5.1 Attentional System

Robotinho shows interest in multiple persons in its vicinity and shifts its attention between them so that they feel involved into the conversation. To determine the focus of attention of the robot, we compute an importance value for each person in the belief, which is based on the distance of the person to the robot, and on its angular position relative to the front of the robot.

The robot always focuses its attention on the person who has the highest importance, which means that it keeps eye-contact with this person. While focusing on one person, from time to time our robot also looks into the direction of other people to involve them into a conversation and to update its belief about their presence.

Turning towards interaction partners is distributed over three levels [17]: the eyes, the neck, and the trunk. We use different time constants for these levels. While the eyes are allowed to move quickly, the neck moves slower, and the trunk follows with the slowest time constant. This reflects the different masses of the moved parts. When a saccade is made, the eyes point first towards the new target. As neck and trunk follow, the faster joints in this cascade move back towards their neutral position. A comfort measure, which incorporates the avoidance of joint limits, is used to distribute the twist angle over the three levels.

### 5.2 Gesture Generation

Our robot performs several natural, human-like gestures. These gestures either support its speech or correspond to unconscious arm movements which we humans also perform. The gestures are generated online. Arm gestures consist of a preparation phase where the arm moves slowly to a starting position, the hold phase that carries the linguistic meaning, and a retraction phase where the hand moves back to a resting position.

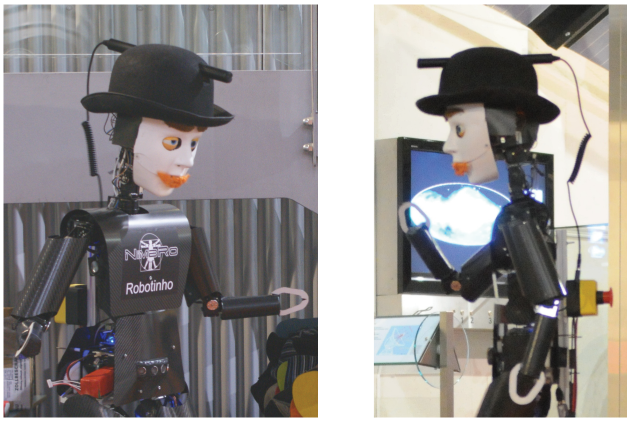


**Fig. 4** Robotinho performs several symbolic gestures, e.g, inquiring (left) and greeting (right) gestures.

**Fig. 5** Robotinho points at different object parts during its explanations to direct the audience's attention.

The gestures are synchronized with the speech synthesis module.

- *Symbolic Gestures:* The symbolic gestures in our dialog system include a single-handed greeting gesture that is used while saying hello to newly detected persons in the surrounding of the robot. Robotinho performs a come-closer gesture with both arms when detected persons are farther away than a nominal conversation distance. It also accompanies certain questions with an inquiring gesture where it moves both elbows outwards to the back (Fig. 4). In certain situations, our robot performs a disappointment gesture by moving, during the stroke, both hands quickly down. To confirm or to disagree, the robot also nods or shakes its head, respectively. If Robotinho is going to navigate and the path is blocked, a both-handed make-room gesture can be performed.
- *Batonic Gestures:* Humans continuously gesticulate to emphasize their utterances while talking to each other. Robotinho also makes small emphasizing gestures with both arms when it is generating longer sentences.

• *Pointing Gestures:* To draw the attention of communication partners towards objects of interest, Robotinho performs pointing gestures. It approaches with its hand the line from the robot head to the referenced object. At the same time, our robot moves the head and the eyes in the corresponding direction and utters the object name. Fig. 5 shows Robotinho explaining different parts of an exhibit, pointing to the currently explained part.

• *Non-Gestural Movements:* Small movements with Robotinho's arms let it appear livelier. To this end, we also implemented a regular breathing motion and pseudo-random eye blinks.

### 5.3 Speech Recognition and Synthesis

In fully autonomous operation, Robotinho recognizes speech using a commercial speaker-independent speech recognition system [28]. It uses a small vocabulary grammar which is changed corresponding to the dialog state. In semi-autonomous mode, an operator can select recognition results using a wireless connection. High-quality human-like speech is synthesized online by a commercial text-to-speech system [28].

### 5.4 Expression of the Emotional State

While talking to each other, human communication partners use emotional expressions to emphasize their utterances. Humans learn early in development to quickly appreciate emotions and interpret the communication partner's behavior accordingly. Robotinho can express emotions by means of emotional speech synthesis and facial expressions. We compute the current facial expression of the robot by interpolating between six premodelled basic expression, following the notion of the Emotion Disc [37]. The six basic emotional states are depicted in Fig. 2. We simulate emotions in our speech synthesis system by adjusting the parameters pitch, speed, and volume [9]. Furthermore, we can use emotional tags to synthesize non-textual sounds, e.g., a cough or laughing.

## 6 People Awareness and Tracking

Robotinho involves visitors actively in the conversation by looking at them alternatingly from time to time. Hence, it has to know their whereabouts. Persons are detected and tracked using fused measurements of vision and the two LRFs. We use the cameras in Robotinho's eyes to detect faces, using a Viola & Jones [51] face detector. The laser-range measurements are used to detect legs and trunks. The respective detections are associated and tracked using Hungarian data association [26] in a multi-hypothesis tracker. We reject face detections without corresponding range measurements. Face detections $z_t^c$ are associated with tracks gained by laser-range measurements $z_t^l$ according to their angular distance within a threshold. The resulting state estimate that also incorporates the prior belief $\overline{bel(x_t)}$ is given as

$$p(x_{1:t}|z_{1:t}^c, z_{1:t}^l) = p(z_t^c|x_t, z_t^l)\overline{bel(x_t)}. \quad (1)$$

We implemented the measurement model $p(z_t^c|x_t, z_t^l)$ as a lookup table and perform the belief update by Kalman filtering [52].

Before fusing the sensor measurements, we update the laser tracks independently. Our tracking pipeline is illustrated in Fig. 6.

The LRF in Robotinho's neck has an field of view (FOV) of 240°. To keep track of a group of people behind the robot, Robotinho gazes alternatingly into the direction of the known person tracks to update their belief. To cover the whole 360° area around it, Robotinho extends the LRF's FOV by turning its upper body.

To track a group of people, it is not necessary to keep an accurate track of every individual. Thus, we prioritize a human-like looking behavior of our robot over gazing at the people the whole time. Robotinho just looks at one random track per time segment and looks into its driving direction for the rest of the time segment. The lengths of these segments are chosen randomly within an interval to reach a more natural looking behavior.

Given a set of person tracks $L$, the current gaze direction $\alpha$ at time $t$ depends on the number of tracks and the active time interval $T_i$. Robotinho explores the space behind it by turning the upper body and its head into the direction of the last known track position, if $L$ is empty. With $\alpha_d$ denoting the angle of the driving direction, $\alpha_{l_t}$ the angle of track $l$ at time $t$, and $\alpha_{\max}$ the maximum possible turn angle, the gaze direction is calculated as follows:

$$l_t = \begin{cases} l \in L_t, \text{ if } \|L_t\| > 0 \\ l_{t-1}, \text{ otherwise} \end{cases},$$

$$\alpha = \begin{cases} \alpha_d, \text{ if } t \in T_1 \wedge \|L_t\| > 0 \\ \alpha_{l_t} \text{ if } t \in T_2 \wedge \|L_t\| > 0 \\ \operatorname{sgn}(\alpha_{l_t})\alpha_{\max} \text{ if } \|L_t\| = 0 \end{cases}.$$

Finally, we perform a sanity check of the remaining tracks given the static map of the environment, as shown in Fig. 6c.


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

**Fig. 6** Person tracking: We use laser-range measurements (a) of the LRF in Robotinho's neck and base. In these scans, we detect trunk and leg features, respectively. Laser scan segments (black lines with red boxes) that are identified as trunk candidates are depicted in (b) by orange boxes. We filter infeasible hypotheses (red box) with a static map of the environment (c). The remaining hypotheses are depicted by green boxes, the robot by the blue box. We increase the likelihood of face detections (d), if a corresponding range measurement exists. The fused measurements and the raw laser measurements are used to keep eye-contact with visitors, to wait or search for guided visitors, and to calculate the belief that the robot is alone (e).

## 7 Interaction Skills for a Tour Guide

The role of a tour guide in a museum implies that the robot has to navigate in a dynamic environment. Most of the people in a museum have never interacted with a robot before. Hence, the robot's reactions are hardly predictable to them. Thus, Robotinho has to indicate its next actions and its abilities in an intuitive human-like manner. For instance, it is not clear to potential communication partners how they can interact with the robot. Furthermore, unexpected actions of the robot, e.g. the sudden start of movements, may startle visitors.

Humans feel uncomfortable if their comfort zone is penetrated. Our approach to safe navigation (Sec. 4) avoids paths close to dynamic obstacles reducing situations where the robot moves in the comfort zone of the visitors.

Robotinho's attentional system reacts to the presence of humans in its vicinity. Our robot looks alternatingly at persons' faces, showing interest in its communication partners. As the LRF offers only a 2D position looking into people's faces relies on visual detections. The 2D positions, however, are used to add new hypotheses to the robot's attentional system. It looks at newly arrived individuals and incorporates the new face detections into its belief. After being alone for a while, Robotinho offers tours to newly detected visitors. It asks them to come closer, combined with a gesture if necessary.

Our description of exhibits include the item's 3D-position, the preferred robot pose (position and orientation) next to the object for navigation, and the explanations Robotinho shall give, divided into a brief initial text and more information provided on request. More complex objects have an optional list of 3D-positions of their parts. The object and object part positions are used for performing pointing gestures during the explanations using inverse kinematics. Furthermore, Robotinho points to the object position before starting to navigate to that exhibit to make the robot's behavior predictable to the guided visitors. After arriving at an exhibit, Robotinho turns towards the tracked visitors and points at the exhibit's display.

In addition to natural interaction during the explanation of exhibits through gestures, facial expressions, and speech, we are convinced that interaction with the visitors during transfers between exhibits is essential. A good tour guide has to keep visitors involved in the tour. Otherwise, it is likely that visitors will leave the tour. Hence, our robot looks alternatingly into its driving direction and to its followers. Looking into the driving direction shows the visitors that it is aware of the situation in front of it and facilitates the prediction of its movement. Looking into the direction of the guided visitors is necessary to update the robots belief about their positions and to show interest in the persons it interacts with. Following the approach described in the previous section, Robotinho gives its attention to a random visitor, if the position of each person is known. Otherwise, it looks over its shoulder to find its followers (see Fig. 7).

If Robotinho is uncertain about the whereabouts of its followers, or if they fall back, its head and upper body are turned and a come-closer gesture supported by a verbal request to follow the guide is performed. Additionally, our robot can turn its base to look and wait for the visitors. If this is successful, the robot indicates verbally that it became aware of the presence of its followers and continues the tour.

The dynamic nature of a museum environment occasionally causes disruptions in the robot's navigation. It is likely, that a planned path to an exhibit is blocked by persons standing around the robot to listen to its explanations or stepping into the safety margins around the robot while driving. In these cases, Robotinho asks

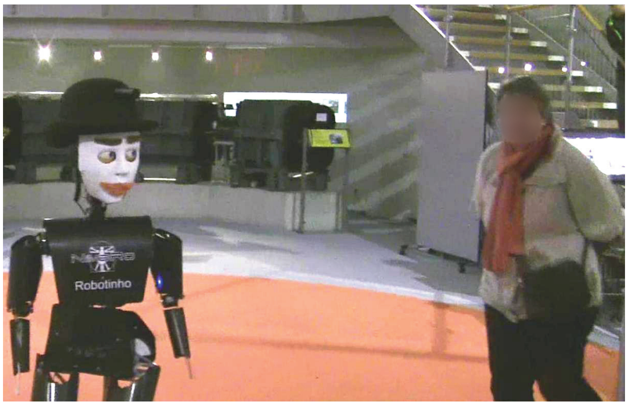


**Fig. 7** To keep guided visitors attended during navigation phases, Robotinho alternates looking into its driving direction and back to the persons following it. If they fall back, Robotinho turns around and request them to catch up.

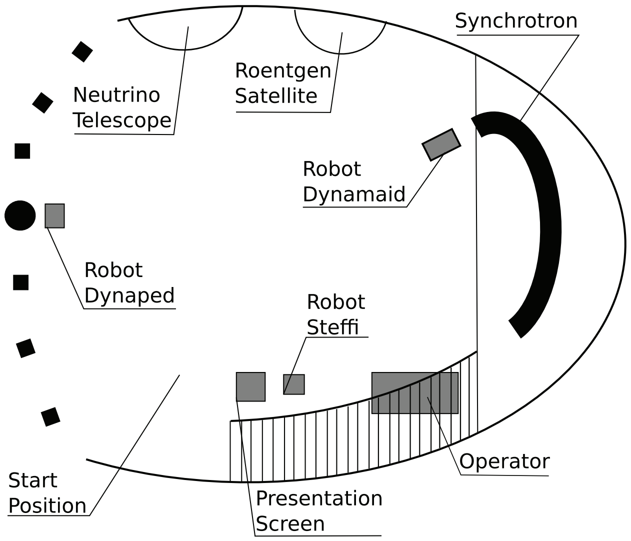


**Fig. 8** Schematic map of the area in the Deutsches Museum Bonn where Robotinho gave tours. One tour included the three permanent exhibits synchrotron, neutrino telescope, and Roentgen satellite. In the other tour the robot explained three other robots from our group.

for clearance and makes an angry face. Supporting the request with an emotional expression is more effective than the verbal request alone [49].

## 8 Evaluation in a Science Museum

### 8.1 Scenario Setup

We evaluated our museum tour guide robot Robotinho in the *Deutsches Museum Bonn*, a public science museum. The focus of the permanent exhibition lies on research and technology in the Federal Republic of Germany. Hence, it is mostly visited by people interested in technology and open to new developments. The museum offers a number of science related workshops for children. This results in a broad range of age groups in the exhibition.

Robotinho gave tours in a central area on the ground floor of the museum. This area hosts three larger permanent exhibits: a synchrotron, parts of a Roentgen satellite, and a neutrino telescope. These three exhibits formed one tour. Our anthropomorphic service robot *Dynamaid* [46], our TeenSize soccer robot *Dynaped* [53], and our KidSize soccer robot *Steffi* [8] formed a second tour. Fig. 8 shows the placement of the exhibits in this area.

Robotinho started from a central position, looking for visitors in its vicinity. If it could attract visitors to take a tour, our robot initiated the conversation by explaining itself and showing some of its gestures and facial expressions. When the robot starts with its explanations is decided by calculation of an *alone belief* using the previously described person awareness algorithm (cf. Sec. 6).

After explaining itself, the visitors can choose between the two different tours. After a tour finishes, Robotinho asks whether it should continue with the other tour. Finally, Robotinho wished farewell and asked the visitors to answer a questionnaire. The overall duration from introduction to farewell, if both tours were given, was about 10 minutes.

The experiments were performed on two consecutive weekends in January 2010. A video summarizing the museum tours is available on our website [5].

### 8.2 Results

After finishing a tour, Robotinho asked the visitors to fill out a questionnaire. The questionnaires contained questions about the communication skills (verbal and non-verbal) of the robot, its general appearance, and the tour itself. The answers could be given on a one-to-seven scale, with the exception of some free text and yes/no answers. In total, 129 questionnaires were completed after 40 tours our robot gave to visitors. Persons that didn't fill in a questionnaire were not counted separately.

In the remainder of this section, we will aggregate the results into negative (1-2), average (3-5), and positive (6-7) answers, unless stated otherwise.

Over 70% of the children, i. e., persons younger than 15 years, answered that they like robots in general. Also over 60% of the adults, i. e., persons of 15 years and older, answered the question positively. Negative answers were given by only 5% of the adults and none of the children (cf. Table 1).

**Table 1** "Do you like robots in general?"

| (in %) | 1 (not at all) | 2 | 3 | 4 | 5 | 6 | 7 (exceedingly) | μ |
|---|---|---|---|---|---|---|---|---|
| adults | 1 | 3 | 4 | 7 | 21 | **34** | 26 | 5.5 |
| children | 0 | 0 | 0 | 10 | 15 | 26 | **47** | 6.1 |

The robot appeared friendly and polite to more than three quarter of the polled persons. 45% of the adults answered that the communication with the robot was convenient, 7% gave a negative answer. More than three quarter of the children answered positively here (cf. Table 2).

Robotinho's attentiveness was perceived positive by 72% of the children and 52% of the adults (cf. Table 2). Furthermore, 63% of the children and 48% of the adults felt adequately attended during the tours (cf. Table 4). Free text answers to the question why the they felt attended include that Robotinho reacts on blocked paths and gazes at persons. The main motivation for attendance of the tours is that the tours are given by a robot.

The average of the answers on how polite, appealing, manlike, and friendly the robot appeared, shows a trend to correspond to how the persons generally like robots. The same correspondence can be observed at the answers to how intuitive and convenient the communication was rated.

We found strong significant correlations (correlation coefficient according to Pearson $> 0.5$) between the rating of the robot's interaction skills (verbal and non-verbal) and the ratings on how convenient the visitors found the communication with the robot and how well they felt attended by the robot. Furthermore, the attentiveness of the robot shows strong correlations to the ratings of how manlike the robot appears and how convenient the communication with it is. An overview over selected correlations is given in Table 5.

How polite the robot was perceived correlates significant to the ratings of the non-verbal (correlation: 0.386) and verbal (correlation: 0.344) interaction skills and inverse to how labored people perceive the communication (correlation: -0.339).

During our tests in the museum, we experienced that the individuals in guided groups give contradicting answers simultaneously to the robot's question. Some of them answered by just nodding or head-shaking. Especially children asked Robotinho interposed questions about the tour, but also about the general exhibition and the robot itself. Hence, to appropriately react on all these questions, we used the Wizard of Oz technique for speech recognition, if the phrase could not be recognized automatically.

In general, children appraised the robot to be more human-like. Consequently, the mean of the answers from children to the questions regarding the similarity of the robot to human appearance and communication (cf. Tables 2, 3) is in both cases more than one mark higher than the mean of the adults' answers. In contrast to adults, many children have no reservation against the robot. Hence, groups of children were often surrounding the robot closely while adults mostly stood back. Also, adults were often more observant, waiting for the robot to progress by itself. This may be induced by the learned expectation that natural interaction with machines is mostly not possible.

**Table 2** "How does the robot appear to you?"

| (in %) | 1 (not at all) | 2 | 3 | 4 | 5 | 6 | 7 (very) | μ |
|---|---|---|---|---|---|---|---|---|
| **Adults** | | | | | | | | |
| appealing | 0 | 2 | 6 | 8 | 25 | **32** | 24 | 5.5 |
| polite | 0 | 1 | 2 | 2 | 7 | 36 | **50** | 6.3 |
| friendly | 0 | 1 | 0 | 3 | 19 | **37** | **37** | 6.1 |
| attentive | 1 | 7 | 3 | 12 | 22 | **31** | 21 | 5.3 |
| manlike | 6 | 6 | **25** | 19 | 24 | 14 | 2 | 4.1 |
| attractive | 2 | 6 | 3 | 14 | 27 | **33** | 12 | 5.1 |
| clumsy | 16 | 14 | 14 | 16 | **18** | 16 | 3 | 3.7 |
| **Children** | | | | | | | | |
| appealing | 7 | 5 | 0 | 5 | 17 | 23 | **41** | 5.5 |
| polite | 2 | 2 | 0 | 0 | 7 | 23 | **64** | 6.3 |
| friendly | 0 | 0 | 2 | 4 | 12 | 29 | **51** | 6.2 |
| attentive | 2 | 5 | 5 | 7 | 7 | 20 | **52** | 5.1 |
| manlike | 5 | 5 | 7 | 12 | 15 | **30** | 23 | 5.3 |
| attractive | 0 | 2 | 2 | 7 | 15 | 27 | **45** | 6.0 |
| clumsy | **42** | 12 | 5 | 17 | 10 | 12 | 0 | 2.8 |

**Table 3** "How did you perceive the communication with the robot?"

| (in %) | 1 (not at all) | 2 | 3 | 4 | 5 | 6 | 7 (very) | μ |
|---|---|---|---|---|---|---|---|---|
| **Adults** | | | | | | | | |
| intuitive | 6 | 6 | 11 | 21 | **23** | 17 | 12 | 4.5 |
| easy | 0 | 4 | 11 | 8 | 22 | 25 | **27** | 5.3 |
| artificial | 1 | 3 | 13 | 21 | **33** | 10 | 16 | 4.8 |
| manlike | 6 | 6 | **25** | 19 | 24 | 14 | 2 | 4.0 |
| convenient | 1 | 6 | 4 | 20 | 21 | **29** | 15 | 5.1 |
| cumbersome | 16 | **32** | 8 | 18 | 15 | 5 | 3 | 3.1 |
| labored | 13 | **25** | 17 | 22 | 13 | 3 | 3 | 3.2 |
| **Children** | | | | | | | | |
| intuitive | 9 | 6 | 6 | 6 | 15 | **28** | **28** | 5.1 |
| easy | 8 | 2 | 2 | 13 | 13 | **32** | 27 | 5.3 |
| artificial | 20 | 7 | 10 | 12 | 15 | **23** | 10 | 4.1 |
| manlike | 5 | 5 | 7 | 12 | 15 | **30** | 23 | 5.1 |
| convenient | 0 | 0 | 7 | 2 | 20 | 20 | **48** | 6.0 |
| cumbersome | **33** | 7 | 10 | 5 | 23 | 7 | 12 | 3.5 |
| labored | **31** | 21 | 5 | 15 | 10 | 5 | 10 | 3.1 |

**Table 4** "Do you think, the robot attended you adequately?"

| (in %) | 1 (not at all) | 2 | 3 | 4 | 5 | 6 | 7 (highly) | μ |
|---|---|---|---|---|---|---|---|---|
| adults | 0 | 1 | 6 | 21 | 21 | **40** | 8 | 5.2 |
| children | 0 | 4 | 0 | 12 | 19 | 24 | **39** | 5.8 |

**Table 5** Significant correlations between answers on the questionnaires (Pearson, $p < 0.01$, value in brackets: $p < 0.05$).

| | friendly | attentive | ad. attent. | conv. comm. | non-verb. int. | verb. int. |
|---|---|---|---|---|---|---|
| friendly | - | .613 | (.228) | .477 | .420 | .534 |
| attentive | .613 | - | .518 | .575 | .484 | .587 |
| adequate attention | .481 | .581 | - | .464 | .585 | .567 |
| convenient communication | .477 | .600 | .464 | - | .522 | .630 |
| non-verbal interaction | .420 | .484 | .485 | .522 | - | .645 |
| verbal interaction | .534 | .587 | .567 | .630 | .645 | - |

**Table 6** "How pronounced did you experience the verbal communication skills / the non-verbal interaction skills of the robot, e.g. eye-contact?"

| | not at all | | | | | | very | |
|---|---|---|---|---|---|---|---|---|
| (in %) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | $\mu$ |
| **Adults** | | | | | | | | |
| non-verbal | 3 | 4 | 6 | 7 | 27 | **29** | 20 | 5.2 |
| verbal | 1 | 9 | 7 | 16 | **29** | 23 | 12 | 4.8 |
| **Children** | | | | | | | | |
| non-verbal | 2 | 2 | 2 | 10 | 17 | 12 | **51** | 5.8 |
| verbal | 0 | 0 | 5 | 20 | 15 | 22 | **37** | 5.7 |

During the first tours in the museum, Robotinho did not announce the next destination in the tour. While working quite well when only a few visitors were listening to Robotinho's explanations, navigation failed when many visitors surrounded the robot. Robotinho had to ask multiple times for clearance, as the visitors were not aware about the robot's driving direction. Finally, the visitors stepped back several meters, allowing Robotinho to start driving. We observed that indicating the robot's intention by announcing the next exhibit and pointing to it causes the visitors to look at the next exhibit and to open a passageway into the right direction.

In our experiments, the importance of interaction with visitors during the navigation from one exhibit to the next became clear. The environment where Robotinho gave tours is clearly arranged. So, many persons stayed back during tours and watched the robot from a distance. The majority of these persons, and some visitors only strolling around in the vicinity of the robot, followed the request of Robotinho to come closer again. In one situation, even a large group of visitors sitting at the periphery of the exhibition area stood up and went to the tour guide after its request.

## 9 Evaluation in RoboCup Competitions

In recent years, robot competitions, such as the DARPA Robotics Challenge and RoboCup, play an important role in assessing the performance of robot systems.

At such competitions, the robot has to perform tasks defined by the rules of the competition, in a given environment at a predetermined time. The simultaneous presence of multiple teams allows for a direct comparison of the robot systems by measuring objective performance criteria, and also by subjective judgment of the scientific and technical merit by a jury.

The international RoboCup competitions, best known for robot soccer, also include the @Home league for domestic service robots [55]. The rules of the league require fully autonomous robots to robustly navigate in a home environment, to interact with human users using speech and gestures, and to manipulate objects that are placed on the floor, in shelves, or on tables. The robots can show their capabilities in several predefined tests, such as following a person, fetching an object, or recognizing persons. In addition, there are open challenges and the final demonstration, where the teams can highlight the capabilities of their robots in self-defined tasks.

### 9.1 RoboCup German Open 2009

Our team NimbRo [47] participated for the first time in the @Home league at RoboCup German Open 2009 during Hannover Fair.

We used our communication robot Robotinho for the *Introduce* task. In this test, the robot has to introduce itself and the team to the audience. It may interact with humans to demonstrate its human-robot interaction skills. The team leaders of the other teams judge the performance of the robot on criteria like quality of human-robot interaction, appearance, and robustness of mobility. Robotinho explained itself and our second robot Dynamaid and interacted with a human in a natural way. The jury awarded Robotinho the highest score of all robots in this test.

In the final, Robotinho gave a tour through the apartment while Dynamaid fetched a drink for a guest. The score in the final is composed of the previous performance of the team in Stage I and Stage II and an evaluation score by independent researchers that judge scientific contribution, originality, usability, presentation, multi-modality, difficulty, success, and relevance. Overall, the NimbRo@Home team reached the second place.

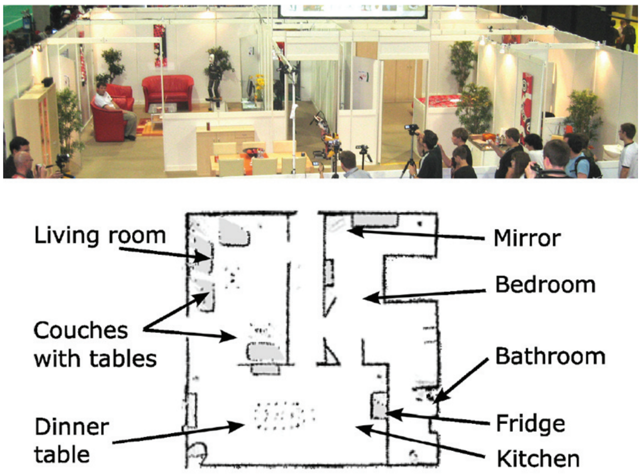


**Fig. 9** Arena of the 2009 RoboCup@Home competition in Graz.

### 9.2 RoboCup 2009

The RoboCup 2009 competition took place in July in Graz, Austria. Figure 9 shows both of our Robots in the arena, which consisted of a living room, a kitchen, a bedroom, a bathroom, and an entrance corridor. 18 teams from 9 countries participated in this competition.

In the *Introduce* test, Robotinho explained itself and Dynamaid, while Dynamaid cleaned-up an object from the table. Together, our robots reached the highest score in this test.

Both robots reached the second highest score in the *Open Challenge*, where Robotinho gave a home tour to a guest while Dynamaid delivered a drink.

Both robots were used in the *Demo Challenge*. The theme of the challenge was 'in the bar'. Robotinho offered snacks to the guests, while Dynamaid served drinks. The jury awarded 90% of the reachable points for this performance.

Overall, our team reached the third place in the @Home competition. We also won the innovation award for "Innovative robot body design, empathic behaviors, and robot-robot cooperation".

### 9.3 RoboCup German Open 2010

In 2010, we participated for the third time in the @Home league with Robotinho. RoboCup German Open 2010 took place in spring in Magdeburg. In the *Demo Challenge*, Robotinho searched for guests in the apartment. After welcoming a guest it guided the guest to Dynamaid, which served drinks, by announcing its position backed by a pointing gesture.

In the final, our two robots cooperated again. Robotinho waited next to the apartment entrance until a guest entered. The robot asked the guest if he/she wanted to eat something and recognized the verbal answer. As Robotinho is solely designed to serve as a communication robot, it has quite limited manipulation capabilities. Hence, it went to Dynamaid and notified the other robot to go to the guest to offer him/her something. The robots emphasized their cooperation by talking to each other, such that the guest and the spectators could predict the robots' actions.

Overall, our team reached the second place in the competition.

## 10 Conclusions

Although our communication robots were successfully evaluated before in different static and mobile scenarios, most of the mobile evaluations in the past took place in non-public environments. In this work, we summarize our evaluations of Robotinho in the partially controllable environments of RoboCup competitions and as a mobile tour guide in a public science museum [33]. Our robot interacted with a large number of users who were unfamiliar with robots.

To guide these users successfully, we had to extend Robotinho's multimodal interaction skills with new behaviors to keep track of and interact with visitors while moving and to announce its intended navigation goals.

The majority of the visitors of the Deusches Museum Bonn answered that they are generally interested in technology and open-minded to robot use. Many persons answered the questions about typical human attributes like the friendliness and politeness of Robotinho with highly marks. The interaction capabilities were also high rated. In the vast majority of tours, the one where Robotinho explained our three robots was chosen first and most communication partners continued with the second available tour after the first tour was finished. We found correlations between how polite and human-like the robot was perceived by the visitors and how intuitive the communication with the robot was rated. This gives us a strong hint that emotional expressions are key to natural human-robot interaction.

Speech understanding in public environments is still a major problem. These environments are typically noisy and the speakers are not known to the system. Speaker independent speech recognition systems robust to noise are often grammar-based and cannot recognize arbitrary sentences. Furthermore, the interpretation of commands in natural language is error-prone—especially if a group of visitors give contradicting commands simultaneously. Hence, we used a Wizard of Oz technique for speech recognition in our experiments.

High expectations in the communication abilities of the robot are induced by it anthropomorphic appearance and the multimodal interaction system. In our experiments, children saw the robot as very human-like. If the robot was turned off, they asked if the robot is ill. They also asked a lot of general questions about the museum and related topics to the robot during the tour. In general, the reception of the robot by the museum's visitors was very good.

During the first tours, the robot did not communicate its navigation goals to the guided persons. This led to disruptions as the tour could often not continue until the confused visitors interpreted the robot's movement intentions correctly. As Robotinho re-plans its path if blocked, the movements may appear random to the people blocking the path. Communicating the next exhibit by announcing its name and pointing towards it yielded a substantial improvement in the navigation between exhibits.

In addition to the experiments at Deutsches Museum, we competed with Robotinho in several RoboCup competitions. It cooperated with our service robot Dynamaid and assisted with its communication skills. For example, Robotinho introduced the team and guided a guest through an apartment. Robotinho's multimodal communication abilities and the cooperation of both robots were well received by the juries. The limited mobile manipulation capabilities of Robotinho prevent its usage as domestic service robot. Hence, we transferred parts of Robotinho's behaviors to our domestic service robots Cosero and Dynamaid [48]. Both robots are capable to perform symbolic and pointing gestures. Furthermore, they gaze into their driving direction and track their communication partner's face. The dialog system was ported to the Robot Operating System [36] to be usable on these robots. So far, the service robots are not equipped with expressive communication heads. Hence, the facial expressions from Robotinho cannot be transferred to them. In the future, we will build new communication heads for our service robots to integrate mobile manipulation and intuitive multimodal communication.

**Acknowledgements** We thank Dr. Andrea Niehaus and her team at *Deutsches Museum Bonn* for providing the location and their support before and during our tests.

This work has been supported partially by grant BE 2556/2-3 of German Research Foundation (DFG).

## References

1. Best of NimbRo@Home. `http://www.nimbro.net/@Home/videos/RoboCup_2009_NimbRo@Home.wmv`
2. The mobile, full-body humanoid, museum tour guide Robotinho. `http://www.nimbro.net/movies/robotinho/robotinho_tourguide.wmv`
3. Robotinho – the communication robot. `http://www.nimbro.net/movies/robotinho/robotinho_static.wmv`
4. Robotinho conducts the 12 cellists of the Berlin Philharmonic. `http://www.nimbro.net/movies/robotinho/Robotinho_conducts.wmv`
5. Testing the museum tour guide robot Robotinho. `http://www.nimbro.net/movies/DMB10/DMB_Robotinho_2010_low_res.wmv`
6. Aoyama, K., Shimomura, H.: Real world speech interaction with a humanoid robot on a layered robot behavior control architecture. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA) (2005)
7. Beck, A., Stevens, B., Bard, K.A., Cañamero, L.: Emotional body language displayed by artificial agents. ACM Transactions on Interactive Intelligent Systems **2**(1), 2:1–2:29 (2012)
8. Behnke, S., Stückler, J., Schreiber, M.: NimbRo KidSize 2009 team description. In: RoboCup 2009 Humanoid League Team Descriptions
9. Bennewitz, M., Faber, F., Joho, D., Behnke, S.: Humanoid Robots: Human-like Machines, chap. Intuitive Multimodal Interaction with Communication Robot Fritz. Intech, Vienna, Austria (2007)
10. Bischoff, R., Graefe, V.: Demonstrating the humanoid robot HERMES at an exhibition: A long-term dependability test. In: Proceedings of the IEEE International Conference on Intelligent Robots and Systems (IROS); Workshop on Robots at Exhibitions (2002)
11. Borst, C., Wimbock, T., Schmidt, F., Fuchs, M., Brunner, B., Zacharias, F., Giordano, P., Konietschke, R., Sepp, W., Fuchs, S., Rink, C., Albu-Schaffer, A., Hirzinger, G.: Rollin' justin - mobile platform with variable base. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), pp. 1597–1598 (2009)
12. Breazeal, C.: Designing Sociable Robots. MIT Press, Cambridge, MA (2002)
13. Breazeal, C., Brooks, A., Gray, J., Homan, G., Kidd, C., Lee, H., Lieberman, J., Lockerd, A., Chilongo, D.: Tutelage and collaboration for humanoid robots. International Journal of Humanoid Robotics (2004). 1(2):315-348
14. Burgard, W., Cremers, A., Fox, D., Hähnel, D., Lakemeyer, G., Schulz, D., Steiner, W., Thrun, S.: Experiences with an interactive museum tour-guide robot. Artificial Intelligence 114(1-2):3-55 (1999)
15. Cui, J., Zha, H., Zhao, H., Shibasaki, R.: Multi-modal tracking of people using laser scanners and video camera. Image and vision Computing **26**(2), 240–252 (2008)
16. Dautenhahn, K., Walters, M., Woods, S., Koay, K., Nehaniv, C., Sisbot, A., Alami, R., Simeon, T.: How may I serve you?: a robot companion approaching a seated person in a helping context. In: Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI) (2006)
17. Faber, F., Bennewitz, M., Behnke, S.: Controlling the gaze direction of a humanoid robot with redundant joints. In: Proceedings of the International Symposium on Robot and Human Interactive Communication (RO-MAN) (2008)

18. Faber, F., Bennewitz, M., Eppner, C., Grg, A., Gonsior, C., Joho, D., Schreiber, M., Behnke, S.: The Humanoid Museum Tour Guide Robotinho. In: Proceedings IEEE-RAS International Conference on Humanoid Robots (Humanoids) (2009)
19. Fox, D.: Adapting the sample size in particle filters through KLD-sampling. International Journal of Robotics Research (IJRR) **22**(12), 985–1003 (2003)
20. Gerkey, B., Vaughan, R.T., Howard, A.: The Player/Stage project: Tools for multi-robot and distributed sensor systems. In: Proceedings of the international conference on advanced robotics (ICAR) (2003)
21. Gorostiza, J., Khamis, R.B.A., Malfaz, M., Pacheco, R., Rivas, R., Corrales, A., Delgado, E., Salichs, M.: Multimodal human-robot interaction framework for a personal robot. In: Proceedings of the International Symposium on Robot and Human Interactive Communication (RO-MAN) (2006)
22. Gouaillier, D., Hugel, V., Blazevic, P., Kilner, C., Monceaux, J., Lafourcade, P., Marnier, B., Serre, J., Maisonnier, B.: Mechatronic design of NAO humanoid. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), pp. 769 –774 (2009)
23. Grisetti, G., Stachniss, C., Burgard, W.: Improved techniques for grid mapping with Rao-Blackwellized particle filters. IEEE Transactions on Robotics **23**(1) (2007)
24. Hart, P., Nilson, N., Raphael, B.: A formal basis for the heuristic determination of minimal cost paths. IEEE Transactions of Systems Science and Cybernetics **4**(2), 100–107 (1968)
25. Hristoskova, A., Aguero, C., Veloso, M., Turck, F.D.: Heterogeneous context-aware robots providing a personalized building tour. International Journal of Advanced Robotic Systems (2012)
26. Kuhn, H.: The hungarian method for the assignment problem. Naval Research Logistics Quarterly **2**(1), 83–97 (1955)
27. Kdzierski, J., Muszyski, R., Zoll, C., Oleksy, A., Frontkiewicz, M.: Emysemotive head of a social robot. International Journal of Social Robotics **5**(2), 237–249 (2013)
28. Loquendo S.p.A.: Vocal technology and services. loquendo.com (2009)
29. Matsui, D., Minato, T., MacDorman, K.F., Ishiguro, H.: Generating natural motion in an android by mapping human motion. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2005)
30. Mianowski, K., Schmitz, N., Berns, K.: Mechatronics of the humanoid robot ROMAN. Robot Motion and Control 2007 pp. 341–348 (2007)
31. Montemerlo, M., Thrun, S., Koller, D., Wegbreit, B.: FastSLAM 2.0: An improved particle filtering algorithm for simultaneous localization and mapping that provably converges. In: Proceedings of the International Joint Conference on Artificial Intelligence (IJCAI (2003)
32. Mori, M.: Bukimi no tani [the uncanny valley]. Energy **7**(4), 33–35 (1970)
33. Nieuwenhuisen, M., Gaspers, J., Tischler, O., Behnke, S.: Intuitive multimodal interaction and predictable behavior for the museum tour guide robot robotinho. In: Proceedings IEEE-RAS International Conference on Humanoid Robots (Humanoids), pp. 653–658. IEEE (2010)
34. Nieuwenhuisen, M., Stückler, J., Behnke, S.: Intuitive Multimodal Interaction for Domestic Service Robots. In: Proceedings of Joint International Symposium on Robotics (ISR 2010) and German Conference on Robotics (ROBOTIK 2010) (2010)
35. Nourbakhsh, I., Kunz, C., Willeke, T.: The mobot museum robot installations: A five year experiment. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2003)
36. Quigley, M., Gerkey, B., Conley, K., Faust, J., Foote, T., Leibs, J., Berger, E., Wheeler, R., Ng, A.: Ros: an open-source robot operating system. In: ICRA workshop on open source software, vol. 3 (2009)
37. Ruttkay, Z., Noot, H., ten Hagen, P.: Emotion Disc and Emotion Squares: Tools to explore the facial expression space. Computer Graphics Forum **22**(1), 49–53 (2003)
38. Saldien, J., Goris, K., Vanderborght, B., Vanderfaeillie, J., Lefeber, D.: Expressing emotions with the social robot probo. International Journal of Social Robotics **2**(4), 377–389 (2010)
39. Salem, M., Kopp, S., Wachsmuth, I., Rohlfing, K., Joublin, F.: Generation and evaluation of communicative robot gesture. International Journal of Social Robotics pp. 1–17 (2012)
40. Schillaci, G., Bodiroa, S., Hafner, V.: Evaluating the effect of saliency detection and attention manipulation in human-robot interaction. International Journal of Social Robotics **5**(1), 139–152 (2013)
41. Schulz, D.: A Probabilistic Exemplar Approach to Combine Laser and Vision for Person Tracking. In: Proceedings of the Robotics: Science and Systems Conference (RSS) (2006)
42. Shin-Ichi, O., Tomohito, A., Tooru, I.: The introduction of the personal robot papero. IPSJ SIG Notes (68), 37–42 (2001)
43. Shiomi, M., Kanda, T., Ishiguro, H., Hagita, N.: A larger audience, please!: encouraging people to listen to a guide robot. In: Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI) (2010)
44. Siegwart, R., Arras, K., Bouabdallah, S., Burnier, D., Froidevaux, G., Greppin, X., Jensen, B., Lorotte, A., Mayor, L., Meisser, M., et al.: Robox at Expo. 02: A large-scale installation of personal robots. Robotics and Autonomous Systems **42**(3-4), 203–222 (2003)
45. Spinello, L., Triebel, R., Siegwart, R.: Multimodal detection and tracking of pedestrians in urban environments with explicit ground plane extraction. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2008)
46. Stückler, J., Behnke, S.: Integrating Indoor Mobility, Object Manipulation and Intuitive Interaction for Domestic Service Tasks. In: Proceedings IEEE-RAS International Conference on Humanoid Robots (Humanoids) (2009)
47. Stückler, J., Dröschel, D., Gräve, K., Holz, D., Schreiber, M., Behnke, S.: NimbRo @Home 2010 team description. In: RoboCup 2010 @Home League Team Descriptions
48. Stückler, J., Holz, D., Behnke, S.: RoboCup@Home: Demonstrating everyday manipulation skills in RoboCup@Home. Robotics & Automation Magazine, IEEE **19**(2), 34 –42 (2012)
49. Thrun, S., Beetz, M., Bennewitz, M., Burgard, W., Cremers, A., Dellaert, F., Fox, D., Hahnel, D., Rosenberg, C., Roy, N., et al.: Probabilistic Algorithms and the Interactive Museum Tour-Guide Robot Minerva. The International Journal of Robotics Research **19**(11), 972 (2000)
50. Ulrich, I., Borenstein, J.: VFH+: Reliable obstacle avoidance for fast mobile robots. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA) (1998)

51. Viola, P., Jones, M.: Rapid Object Detection using a Boosted Cascade of Simple Features. In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR) (2001)
52. Welch, G., Bishop, G.: An introduction to the Kalman filter. University of North Carolina at Chapel Hill, Chapel Hill, NC (1995)
53. Wilken, T., Missura, M., Behnke, S.: Designing falling motions for a humanoid soccer goalie. In: Proceedings of the 4th Workshop on Humanoid Soccer Robots, International Conference on Humanoid Robots (Humanoids) (2009)
54. Willow Garage: PR2 Manual
55. Wisspeintner, T., Zan, T., Iocchi, L., Schiffer, S.: Robocup@home: Results in benchmarking domestic service robots. In: J. Baltes, M. Lagoudakis, T. Naruse, S. Ghidary (eds.) RoboCup 2009: Robot Soccer World Cup XIII, *Lecture Notes in Computer Science*, vol. 5949, pp. 390–401. Springer Berlin Heidelberg (2010)
56. Yousuf, M., Kobayashi, Y., Kuno, Y., Yamazaki, A., Yamazaki, K.: Development of a mobile museum guide robot that can configure spatial formation with visitors. In: Intelligent Computing Technology, *Lecture Notes in Computer Science*, vol. 7389, pp. 423–432. Springer Berlin Heidelberg (2012)

Matthias Nieuwenhuisen received a Diploma in Computer Science from Rheinische Friedrich-Wilhelms Universität Bonn in 2009. Since May 2009, he works as a member of the scientific staff in the Autonomous Intelligent Systems Group at the University of Bonn. His current research interests include human-robot interaction, path and motion planning

Sven Behnke received his Diploma in Computer Science from Martin-Luther-Universität Halle-Wittenberg in 1997 and Ph.D. from Freie Universität Berlin in 2002. He worked in 2003 as postdoctoral researcher at the International Computer Science Institute, Berkeley. From 2004 to 2008, he headed the Humanoid Robots Group at Albert-Ludwigs-Universität Freiburg. Since 2008, he is professor for Autonomous Intelligent Systems at the University of Bonn. His research interests include cognitive robotics, computer vision, and machine learning.