

**A Survey of Socially Interactive Robots:  
Concepts, Design, and Applications**

Terrence Fong, Illah Nourbakhsh,  
and Kerstin Dautenhahn

CMU-RI-TR-02-29

The Robotics Institute  
Carnegie Mellon University  
5000 Forbes Avenue  
Pittsburgh, Pennsylvania 15213

November 2002

© 2002 by Terrence Fong, Illah Nourbakhsh, and Kerstin Dautenhahn.  
All rights reserved.



# A Survey of Socially Interactive Robots: Concepts, Design, and Applications

Terrence Fong<sup>a,b</sup>, Illah Nourbakhsh<sup>a</sup>, and Kerstin Dautenhahn<sup>c</sup>

<sup>a</sup>*The Robotics Institute, Carnegie Mellon University  
Pittsburgh, Pennsylvania 15213, USA*

<sup>b</sup>*Institut de production et robotique, Ecole Polytechnique Fédérale de Lausanne  
CH-1015 Lausanne, Switzerland*

<sup>c</sup>*Department of Computer Science, The University of Hertfordshire  
College Lane, Hatfield, Hertfordshire AL10 9AB, United Kingdom*

---

## Abstract

This report reviews “socially interactive robots”: robots for which social human-robot interaction is important. We begin by discussing the context for socially interactive robots, emphasizing the relationship to other research fields and the different forms of “social robots”. We then present a taxonomy of design methods and system components used to build socially interactive robots. Following this taxonomy, we survey the current state of the art, categorized by use and application area. Finally, we describe the impact of these robots on humans and discuss open issues. An abbreviated version of this report, which does not contain the application survey, is available as [T. Fong, I. Nourbakhsh, K. Dautenhahn, A survey of socially interactive robots, *Robotics and Autonomous Systems* 42 (3-4) (2003)].

*Key words:* Human-robot interaction, sociable robot, social robot, socially interactive robot

---

## 1 Introduction

### 1.1 The history of social robots

From the beginning of biologically inspired robots, researchers have been fascinated by the possibility of robots interacting with each other. Fig. 1 shows the robotic tortoises built by Walter in the late 1940’s[104]. By means of headlamps attached to the robot’s front and positive phototaxis, the two robots interacted in a seemingly “social” manner,

even though there was no explicit communication or mutual recognition.

As the field of artificial life emerged, researchers began applying principles such as stigmergy (indirect communication between individuals via modifications made to the shared environment) to achieve “collective” or “swarm” robot behavior. Stigmergy was first used by Grassé to explain how social insect societies can collectively produce complex behavior patterns and physical structures, even if each individual appears to work alone[19].

Deneubourg and his collaborators pioneered the first experiments on stigmergy in simulated and physical “ant-like robots” [75,13] in the early 1990’s. Since then, numerous researchers have developed

---

*Email addresses:* terry@ri.cmu.edu (Terrence Fong), illah@ri.cmu.edu (Illah Nourbakhsh), K.Dautenhahn@herts.ac.uk (Kerstin Dautenhahn).



Fig. 1. Precursors of social robotics: Walters tortoises, Elmer and Elsie, “dancing” around each other.



Fig. 2. U-Bots sorting objects[150]

robot collectives[130,150] and have used robots as models for studying social insect behavior[129].

Similar principles can be found in multi-robot or distributed robotic systems research[144]. Some of the interaction mechanisms employed are communication[9], interference[98], and aggressive competition[233]. Common to these group-oriented social robots is maximizing benefit (e.g., task performance) through collective action (Figs. 2–4).

The research described thus far uses principles of self-organization and behavior inspired by social insect societies. Such societies are anonymous, homogeneous groups in which individuals do not matter. This type of “social behavior” has proven to be an

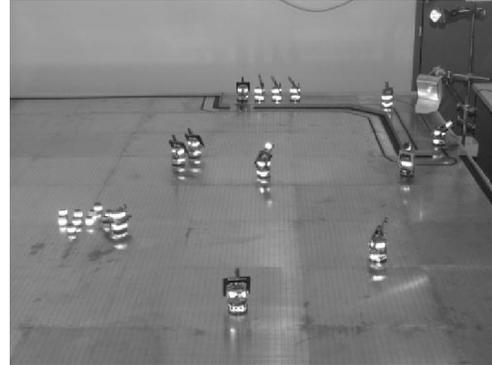


Fig. 3. Khepera robots foraging for “food” [129]



Fig. 4. Collective box-pushing[130]

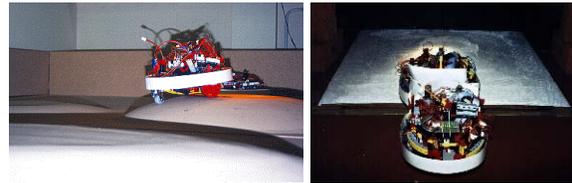


Fig. 5. Early “individual” social robots: “getting to know each other” (left, [56]) and learning by imitation (right, [15,16])

attractive model for robotics, particularly because it enables groups of relatively simple robots perform difficult tasks (e.g., soccer playing).

However, many species of mammals (including humans, birds, and other animals) often form individualized societies. Individualized societies differ from anonymous societies because the individual matters. Although individuals may live in groups, they form relationships and social networks, they create alliances, and they often adhere to societal norms and conventions[56] (Fig. 5).

In [63], Dautenhahn and Billard proposed the following definition:

Social robots are embodied agents that are part of a heterogeneous group: a society of robots or

humans. They are able to recognize each other and engage in social interactions, they possess histories (perceive and interpret the world in terms of their own experience), and they explicitly communicate with and learn from each other.

Developing such “individual social” robots requires the use of models and techniques different from “group social” collective robots (Fig. 6). In particular, social learning and imitation, gesture and natural language communication, emotion, and recognition of interaction partners are all important factors. Moreover, most research in this area has focused on the application of “benign” social behavior. Thus, social robots are usually designed as assistants, companions, or pets, in addition to the more traditional role of servants.

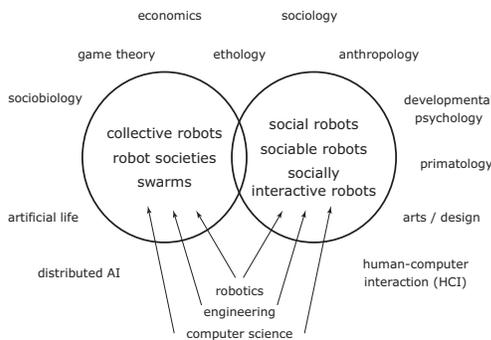


Fig. 6. Fields of major impact. Note that “collective robots” and “social robots” overlap where individuality plays a lesser role.

### 1.2 Social robots and social embeddedness: concepts and definitions

Robots in individualized societies exhibit a wide range of social behavior, regardless if the society contains other social robots, humans, or both. In [28], Breazeal defines four classes of social robots in terms of (1) how well the robot can support the social model that is ascribed to it and (2) the complexity of the interaction scenario that can be supported:

*Socially evocative.* Robots that rely on the human tendency to anthropomorphize and capitalize on feelings evoked when humans nurture, care, or involved with their “creation”.

*Social interface.* Robots that provide a “natural” interface by employing human-like social cues and communication modalities. Social behavior is only modeled at the interface, which usually results in shallow models of social cognition.

*Socially receptive.* Robots that are socially passive but that can benefit from interaction (e.g. learning skills by imitation). Deeper models of human social competencies are required than with social interface robots.

*Sociable.* Robots that pro-actively engage with humans in order to satisfy internal social aims (drives, emotions, etc). These robots require deep models of social cognition.

Complementary to this list we can add the following three classes:

*Socially situated.* Robots that are surrounded by a social environment that they perceive and react to [70]. Socially situated robots must be able to distinguish between other social agents and various objects in the environment<sup>1</sup>.

*Socially embedded.* Robots that are: (a) situated in a social environment and interact with other agents and humans; (b) structurally coupled with their social environment; and (c) at least partially aware of human interactional structures (e.g., turn-taking) [70].

*Socially intelligent.* Robots that show aspects of human style social intelligence, based on deep models of human cognition and social competence [56,58].

### 1.3 Socially interactive robots

For the purposes of this paper, we use the term “socially interactive robots” to describe robots for which social interaction plays a key role. We do this,

<sup>1</sup> Other researchers place different emphasis on what *socially situated* implies (e.g., [140]).

not to introduce another class of social robot, but rather to distinguish these robots from other robots that involve “conventional” human-robot interaction, such as those used in teleoperation scenarios.

In this paper, we focus on peer-to-peer, human-robot interaction. Specifically, we describe robots that exhibit the following “human social” characteristics:

- express and/or perceive emotions
- communicate with high-level dialogue
- learn/recognize models of other agents
- establish/maintain social relationships
- use natural cues (gaze, gestures, etc.)
- exhibit distinctive personality and character
- may learn/develop social competencies

Socially interactive robots can be used for a variety of purposes: as research platforms, as toys, as educational tools, or as therapeutic aids. The common, underlying assumption is that humans prefer to interact with machines in the same way that they interact with other people. A survey and taxonomy of current applications is given in Section 3.

Socially interactive robots operate as partners, peers or assistants, which means that they need to exhibit a certain degree of adaptability and flexibility to drive the interaction with a wide range of humans. Socially interactive robots can have different shapes and functions, ranging from robots whose sole purpose and only task is to engage people in social interactions (Kismet, Cog, etc.) to robots that are engineered to adhere to social norms in order to fulfill a range of tasks in human-inhabited environments (Pearl, Sage, etc.)[27,171,187,205].

Some socially interactive robots use deep models of human interaction and pro-actively encourage social interaction. Others show their social competence only in reaction to human behavior, relying on humans to attribute mental states and emotions to the robot[57,66,78,183]. Regardless of function, building a socially interactive robot requires considering the human in the loop: as designer, as observer, and as interaction partner.

#### 1.4 Why socially interactive robots?

Socially interactive robots are important for domains in which robots must exhibit peer-to-peer interaction skills, either because such skills are required for solving specific tasks, or because the primary function of the robot is to interact socially with people. A discussion of application domains, design spaces, and desirable social skills for robots is given in [61] and [62].

One area where social interaction is desirable is that of “robot as persuasive machine”[83], i.e., the robot is used to change the behavior, feelings or attitudes of humans. This is the case when robots mediate human-human interaction, as in autism therapy[240]. Another area is “robot as avatar”[181], in which the robot functions as a representation of, or representative for, the human. For example, if a robot is used for remote communication, it may need to act socially in order to effectively convey information.

In certain scenarios, it may be desirable for a robot to develop its interaction skills over time. For example, a pet robot that accompanies a child through his childhood may need to improve its skills in order to maintain the child’s interest. Learned development of social (and other) skills is a primary concern of epigenetic robotics[248,63].

Some researchers design socially interactive robots simply to study embodied models of social behavior. For this use, the challenge is to build robots that have an intrinsic notion of sociality, that develop social skills and bond with people, and that can show empathy and true understanding. At present, such robots remain a distant goal[57,63], the achievement of which will require contributions from other research areas such as artificial life, developmental psychology and sociology[195].

Although socially interactive robots have already been used with success, much work remains to increase their effectiveness. For example, in order for socially interactive robots to be accepted as “natural” interaction partners, they need more sophisticated social skills, such as the ability to recognize social context and convention.

Additionally, socially interactive robots will eventually need to support a wide range of users: different genders, different cultural and social backgrounds, different ages, etc. In many current applications, social robots engage only in short-term interaction (e.g., a museum tour) and can afford to treat all humans in the same manner. But, as soon as a robot becomes part of a person’s life, that robot will need to be able to treat him as a distinct individual[58].

In the following, we closely examine the concepts raised in this introductory section. We begin by describing different design methods. Then, we present a taxonomy of system components, focusing on the design issues unique to socially interactive robots. We conclude by discussing open issues and core challenges.

## 2 Methodology

### 2.1 Design approaches

Humans are experts in social interaction. Thus, if technology adheres to human social expectations, people will find the interaction enjoyable, feeling empowered and competent[192]. Many researchers, therefore, explore the design space of anthropomorphic (or zoomorphic) robots, trying to endow their creations with characteristics of intentional agents. For this reason, more and more robots are being equipped with faces, speech recognition, lip-reading skills, and other features and capacities to make robot-human interaction more “human-like” or at least “creature-like” [60,70].

From a design perspective, we can classify how socially interactive robots are built in two primary ways. With the first approach, “biologically inspired”, designers try to create robots that internally simulate, or mimic, the social intelligence found in living creatures. With the second approach, “functionally designed”, the goal is to construct a robot that outwardly appears to be socially intelligent, even if the internal design does not have a basis in science.

Robots have limited perceptual, cognitive, and be-

havioral abilities compared to humans. Thus, for the foreseeable future, there will continue to be significant imbalance in social sophistication between human and robot[29]. As with expert systems, however, it is possible that robots may become highly sophisticated in restricted areas of socialization, e.g., infant-caretaker relations.

Finally, differences in design methodology means that the evaluation and success criteria are almost always different for different robots. Thus, it is hard to compare socially interactive robots outside of their target environment and use.

#### 2.1.1 Biologically inspired

With the “biologically inspired” approach, designers try to create robots that internally simulate, or mimic, the social behavior or intelligence found in living creatures. Biologically inspired designs are based on theories drawn from natural and social sciences, including anthropology, cognitive science, developmental psychology, ethology, sociology, structure of interaction, and theory of mind. Generally speaking, these theories are used to guide the design of robot cognitive, behavioral, motivational (drives and emotions), motor and perceptual systems.

Two primary arguments are made for drawing inspiration from biological systems. First, some researchers contend that nature is the best model for “life-like” activity. Specifically, they hypothesize that for a robot to be understandable by humans, it must have a naturalistic embodiment, it must interact with its environment in the same way living creatures do, and it must perceive the same things that humans find to be salient and relevant[248].

The second rationale for biological inspiration is that it allows us to directly examine, test and refine those scientific theories upon which the design is based[1]. This is particularly true with humanoid robots. Cog, for example, is a general-purpose humanoid platform intended for exploring theories and models of intelligent behavior and learning [205].

Some of the theories commonly used in biologically

inspired design are:

*Ethology.* Ethology refers to the observational study of animals in their natural setting[137]. Ethology can serve as a basis for design because it describes the types of activity (comfort-seeking, play, etc.) a robot needs to exhibit in order to appear life-like [6]. Ethology is also useful for addressing a range of behavioral issues such as concurrency, motivation, and instinct.

*Structure of interaction.* Analysis of interactional structure (such as instruction, cooperation, etc.) can help focus design of perception and cognition systems by identifying key interaction patterns [240]. Dautenhahn, Ogden and Quick use explicit representations of interactional structure to design “interaction aware” robots[70]. Dialogue models, such as turn-taking in conversation, can also be used in design as in [147].

*Theory of mind.* Theory of mind refers to those social skills that allow humans to correctly attribute beliefs, goals, perceptions, feelings, and desires to themselves and others[241]. One of the critical precursors to these skills is joint (or shared) attention: the ability to selectively attend to an object of mutual interest [10]. Joint attention can aid design, by providing guidelines for recognizing and producing social behaviors such as gaze direction, pointing gestures, etc.[33,205].

*Developmental psychology.* Developmental psychology has been cited as effective mechanism for creating robots that engage in natural social exchanges. As an example, the design of Kismet’s “synthetic nervous system”, particularly the perceptual and behavioral aspects, is heavily inspired by the social development of human infants[27]. Additionally, theories of child cognitive development, such as Vygotsky’s “child in society” [134], can offer a framework for constructing robot architecture and social interaction design [63,64].

### 2.1.2 Functionally designed

With the “functionally designed” approach, the objective is to design a robot that outwardly appears to be socially intelligent, even if the internal de-

sign does not have a basis in science or nature. This approach assumes that if we want to create the impression of an artificial social agent driven by beliefs and desires, we do not necessarily need to understand how the mind really works. Instead, it is sufficient to describe the mechanisms (sensations, traits, folk-psychology, etc.) by which people in everyday life understand socially intelligent creatures[183].

In contrast to their biologically inspired counterparts, functionally designed robots generally have constrained operational and performance objectives. Consequently, these “engineered” robots may need only to generate certain effects and experiences with the user, rather than having to withstand extensive scrutiny for “life-like” capabilities.

Some motivations for “functional design” are:

- The robot may only need to be superficially socially competent. This is particularly true when only short-term interaction or limited quality of interaction is required.
- The robot may have limited embodiment, capability for interaction, or may be constrained by the environment.
- Even limited social expression can help improve the affordances and usability of a robot. In some applications, recorded or scripted speech may be sufficient for human-robot dialogue.
- Artificial designs can provide compelling interaction. Many video games and electronic toys fully engage and occupy attention, even if the artifacts do not have real-world counterparts.

The three techniques most often used in functional design are:

*Human-Computer Interaction (HCI) design.* Robots are increasingly being developed using HCI techniques, including cognitive modeling, contextual inquiry, heuristic evaluation, and empirical user testing[168]. User studies are conducted, often throughout development, in order to understand the user’s activities and to assess the interface (or system) usability.

Nourbakhsh describes the design of a personal

rover, which is intended to be a creative and expressive tool, for non-specialists such as children [82]. The design of this rover is guided by an experience design document developed through a user study. Scheeff et al. discusses the development of Sparky, a telerobotic “creature” built to explore non-conventional HCI[207]. Sparky’s design was inspired both by principles of traditional animation and cartooning (e.g., how to evoke emotional state through motion) as well as heuristic design goals (exhibit smooth motion, make the body active, etc.).

*Systems Engineering.* Systems engineering involves the top-down development of a systems’ functional and physical requirements from a basic set of objectives. The purpose is to organize information and knowledge to facilitate and control the planning, development, and operation of the system[199]. Systems engineering is frequently used in robot development, although structured design techniques (configuration control, work breakdown structure, etc.) tend to be applied informally.

A basic characteristic of system engineering is that it only places emphasis on the design of critical-path system elements. Pineau et al., for example, describe mobile robots designed to assist the elderly in daily living[187]. Because these robots operate in a highly structured domain their design centers on a collection of task-based behaviors: autonomous navigation, speech recognition, face tracking, etc. rather than broad social interaction.

*Iterative design.* Iterative (or sequential) design, is the process of revising a design through a series of test and redesign cycles[217]. It is typically used to address design failures or to make improvements based on information from evaluation or use. Iterative design can be an effective design technique, particularly when a system or its target environment are difficult to model analytically. However, because suggestions for improvement are often based on anecdotal data, design changes may result in little or no improvement.

Willeke et al. describe a series of museum robots, each of which was designed based on lessons learned from preceding generations[243]. The design objective was to attract people to interact, based on en-

vironmental constraints and using simple interaction models. Schulte et al. discuss design for short-term and spontaneous interaction between Minerva[230], another tour guide robot, and crowds of people[208].

## 2.2 Design issues

All robot systems, whether socially interactive or not, must address a number of common design problems. These include cognition (planning, decision making), perception (navigation, environment sensing), action (mobility, manipulation), human-robot interaction (user interface, input devices, feedback display) and architecture (control, electromechanical, system). Socially interactive robots, however, must also address those issues imposed by social interaction[27,58].

*Human-oriented perception.* A socially interactive robot must proficiently perceive and interpret human activity and behavior. This includes detecting and recognizing gestures, monitoring and classifying activity, discerning intent and social cues, and measuring the human’s feedback.

*Natural human-robot interaction.* Humans and robots should communicate as peers who know each other well, such as musicians playing a duet [210]. To achieve this, the robot must manifest believable behavior: it must establish appropriate social expectations, it must regulate social interaction (using dialogue and action), and it must follow social convention and norms.

*Readable social cues.* A socially interactive robot must send signals to the human in order to: (1) provide feedback of its internal state; and (2) allow human to interact in a facile, transparent manner. Because robots are constructed, they have limited channels and capacity for emotional expression. These include facial expression, body and pointer gesturing, and vocalization (both speech and sound).

*Real-time performance.* Socially interactive robots must operate at human interaction rates. Thus, a robot needs to simultaneously exhibit competent behavior, convey attention and intentionality, and

handle social interaction.

In the following sections, we review design issues that are unique to socially interactive robots. Although we do not discuss every aspect of design (e.g., architecture), we feel that addressing each of the following is critical to building an effective social robot.

### 2.3 Embodiment

Biological bodies have evolved in order to adapt to specific internal and environmental constraints. This “evolved embodiment” plays a significant role in the emergence of cognition and emotion[184]. In particular, the design of effectors and sensors is often tightly coupled to how neural processing is performed. For example, the visual axes in a fly’s eye have non-uniform sampling, which enables simple processing for motion parallax.

We define embodiment as “that which establishes a basis for structural coupling by creating the potential for mutual perturbation between system and environment”[70]. Thus, embodiment is grounded in the relationship between a system and its environment. The more a robot can perturb an environment, and be perturbed by it, the more it is embodied[59]. This also means that social robots do not necessarily need a *physical* body. For example, conversational agents[47] might be embodied to the same extent as robots with limited acuation.

An important benefit of this “relational definition” is that it provides an opportunity to quantify embodiment. For example, one might measure embodiment in terms of the complexity of the relationship between robot and environment over all possible interactions (i.e., all perturbatory channels).

All robots are embodied, but some are more embodied than others[70]. Consider the difference between Aibo (Sony) and Khepera (K-Team), as shown in Fig. 7. Aibo has approximately 20 actuators (joints across mouth, heads, ears, tails, and legs) and a variety of sensors (touch, sound, vision and proprioceptive). In contrast, Khepera has 2 actuators (independent wheel control) and an array of infrared proximity sensors. Because Aibo has more

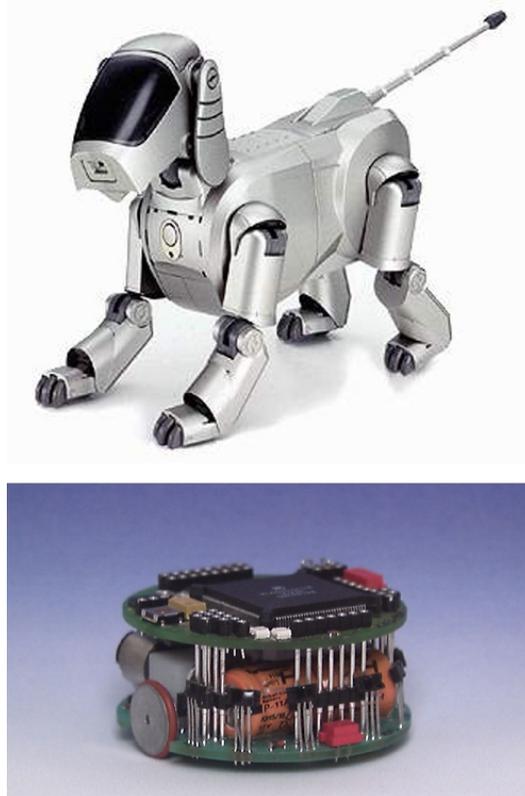


Fig. 7. Sony Aibo ERS-110 (top) and K-Team Khepera (bottom)

perturbatory channels and bandwidth at its disposal than does Khepera, it can be considered to be more strongly embodied than Khepera.

#### 2.3.1 Morphology

The form and structure of a robot is important because it helps establish social expectations. Physical appearance biases interaction. A robot that resembles a dog will be treated differently (at least initially) than one which is anthropomorphic. Moreover, the relative familiarity (or strangeness) of a robot’s morphology can have profound effects on its accessibility, desirability, and expressiveness.

The choice of a given form may also constrain the human’s ability to interact with the robot. For example, Kismet has a highly expressive face. But because it is designed as a head, Kismet is unable

to interact when touch (e.g., manipulation) or displacement (self movement) is required.

To date, most research in human-robot interaction has not explicitly focused on design, at least not in the traditional sense of industrial design. Although knowledge from other areas of design (including product, interaction and stylized design) can inform robot construction, much research remains to be performed.

### 2.3.2 Design considerations

When designing a robot’s form and structure, there are a number of considerations that should be taken in to account [76]. First, a robot’s morphology must match its intended function. If a robot is designed to perform tasks for the human, then its form must convey an amount of “product-ness” so that the user will feel comfortable using the robot. Similarly, if peer interaction is important, the robot must project an amount of “human-ness” so that the user will feel comfortable in socially engaging the robot.

At the same time, however, a robot’s design needs to reflect an amount of “robot-ness”. This is needed so that the user does not develop detrimentally false expectations of the robot’s capabilities [78].

Finally, if a robot needs to portray a living creature, it is critical that an appropriate degree of familiarity be maintained. Mashiro Mori contends that the progression from a non-realistic to realistic portrayal of a living thing is nonlinear. In particular, there is an “uncanny valley” (see Fig. 8) as similarity becomes almost, but not quite perfect. At this point, the subtle imperfections of the recreation become highly disturbing, or even repulsive[193]. Consequently, caricatured representations may be more useful, or effective, than more complex, “realistic” representations.

We classify social robots as being embodied in four broad categories: anthropomorphic, zoomorphic, caricatured, and functional.

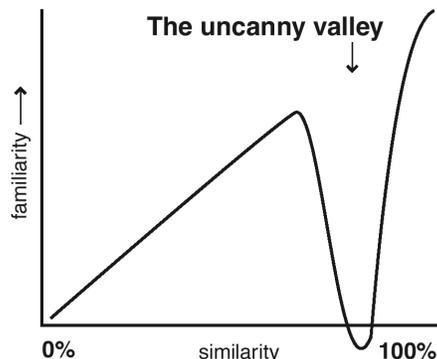


Fig. 8. Mori’s “Uncanny Valley” (from [76]).

### 2.3.3 Anthropomorphic

Anthropomorphism, from the Greek “anthropos” for man and “morphe” for form/structure, is the tendency to attribute human characteristics to objects with a view to helping rationalize their actions[78]. Anthropomorphic paradigms have widely been used to augment the functional and behavioral characteristics of social robots (see Section 3.5).

Having a naturalistic embodiment is often cited as necessary for meaningful social interaction[122,27,205]. In part, the argument is that in order for a robot to interact with humans as humans do (through gaze, gesture, vocalization, etc.), it must be structurally and functionally similar to a human. Moreover, if a robot is to learn from humans (e.g., through imitation), then it should be capable of behaving similarly to humans [14].

The role of anthropomorphism is to function as a mechanism (for design, for interpreting behavior, etc.) through which social interaction can be facilitated. Thus, the ideal use of anthropomorphism is to present an appropriate balance of illusion (to lead the user to believe that the robot is sophisticated in areas where the user will not encounter its failings) and functionality (to provide capabilities necessary for supporting human-like interaction) [76,116].



Fig. 9. Leonardo has a “creature-like” appearance (courtesy Cynthia Breazeal, MIT Media Lab)

#### 2.3.4 Zoomorphic

An increasing number of entertainment, personal, and toy robots have been designed to imitate living creatures (see Section 3.3). For these robots, a zoomorphic embodiment is important for establishing human-creature relationships.

The most common designs are inspired by household animals, such as the Sony Aibo (Figs. 7 and 22) dog and the Omron NeCoRo (Fig. 25), with the objective of creating robotic “companions”. Other designs, such as Leonardo (Fig. 9), have “creature-like” appearance but do not have real-world counterparts.

Avoiding the “uncanny valley” may be easier with zoomorphic design because human-creature relationships (e.g., owner-pet) are often simpler than human-human relationships. Thus, our expectations of what constitutes “realistic” and “unrealistic” animal morphology tends to be lower.

#### 2.3.5 Caricatured

Animators have long demonstrated that a character does not have to appear realistic in order to be believable[228]. Caricature, for example, exaggerates distinctive or striking features in order to produce comic effect. Moreover, simplified or stereotypical representations, such as cartooning, can be used to create desired interaction biases (e.g., implied abilities) and to focus attention on, or distract



Fig. 10. CERO (from Severinson-Eklund 2002)

attention from, specific robot features.

Scheeff et al. discusses how techniques from traditional animation and cartooning can be used in social robot design[207]. Schulte et al. describe how a caricatured human face (two eyes with eyebrows and a mouth) can provide an explicit “focal point” on which people can focus their attention[208]. Similarly, Severinson-Eklund et al. describe the use of a small mechanical character, CERO, as a robot “representative” (see Fig. 10)[209].

#### 2.3.6 Functional

Some researchers argue that a robot’s embodiment should first, and foremost, reflect the tasks it must perform. The choice and design of physical features is thus guided purely by operational objectives. This type of embodiment appears most often with functionally designed robots, especially service robots.

Health care robots, for example, may be required to assist elderly, or disabled, patients in moving about. Thus, features such as handle bars and cargo space, may need to be part of the design [187].

The design of toy robots also tends to reflect func-

tional requirements. Toys must minimize production cost, be appealing to children, and be capable of facing the wide variety of situations that can experienced during play [152].

## 2.4 Emotion

Emotions play a significant role in human behavior, communication and social interaction[7,114]. Emotions influence cognitive processes, particularly problem solving and decision making. Emotions also guide action, control resource usage, and shape dialogue. Emotions are complex phenomena and often tightly coupled to social context. Moreover, much of emotion is physiological and depends on embodiment[86,180,184].

Three primary theories are used to describe emotions. The first approach describes emotions in terms of discrete categories (e.g., happiness). A good review of “basic emotions” is [80]. The second approach characterizes emotions using continuous scales or basis dimensions, such as *arousal* and *valence*[202]. The third approach, componential theory, acknowledges the importance of both categories and dimensions[189,217].

In recent years, emotion has increasingly been used in interface and robot design, primarily because of the recognition that people tend to treat computers as they treat other people[8,41,43,47,179,192]. Moreover, many studies have been performed to integrate emotions into products including electronic games, toys, and software agents[11].

### 2.4.1 Artificial Emotions

Artificial emotions are used in social robots for several reasons. The primary purpose, of course, is that emotion helps facilitate believable human-robot interaction[42,173]. Artificial emotion can also provide feedback to the user, such as indicating the robot’s internal state, goals and (to an extent) intentions[11,21,123]. Lastly, artificial emotions can act as a control mechanism, driving behavior and reflecting how the robot is affected by, and adapts to, different factors over time [25,40,153,234,235].

Two overviews of emotional control are [44] and [45].

Numerous architectures have been proposed for artificial emotions[27,40,81,106,194,234,235]. Some closely follow emotional theory, particularly in terms of how emotions are defined and generated. Arkin et al. discuss how ethological and componential emotion models are incorporated into Sony’s entertainment robots[6]. Cañamero and Fredslund describe an affective activation model that regulates emotions through stimulation levels[42].

Other architectures are only loosely inspired by emotional theory and tend to be designed in an ad-hoc manner. Nourbakhsh et al. detail a fuzzy state machine based system, which was developed through a series of formative evaluation and design cycles[171]. In this system, the state machine controls both emotion expression and robot action selection. Schulte et al. summarize the design of a simple state machine that produces four basic “moods”[208]. In their approach, mood is viewed purely as a mechanism for facilitating the robot’s achievement of navigation goals.

In terms of expression, some robots are only capable of displaying emotion in a limited way, such as individually actuated lips or flashing lights (usually LEDs). Other robots have many active degrees of freedom and can thus provide richer movement and gestures. Kismet, for example, has controllable eyebrows, ears, eyeballs, eyelids, a mouth with two lips and a pan/tilt neck[27].

### 2.4.2 Emotions as control mechanism

Emotion can be used to determine control precedence between different behavior modes, to coordinating planning, and to trigger learning and adaptation, particularly when the environment is unknown or difficult to predict. One approach is to use computational models of emotions that mimic animal survival instincts, such as escape from danger, look for food, etc.[25,40,92,153,235].

Several researchers have investigated the use of emotion in human-robot interaction. Suzuki et al. describe an architecture in which interaction

leads to changes in the robot’s emotional state and modifications in its actions[224]. Breazeal discusses how emotions influence the operation of Kismet’s motivational system and how this affects its interaction with humans[30]. Nourbakhsh et al. discusses how mood changes can trigger different behavior in Sage, a museum tour robot[171].

### 2.4.3 Speech

Speech is a highly effective method for communicating emotion. The primary parameters that govern the emotional content of speech are loudness, pitch (level, variation, range), and prosody. Murray and Arnott contend that the vocal effects caused by particular emotions are consistent between speakers, with only minor differences[162].

The quality of synthesized speech is significantly poorer than synthesized facial expression and body language [12]. In spite of this shortcoming, it has proved possible to generate emotional speech. Cahn describes a system for mapping emotional quality (e.g., sorrow) onto speech synthesizer settings, including articulation, pitch, and voice quality[39].

To date, emotional speech has been used in few robot systems. In [26], Breazeal describes the design of Kismet’s vocalization system, in which expressive utterances are generated by assembling strings of phonemes with pitch accents. In [171], Nourbakhsh et al. describe how emotions influence synthesized speech production in a tour guide robot, e.g., when the robot is frustrated, voice level and pitch are increased.

### 2.4.4 Facial expression

The human face serves many purposes. It displays an individual’s motivation, which helps make behavior more predictable and understandable to others. It supplements verbal communication by signaling the speaker’s attitude towards the information being spoken. Facial gestures and expressions also communicate information, such as a shrug to express “I don’t know”, and help regulate dialogue by providing turn-taking cues [27].

The expressive behavior of robotic faces is generally

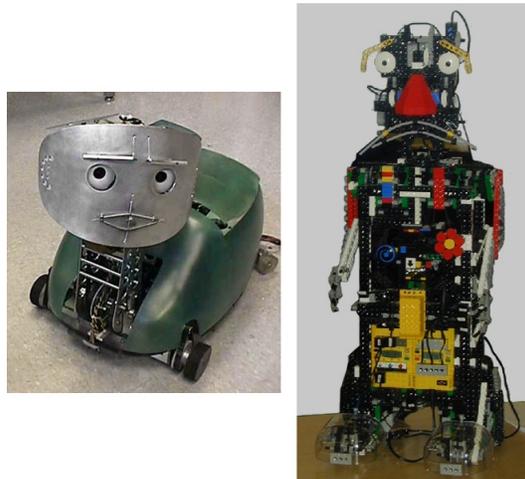


Fig. 11. Actuated faces: Sparky (left) and Felix (right)

not life-like. This reflects limitations of mechatronic design and control. For example, transitions between expressions tend to be abrupt, occurring suddenly and rapidly, which rarely occurs in nature. The primary facial components used are mouth (lips), cheeks, eyes, eyebrows and forehead. Most robot faces express emotion in accordance with Ekman and Frieser’s FACS system[79,216].

Two of the simplest faces (Fig. 11) appear on Sparky[207] and Felix[42]. Sparky’s face has 4-DOF (eyebrows, eyelids, and lips) which portray a set of discrete, basic emotions. Felix is a robot built using the LEGO Mindstorms™ robotic construction kit. Felix’s face also has 4-DOF (two eyebrows, two lips), designed to display six facial expressions (anger, sadness, fear, happiness, surprise, neutral) plus a number of blends.

In contrast to Sparky and Felix, Kismet’s face has fifteen actuators, many of which often work together to display specific emotions (see Fig. 12). Kismet’s facial expressions are generated using an interpolation-based technique over a three-dimensional componential “affect space” (arousal, valence, and stance). Kismet is able to display expressions that map to anger, distrust, fear, happiness, sorrow and surprise[23].

Perhaps the most realistic robot faces are those designed at the Science University of Tokyo[120]. These faces (Fig. 13) are explicitly designed to be

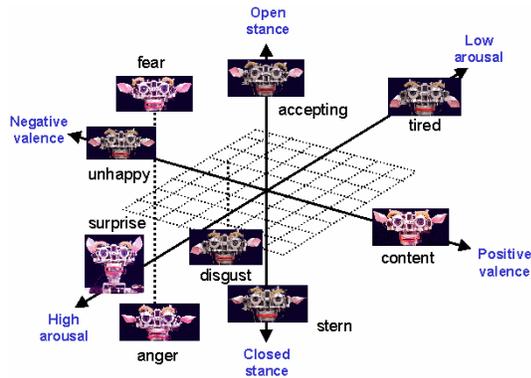


Fig. 12. Various emotions displayed by Kismet

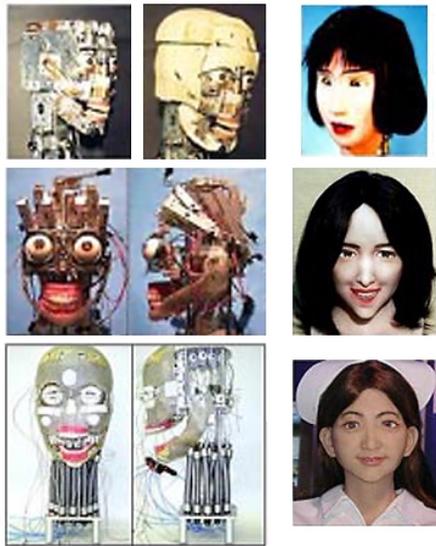


Fig. 13. Saya face robots (Science University of Tokyo)

human-like and incorporate hair, teeth, and a covering silicone skin layer. Numerous control points actuated beneath the “skin” produce a wide range of facial movements and human expression.

Instead of using mechanical actuation, another approach to facial expression is to rely on computer graphics and animation techniques[142]. Vikia, for example, has a 3D rendered face of a woman based on Delsarte’s code of facial expressions[37]. Because Vikia’s face (see Fig. 14) is graphically rendered, many degrees of freedom are available for generating expressions.



Fig. 14. Vikia has a computer generated face

Table 1  
Emotional body movements (adapted from [87]).

Emotion	Body movement
anger	fierce glance; clenched fists; brisk, short motions
fear	bent head, truck and knees; hunched shoulders; forced eye closure or staring
happiness	quick, random movements; smiling;
sadness	depressed mouth corners; weeping
surprise	wide eyes; held breath; open mouth

#### 2.4.5 Body Language

In addition to facial expressions, non-verbal communication is often conveyed through gestures and body movement[12]. Over 90% of gestures occur during speech and provide redundant information[127,149]. To date, most studies on emotional body movement have been qualitative in nature. Frijda, for example, described body movements for a number of basic emotions (Table 1)[87]. Recently, however, some work has begun to focus on implementation issues, such as in [53].

Nakata et al. state that humans have a strong tendency to be cued by motion[164]. In particular, they refer to analysis of dance that shows humans are emotionally affected by body movement. Breazeal and Fitzpatrick contend that humans perceive all motor actions to be semantically rich, whether or not they were actually intended to be[31]. For example, gaze and body direction is generally inter-

preted as indicating locus of attention.

Mizoguchi et al. discuss the use of gestures and movements to create a sense of familiarity[160]. In their system, they exploit a set of designed expressions, similar to ballet poses, to show emotion through movement. Scheeff et al. describe the design of smooth, natural motions for Sparky[207]. Lim, Ishii and Takanishi describe how walking motions (foot dragging, body bending, etc.) can be used to convey emotions [135].

## 2.5 Dialogue

Dialogue is a joint process of communication. It involves sharing of information (data, symbols, context) and control between two (or more) parties [132]. Humans employ a variety of para-linguistic social cues (facial displays, gestures, etc.) to regulate the flow of dialogue [46]. These social cues have also proven to be effective for controlling human-robot dialogue, which is important because the current performance of robot perception (e.g., speech processing) limits the rate at which human-robot dialogue can proceed[24,28].

Dialogue, regardless of form, is meaningful only if it is grounded, i.e., when the symbols used by each party describe common concepts. If the symbols differ, information exchange or learning must take place before communication can proceed. Although human-robot communication can occur in many different ways, we consider there to be three primary types of dialogue: low-level (pre-linguistic), non-verbal, and natural language.

*Low-level.* Billard and Dautenhahn describe a number of experiments in which an autonomous mobile robot was taught a synthetic proto-language[15–17]. Language learning results from multiple spatio-temporal associations across the robot’s sensor-actuator state space.

Steels has examined the hypothesis that communication is bootstrapped in a social learning process and that meaning is initially context-dependent[220,221]. In his experiments, a robot dog learns simple words describing the presence of objects (ball, red, etc), its behavior (walk, sit) and

its body parts (leg, head).

*Non-verbal.* There are many non-verbal forms of language, including body positioning, gesturing, and physical action. Since most robots have fairly rudimentary capability to recognize and produce speech, non-verbal dialogue is a useful alternative. Nicolescu and Mataric, for example, describe a robot that asks humans for help, communicating its needs and intentions through its actions[169].

Social conventions, or norms, can also be expressed through non-verbal dialogue. Proxemics, the social use of space, is one such convention [100]. Proxemic norms include knowing how to stand in line, how to enter elevators, how to pass in hallways, etc. Respecting these spatial conventions may involve consideration of numerous factors (administrative, cultural, etc.)[165].

*Natural language.* Natural language dialogue is determined by a set of factors ranging from the physical and perceptual capabilities of the participants, to the social and cultural features of the situation in which the dialogue is carried out To what extent natural language dialogue interfaces for robots should be based on human-human dialogue is clearly an open issue[209]. Moreover, creating a robot that communicates at a human peer level using natural language remains a grand challenge.

Severinson-Eklundh et al. discuss how users need explicit feedback when interacting with service robots[209]. In particular, they contend that the user always needs to understand what instructions the robot has received and is about to carry out. One way of achieving this is to emphasize providing conversational feedback (e.g., through natural language) through dialogue design.

Fong, Thorpe, and Baur describe how high-level dialogue can enable a human to provide assistance to a robot[84,85]. In their system, dialogue is limited to mobility issues (navigation, obstacle avoidance, etc) with an emphasis on query-response speech acts. They note that a significant side-effect of this type of dialogue is that it can affect how users perceive and treat the robot.

## 2.6 Personality

### 2.6.1 What is personality?

In psychological terms, personality is the set of distinctive qualities that, taken collectively, distinguish individuals. The majority of research in personality psychology examines the perception of personality, i.e., how other individuals, or the group, perceive a particular individual. The conventional approach is to focus on trait ratings.

Since the late 1980's, the most widely accepted taxonomy of basic individual personality traits has been the "Big Five Inventory" [112]. This taxonomy was developed through lexical analysis of words that are commonly used to describe individual differences. With the "Big Five", an individual's personality can be evaluated in terms of five primary traits:

- extroversion (sociable, outgoing, confidence)
- agreeableness (friendliness, nice, pleasant)
- conscientiousness (helpful, hard-working)
- neuroticism (emotional stability, adjusted)
- openness (intelligent, imaginative, flexibility)

Alternatives to the "Big Five", and other systems based on lexical analysis, include questionnaire-based scales such as the *Myers-Briggs Type Indicator (MBTI)*[163].

### 2.6.2 Personality in social robots

There is reason to believe that if a robot had a compelling personality, people would be more willing to interact with it and to establish a relationship with it[27,116]. In particular, personality may provide a useful affordance, giving users a way to model and understand robot behavior[209].

In designing robot personality, there are numerous questions that need to be addressed. Should the robot have a designed or learned personality? Should it mimic a specific human personality, exhibiting (or evoking) specific human traits? Is it beneficial to encourage a specific type of interaction (e.g., infant-caregiver)? What type of personality will best serve a robot's function and capabilities?

There are five common personality types used in social robots:

*Tool-like.* Used for robots that operate as "smart appliances". Because these robots perform service tasks on command, they exhibit traits usually associated with tools (dependability, reliability, etc).

*Pet or creature.* These toy and entertainment robots exhibit characteristics that are associated with domesticated animals (cats, dogs, etc.).

*Cartoon.* These robots exhibit caricatured personalities, such as seen in animation. Exaggerated traits (shyness, stubbornness, etc.) are easy to portray and can be useful for attracting interest and for facilitating interaction with non-specialists.

*Artificial being.* Inspired by literature and film, primarily science fiction, these robots tend to display artificial (e.g., mechanistic) characteristics.

*Human-like.* Robots are often designed to exhibit human personality traits. The extent to which a robot must have (or appear to have) human personality depends on its use.

Robot personality is conveyed in numerous ways. Emotions are often used to portray stereotype personalities: timid, friendly, etc.[247]. A robot's embodiment (size, shape, color), its motion, and the manner in which it communicates (e.g., natural language) also contribute strongly[209]. Finally, the tasks a robot performs may also influence the way its personality is perceived.

## 2.7 Human-oriented perception

To interact meaningfully with humans, social robots must be able to perceive the world as humans do, i.e., sensing and interpreting the same phenomena that humans observe. This means that, in addition to the perception required for conventional functions (localization, navigation, obstacle avoidance), social robots must possess perceptual abilities similar to humans.

In particular, social robots need perception that is human-oriented: optimized for interacting with humans and on a human level. Social robots need

to be able to track human features (bodies, faces, hands). They also need to be capable of interpreting human speech including affective speech, discrete commands, and natural language. Finally, they often must have the capacity to recognize facial expressions, gestures (e.g., hand pointing), and human activity.

Similarity of perception requires more than similarity of sensors (i.e., sensors with characteristics and performance that match human senses). It also is important that humans and robots find the same types of stimuli salient[33]. Moreover, robot perception may need to mimic the way human perception works. For example, the human ocular-motor system is based on foveate vision, uses saccadic eye movements, and exhibits specific visual behaviors (staring vs. glancing, breaking contact, etc.). Thus, in order for a robot to be readily understood, its visual motor control may need to have similar characteristics[31,35,27].

Human-oriented perception is an important research topic for applications other than social robots. Human tracking is considered to be an essential component of intelligent environments and smart spaces (e.g., [232]). Speech and gesture recognition is an integral component of multimodal and perceptual user interfaces [118]. Activity detection and recognition plays a fundamental role in automated surveillance[175,49].

### 2.7.1 *Types of perception*

Most human-oriented perception is based on passive sensing, typically computer vision and spoken language recognition. Passive sensors, such as CCD cameras, are cheap, require minimal infrastructure, and can be used for a wide range of perception tasks[2,54,95,197].

Active sensors (ladar, ultrasonic sonar, etc.), though perhaps less flexible than their passive counterparts, have also received attention. In particular, active sensors are often used for detecting and localizing human in dynamic settings.

### 2.7.2 *People tracking*

For human-robot interaction, the challenge is to find efficient methods for people tracking in the presence of occlusions, variable illumination, moving cameras, and varying background. A broad survey of human tracking is presented in [95]. Specific robotics applications can be reviewed in [225], [165], [37], and [187].

### 2.7.3 *Speech recognition*

Speech recognition is generally a two-step process: signal processing (to transform an audio signal into feature vectors) followed by graph search (to match utterances to a vocabulary). Most current systems use Hidden Markov Models to stochastically determine the most probable match. An excellent introduction to speech recognition is [191].

Human speech contains three types of information: who the speaker is, what the speaker said, and how the speaker said it[27]. Depending on what information the robot requires, it may need to perform speaker tracking, dialogue management, or emotion analysis. Recent applications of speech in robotics include [27], [133], [146], [174], and [218].

### 2.7.4 *Gesture recognition*

When humans converse, we use gestures to clarify speech and to compactly convey geometric information (location, direction, etc.). Very often, a speaker will use hand movement (speed and range of motion) to indicate urgency and will point to disambiguate spoken directions (e.g., “I parked the car over there”).

Although there are many ways to recognize gestures, vision-based recognition has several advantages over other methods. Vision does not require the user to master or wear special hardware. Additionally, vision is passive and can have a large workspace. Recognizing gestures is a complex task that involves motion modeling, motion analysis, pattern recognition, and machine learning. Two excellent overviews of vision-based gesture recognition are [182] and [245]. Details of specific systems appear in [126], [246], and [238].

### 2.7.5 Facial perception

*Face detection and recognition.* A widely used approach for identifying people is face detection. Two comprehensive surveys are [48] and [88]. A large number of real-time face detection and tracking systems have been developed in recent years, such as [231] and [204,205].

*Facial expression.* Since Darwin[55], facial expressions have been considered to convey emotion. More recently, facial expressions have also been thought to function as social signals of intent. A comprehensive review of facial expression recognition (including a review of ethical and psychological concerns) is [136]. A survey of older techniques is [201].

There are three basic approaches to facial expression recognition [136]. Image motion techniques identify facial muscle actions in image sequences. One problem with this approach is that head motion involves both rigid and non-rigid motion, which can be difficult to separate. Anatomical models track facial features, such as the distance between eyes and nose. A limitation of this approach is that it is hard to construct a model that remains valid across many individuals. Principal component analysis (PCA) reduce image-based representations of faces into principal components such as eigenfaces or holons. The primary difficulty with these appearance-based approaches is that they are very sensitive to imaging issues including illumination, head orientation, and sensor noise.

*Gaze tracking.* Gaze is a good indicator of what a person is looking at and paying attention to. A person's gaze direction is determined by two factors: head orientation and eye orientation. Although numerous vision systems have been developed to track head orientation (generally based on frontal faces), few researchers have attempted to track eye gaze using only passive vision. Furthermore, such trackers have not proven to be dependable nor highly accurate[231]. Gaze tracking research includes [204] and [223].

### 2.8 User modeling

In order to interact with people in a human-like manner, socially interactive robots must perceive and understand the richness and complexity of natural human social behavior[27]. Detecting and recognizing human action and communication provides a good starting point. More important, however, is being able to interpret and reacting to human behavior. A key mechanism for performing this is user modeling.

User modeling can be quantitative, based on the evaluation of parameters or metrics. The stereotype approach, for example, classifies users into different subgroups (stereotypes), based on the measurement of pre-defined features for each subgroup[227]. User modeling may also be qualitative in nature. Interactional structure analysis, story and script based matching, and BDI all focus on identifying subjective aspects of user behavior.

There are many types of user models: cognitive, emotional, attentional, etc. A user model generally contains a set of attributes that describe a user, or group, of users. Models may be static (defined *a priori*) or dynamic (adapted or learned). Information about users may be acquired explicitly (through questioning) or implicitly (inferring through observation). The former can be time consuming and the latter can be difficult, especially if the user population is diverse or has broad characteristics[99].

User models are employed for a variety of purposes. First, user models help the robot understand human behavior and dialogue. Many spoken dialogue systems depend on user models for recognizing and generating speech acts. Second, user models shape and control feedback given to the user. Robot motions (body position, gaze direction, etc.) and interaction pacing (e.g., knowing when to insert pauses) can be directed by appropriate models. Finally, user models are useful for adapting the robot's behavior to accommodate users with varying skills, experience, and knowledge.

Fong, Thorpe and Baur employ a stereotype user model to adapt human-robot dialogue and to modify robot behavior to fit the needs of different

users[84]. This occurs in three ways: the questions the robot asks to the human are based on an estimate of the user’s knowledge; the weight the robot gives to human responses are based on an estimate of the user’s ability to provide accurate responses; and the independence the robot exhibits (i.e., its level of autonomy) is adapted to fit human decision making (e.g., how quickly a user is able to respond to safety critical questions).

Pineau et al. discuss social interaction between a nurse robot and elderly individuals[187]. Because many elderly have difficulty understanding synthesized speech, as well as articulating responses in a computer understandable way, the robot needs to adapt to individuals. To do this, a cognitive orthotic system, “Autominder”, is used to provide individual-specific reminders about daily activities. Autominder maintains a model of the user’s daily schedule, monitors performance of activities, and plans reminders accordingly. The user model is a Quantitative Temporal Bayes Net, which can reason about probabilistic temporal constraints.

Schulte et al. describe adaptation in Minerva, a tour guide robot[208]. Minerva employs a memory-based learner for learning how to interact with different people. In particular, between museum tours, Minerva enters an “attraction interaction” state, in which the goal is to attract people in preparation for the next tour. Using a continuous adaptation strategy, Minerva autonomously learned to select actions (speech acts, facial expressions, etc.) that improved its ability to attract user interest.

## 2.9 Socially situated learning

In socially situated learning, an individual interacts with his social environment to acquire new competencies. Humans and some animals (e.g., primates) learn through a variety of techniques including direct tutelage, observational conditioning, goal emulation, and imitation[93]. One prevalent form of influence is local, or stimulus, enhancement in which a teacher actively manipulates the perceived environment to direct the learner’s attention to relevant stimuli[139].

### 2.9.1 Robot social learning

For social robots, learning is used for transferring skills, tasks, and information. Learning is important because the knowledge of the teacher, or model, and robot may be very different. Additionally, because of differences in sensing and perception, the model and robot may have very different views of the world. Thus, learning is often essential for improving communication, facilitating interaction, and sharing knowledge [119].

A number of studies in robot social learning have focused on robot-robot interaction. Some of the earliest work focused on cooperative, or group, behavior[143,9]. A large research community continues to investigate group social learning, often referred to as “swarm intelligence” and “collective robotics”. Other robot-robot work has addressed the use of “leader following” [103,56], inter-personal communication[18,16,219], imitation[17,94], and multi-robot formations[156].

In recent years, there has been significant effort to understand how social learning can occur through human-robot interaction. One approach is to create sequences of known behaviors to match a human model [145]. Another approach is to match observations (e.g., motion sequences) to known behaviors, such as motor primitives [73,74]. Recently, Kaplan et al. have explored the use of animal training techniques for teach an autonomous pet robot to perform complex tasks[113]. The most common social learning method, however, is imitation.

### 2.9.2 Imitation

Imitation is an important mechanism for learning behaviors socially in primates and other animal species[67]. At present, there is no commonly accepted definition of “imitation” in the animal and human psychology literature. An extensive discussion is given in [102]. Researchers often refer to Thorpe’s definition[229], which defines imitation as the “copying of a novel or otherwise improbable act or utterance, or some act for which there is clearly no instinctive tendency”.

With robots, imitation relies upon the robot hav-

ing many perceptual, cognitive, and motor capabilities[34]. Researchers often simplify the environment or situation to make the problem tractable. For example, active markers or constrained perception (e.g., white objects on a black background) may be employed to make tracking of the model amenable.

Breazeal and Scassellati argue that even if a robot has the skills necessary for imitation, there are still several questions that must be addressed[34]:

- *How does the robot know when to imitate?* In order for imitation to be useful, the robot must decide not only when to start/stop imitating, but also when it is appropriate (based on the social context, the availability of a good model, etc).
- *How does the robot know what to imitate?* Faced with a stream of sensory data, the robot must decide what actions are worth imitating. Furthermore, the robot must determine which of the model's actions are relevant to the task, which are part of the instruction process, and which are circumstantial.
- *How does the robot map observed action into behavior?* Once the robot has identified and observed salient features of the model's actions, it must ascertain how to reproduce these actions through its behavior.
- *How does the robot evaluate its behavior, correct errors, and recognize when it has achieved its goal?* In order for the robot to improve its performance, it must be able to measure to what degree its imitation is accurate and to recognize when there are errors.

Imitation has been used as a mechanism for learning simple motor skills from observation, such as block stacking[131] or pendulum balancing[206]. For these tasks, the robot must be capable of observing and replicating geometric relationships (e.g., relative arm position). One way to do achieve this is to use movement matching, such as discussed by Demiris and Hayes[73].

Andry et al. have used imitation to speed up the learning of sensor-motor associations[4]. In their system, a neural network architecture enables a robot to perform low-level imitations (i.e., repro-

ducing simple and meaningless movements). Imitative behavior is triggered by perception ambiguity and enables the system to learn new sensor-motor associations without explicit reinforcement.

Nicolescu and Mataric describe a robot that follows a human teacher, gathering observations from which it constructs task representations (a network of robot behaviors)[169]. The ability to learn from observation is based on the robot's ability to relate the observed states of the environment to the known effects of its own behaviors.

## 2.10 Intentionality

Dennett contends that humans use three strategies to understand and predict behavior[72]. The *physical stance* (predictions based on physical characteristics) and *design stance* (predictions based on the design and functionality of artifacts) are sufficient to explain simple devices. With complex systems (e.g., humans), however, we often do not have sufficient information, to perform physical or design analysis. Instead, we tend to adopt an *intentional stance* and assume that the systems' actions result from its beliefs and desires.

In order for a robot to interact socially, therefore, it needs to provide evidence that is intentional (even if it is not intrinsically [203]). For example, a robot could demonstrate goal-directed behaviors, or it could exhibit the attentional capacity. If it does so, then the human will consider the robot to act in a rational manner.

### 2.10.1 Attention

Scassellati discusses the recognition and production of joint attention behaviors in Cog[204]. Just as humans use a variety of physical social cues to indicate which object is currently under consideration, Cog performs gaze following (detecting eye contact and extracting angle of gaze), imperative pointing (foveating a target and ballistic reach), and declarative pointing (simple mimicry of gestures such as head nods).

Kopp and Gardenfors also claim that attentional

capacity is a fundamental requirement for intentionality[125]. In their model, a robot must be able to identify relevant objects in the scene, direct its sensors towards an object, and maintain its focus on the selected object.

Marom and Hayes (1999, 2001a,b) consider attention to be a collection of mechanisms that determine the significance of stimuli[139–141]. Their research focuses on the development of pre-learning attentional mechanisms, which help reduce the amount of information that an individual has to deal with.

### 2.10.2 Expression

Kozima and Yano argue that to be intentional, a robot must exhibit goal-directed behavior[122,123]. To do so, it must possess a sensorimotor system, innate reflexes (behaviors), drives that trigger these behaviors, a value system for evaluating perceptual input, and an adaptation mechanism.

Breazeal and Scassellati describe how Kismet conveys intentionality through motor actions and facial expressions[32]. In particular, by exhibiting proto-social responses (affective, exploratory, protective, and regulatory) in the same manner as infants, the robot provides cues that enable adults to interpret its actions as intentional.

Schulte et al. discuss how a caricatured human-face and simple emotion expression can convey intention during spontaneous short-term interaction[208]. For example, a tour guide robot might have the intention of making progress while giving a tour. Its facial expression and recorded speech playback can communicate this information.

## 3 Applications

### 3.1 Robots as test subjects

Evaluating models of social and biological development is difficult in natural settings. Ethical concerns, complications preventing test procedure implementation, and difficulties isolating hypothesized variables often make experimental evidence

difficult (or impossible) to obtain. As a result, numerous researchers have begun exploring how social robots can serve as experimental test subjects[204,205].

In particular, robots are increasingly being used as research tools to perform a wide range of comparative studies[64,4]. To date, robots have been used to examine, validate and refine theories of social and biological development, psychology, neurobiology, emotional and non-verbal communication, and social interaction.

There are numerous reasons why using robots as test subjects is useful, especially compared with computational simulation[204,220]:

- Implementing a model for physical experimentation requires specifying, in detail, all internal structures and processes. This makes it explicitly clear how all theoretical assumptions have been operationalized.
- Internal model structures can be manipulated and examined. This is not possible with human beings, except via indirect measures (e.g., subject questioning).
- Experiments can be repeated with nearly identical conditions and small variations can be used to isolate single factors. This is difficult to achieve with conventional, observation-based studies.
- We can easily examine alternative hypotheses. For example, we can compare what an individualistic inductive learning process would achieve with the same data as a social learning process.
- Robots can be subjected to testing that may be hazardous, costly, or unethical to conduct on humans. This includes assessing intervention strategies or treatments, which may be controversial to test on human subjects.

At the same time, there are obviously also important limits to this methodology. For example, current robots cannot fully represent human (even infant) cognition, perception and behavior. Thus, for now, the most that experimentation on robots can achieve is examination of specific (or limited) model features.

### 3.1.1 *Social development*

Perhaps the most obvious use of social robots as test subjects is to examine theories of social development. For the most part, the focus of these experiments is to confirm, or to refute, claims of how infants and young children develop in social learning skills such as imitation and joint attention.

Infanoid is an infant-like humanoid robot (see Fig. 34) used to investigating the underlying mechanisms of social development [121,122]. In particular, it is being used to explore how socially meaningful behaviors develop through physical and socio-cultural interaction with human caregivers. Infanoid is designed to have the same size and kinematic structure of a three-year-old child's upper body.

Cog is a general-purpose humanoid platform (see Fig. 36) intended for exploring theories and models of intelligent behavior and learning[1]. Cog's design implements two popular theories for the development of theory of mind. Scassellati describes experimentation with a partial implementation of Baron-Cohen's model of social development[10] that focuses on the recognition and production of joint attention behaviors[204,205].

Andry et al. present an imitative robot architecture that is designed to exhibit different phases of social development, comparable to those seen in children[4]. They are using this architecture to test psychological and neurobiological models in an effort to understand mental development problems (e.g., autism) as well as to ascertain the fundamental properties of imitation games engaged in by children.

### 3.1.2 *Social interaction*

Another area of active experimentation with robots is social interaction. In these studies, the primary emphasis is to examine theories that describe how interaction in a social context influences cognition. Of secondary interest is exploring how social interaction provides a basis for symbol grounding and communication.

Since its creation in 1997, Kismet has been used

to examine various aspects of infant-caregiver interaction[22,27]. In numerous studies, a wide range of infant-level social competencies have been examined, including turn-taking, low-level emotional exchanges, and acquisition of meaningful communication acts.

Dautenhahn and Billard discuss experiments carried out in teaching a synthetic language-like system to a robot[64]. These experiments were designed to test claims made in Vygotsky's theory of child cognitive development, i.e., that social interactions are fundamental to initial cognitive development and provide a context that can scaffold richer cognitive functions.

In order to identify the key factors in non-verbal communication, Aoki et al. investigated interactions between laboratory rats and rat-like robots[5]. They report that the movement of the robot acts as stimulation for discriminative learning, enabling it to guide real rats in forming associations such as social pecking order. Aoki et al. contend that studies of rat-like robots will lead to better understanding of human behavior, in the same manner that animal experimentation (especially on rats) does.

### 3.1.3 *Emotion, attachment and personality*

Social robots have also been used to examine and validate a variety of theories of individual behavior. Nakata et al. conducted a study of robot movement using theories of dance psychology[164]. In this study, they attempted to verify predictions of how various types of movement are perceived by humans working in close proximity. A primary objective was to better understand how observed body movement may affect the emotional state of human.

Shibata et al. have begun investigating how emotional behaviors develop through long-term physical contact and interaction[211–213]. They contend that when a human and a pet robot interact, they mutually stimulate and affect each other. Furthermore, they claim that as consequence of this interaction, that humans can develop the same attachment to the robot as to a real pet, especially if the relationship occurs over the long-term.

Miwa et al. implemented a number of robot personalities on a head robot[159]. The personality model was directly based on one of the “Big Five” taxonomies of basic individual personality traits. They then conducted a series of tests to verify how different personalities can influence, and be influenced by, various emotional and perception models.

### 3.2 Service

Robots are clearly of great functional value when they provide concrete services for humans. For example, welding robots have significantly increased throughput in automotive assembly plants by providing very fast and precise welding services for the assembly line. In this section, we examine research projects in which a social robot is designed and tested for a task-focused mission.

There are various reasons why a task-oriented robot can find social interaction to be beneficial. Perhaps the most evident is usability. In any case where a robot is to interact directly with one or more humans, social engagement such as spoken dialogue and gestures may help to make the robot easier-to-use for the novice and also more efficient-to-use for the expert. One psychological mechanism that also falls within this class involves the comfort level of humans interacting with the robot. Social interaction can be designed to make the humans more comfortable as they share a space with the robot, just as appropriate social interaction does so between humans sharing a space.

This section proceeds by describing several research projects that inhabit three different categories. First, we examine the robot whose role is to aid one or more humans over the long term. Second, we turn to robots that serve as members of a larger team with a common goal. Finally, we examine robots whose tasks require spontaneous, short-term interaction with large numbers of humans in public spaces.

#### 3.2.1 Robots as durative assistants

One important reason for Japan’s large investment in personal robotics has to do with the significant



Fig. 15. Pearl is a Nursebot, providing cognitive and spatial aide

proportion of elderly Japanese, both today and increasingly in future years. Robots that serve as aides to the elderly may prolong the autonomy of individuals, staving off a move to managed care facilities for months or even years.

Pineau et al. describe a robotic assistant for nursing homes that is just such a durative aide to the elderly[187]. The robot, Pearl, has two main functions: to serve as a cognitive orthotic to its users; and to serve as a spatial guide for navigating the environment (Fig. 15). As a cognitive orthotic, Pearl can remind individuals to use the restroom, eat and turn on the television for a favorite show. As a guide, Pearl can not only remind one of a physical therapy appointment, but can also lead the way to the exercise room, for instance.

The job of Pearl is heavily social, and so basic skills required by the robot include social perception (i.e. people-tracking, speech recognition) as well as social closed-loop control (i.e. dialogue management, leading the way while matching walking speed, reminding and verifying). Dialogue management includes reasoning and acting based on knowledge or lack thereof. For instance Pearl is able to ask clarification questions if it failed to understand a persons directive or response. The authors are able to show that such adaptive dialogue improves overall error rates for the robot considerably.

Severinson-Eklundh et al. have also implemented



Fig. 16. eMuu (left) and Muu2 (right)

and tested a robot that can serve as a long-term aide to one or more individuals[209]. In this case, rather than serving a cognitive function, the robot is meant to provide fetch-and-carry services for motion-impaired users in the office environment. As a social agent, this robot will not only have a social relationship with the user but also with all other persons in the office building, who will encounter this robot as it performs its activities.

Following their ethic of task-based and context-based design, Severinson-Eklundh et al. identified two critical communicative needs of a fetch-and-carry robot. First, the robot must be able to signal its comprehension of commands given to it. Second, the robot must be able to indicate the direction in which it desires to navigate. In particular, given the round Nomad Scout platform, the question of direction of motion proved to be important for bystanders who wish to help the robot by getting out of its way.

Fig. 10 shows the CERO representative mounted on the mobile platform. By creating a social representative for the whole robot, Severinson-Eklundh takes a fascinating approach to social robot design, in which a focal point, in this case CERO, represents the social interactive aspects of the whole.

Bartneck suggests similarly that robotic social agents may serve as representatives between humans and complex systems[11,12]. In this case, eMuu and Muu2 are proposed as interfaces between a homeowner and the smart appliances in the home, or even the intelligent home itself. As with CERO, the robots shown in Fig. 16 demonstrate a departure from anthropomorphic design

while still achieving engagement at the social level.

### 3.2.2 Robots as collaborators

As another application groups of humans and robots will someday together comprise teams with a common goal. Thus the robot becomes, not just an assistant, but a partner in accomplishing the team objectives. Fong et al. propose that such robots will maximize their contributions by being able to take advantage of human skills and human advice and decision-making as appropriate[84]. Thus although there is no reason for such robots to be viewed as peers to humans, they must nonetheless be active partners, recognizing their limitations and requesting help as needed.

Fong proposes four key qualities that a collaborator robot must have in order to take part in such a social niche. First, the robot must have sufficient self-awareness, or introspection, to recognize its limitations. This is critical in making the determination to request human help. Second, the robot must be self-reliant at the most basic level. Thus it should be able, in any condition, to safe itself and thus avoid the hazards that it may face. Third, the robot must have dialogue competence so that two-way information exchange between robot and human is possible. Finally the robot should be adaptive, and thereby able to make use of all variety of human resources, from the robot-novice to the experienced human team members.

The coupling of human to robot in this collaboration model is many-to-many. Groups of humans and groups of robots may be part of the system, and it is through their collaboration with one-another that the group goals are achieved. This model breaks out of the master-slave control formula, due to several important limitations. First, the master-slave control architecture fixes the robots level of autonomy and thereby the degree of control exerted by the human master. Furthermore, such an architecture tends to enforce a fixed relationship, not only through time between a single master and slave, but also as implemented for various masters.

As an alternative to master-slave control, Fong et



Fig. 17. Collaborative control. Robot in need of assistance (left) and its query to the human (right).

al. suggests collaborative control, a system model based on human-robot dialogue[84]. With this model, the robot asks questions to the human in order to obtain assistance with cognition and perception (Fig. 17). This enables the human to function as a resource for the robot and to help compensate for limitations of autonomy.

In [85], Fong et al. describe an experiment in which robot-human dialogue is used to achieve remote robotic exploration, a task traditionally performed with direct teleoperation. Using a contextual inquiry based approach, the authors present both expert and novice robot-users with a collaborative control scenario in which a room not directly visible must be explored by a robot-human team. The use of simulated error conditions (e.g. temperature sensor fluctuations) enriches the dialogue between robot and human, as the robot requests clarification of its safe operational parameters during execution.

### 3.2.3 Short-term public interaction robots

In contrast to both personal assistant robots and collaborative robots, an important quality of public interaction robots is that the human-robot relationship is uninitiated, untrained and very short-term. Indeed, by public we also imply that the variance among potential human targets is quite high: some will be more technologically savvy and robot-friendly than others. Finally, unlike the previous categories public spaces are not well-suited to gating social interaction for one-on-one relation-



Fig. 18. The Robox installation at Switzerland's Expo 2002

ships. Crowds naturally form, and interested persons cluster automatically. Thus, one-on-one engagement alone is unacceptable.

The task-based robots that we consider in this section all have missions revolving about information: either the deployment of information to the public, or the acquisition of information about the public. Thus the challenge in the former case is to deliver the information effectively to the right persons; and in the latter case to collect the desired information from the right persons.

A number of social robots have been designed with specific public missions at hand. These robots have all demonstrated that, with the right behavior, mobile robots can successfully attract, engage and interact with the public in busy spaces.

A recent application of public robotics is the Robox series of robots (Fig. 18) installed at Switzerland's Expo 2002[215]. During this national exposition, the public robots were charged with two goals: present themselves as demonstrations of robotic technology; and guide visitors through a roomful of robotic exhibits, presenting these external robotic exhibits on the nature of robotic technology.

The physical design of the exhibition robot reflects its social charter. Using eyebrows and asymmetric eyes, each robot is capable of affective expression as well as communication of intentionality- such as its desired direction of travel for example. Sen-



Fig. 19. Minerva (Carnegie Mellon University)

sors for human detection and tracking include laser rangefinding, color vision and tactile sensors.

At the heart of each robot’s behavior are interaction sequences which lead humans through the exhibit space and provide tour content. To implement this sequential tour controller, while also performing adaptation based on the behavior of the humans around each robot, a hybrid controller sequences static interaction sequences while monitoring sensor conditions that would trigger asynchronous departures from the nominal interaction. For instance if a visitor blocks the robots path repeatedly, then the static sequence is interrupted by a dynamic interaction sequence designed to convince the visitors to allow the robot to do its job.

In earlier work other researchers have demonstrated that affect can have a measurable, quantitative influence on the efficacy of the robot at providing tours to the public. Schulte et al. describe the critical differences between the Minerva tour guide robot (Fig. 19), which provided tours for a two-week period at the Smithsonian Institutions Museum of American History, and an earlier robot, Rhino, which provided tours in a German science museum[208].

In [208], three characteristics are suggested as critical to the success of robots that must exhibit spontaneous interactions in public settings. First, the robot must include a focal point, which serves as an obvious focus of attention for the human. A robotic face or animated face serves this function on many tour-guide robots. Second, the robot should



Fig. 20. The Mobot robots Chips (top left), Sweetlips (right) and Joe Historybot (bottom left)

communicate emotional state to the visitors as a way of efficiently conveying its intention- for example its frustration at being blocked by playful tourists. Third, the robot should have the capability to adapt its human interaction parameters based on the outcome of past interactions so that it can continue to demonstrate open-ended behavior as the visitors in its environment change.

Minerva uses a motorized facial caricature consisting of eyes, lips and eyebrows to provide both a focal point and a means for the communication of emotional state. A simple state transition diagram modulates facial expression and speech, from happy to neutral to angry, based on the length of time for which Minervas path has been blocked. The authors notes that Rhino, a robot with no such face but with relatively similar navigation means, achieved average tour speeds approximately 20% slower than Minerva, thus providing some empirical evidence as to the efficacy of affective interaction.

The Mobot Museum Robot series of robots, comprised of four robots deployed and tested sequentially over a five-year period, forms a basis for observations about the evolution of public, social robots[243]. The goals of these robot installations were unchanging: deployment of mobile robots in

museum spaces that bring about compelling and fruitful interactions between the robots, human visitors and the exhibits in the space. Yet, with the re-design of subsequent robots significant trends were identified by the authors pertaining to lessons learned with each deployment.

In terms of interaction content, the authors studied a gradual evolution from one-way, didactic teaching to short-term, two-way, challenge-based interaction (Fig. 20). The first robot, Chips (also known as “Sage”), provided two- and three-minute long tour speeches at special locations along its travel path. The user faced a single button and was only capable of asking the robot to present or skip each such tour stop.

The second robot, Sweetlips, equipped with five buttons, encouraged the visitor to select from several tour themes (e.g. predator-prey relationships; animals and their young; etc.). Depending on the visitors choice, a somewhat customized tour with only 30-second tour stops would proceed.

The third robot, Joe Historybot, sported a touch screen, offering not only customized tours, but also secondary information about the space (e.g. location of other exhibits and the restrooms). Furthermore, this robot provided, not unidirectional tours but rather a series of puzzles and questions along the tour paths, encouraging the visitors to stay engaged and challenged throughout the tour process.

The primary lesson learned from the Mobot series is that user learning is more effective and enjoyable when there is strong interaction and dialogue between robot and human. In particular, information is more effectively conveyed to humans when given within the context of two-way questions and answers.

A challenge in assessing robot-human interaction in public spaces revolves is the lack of appropriate controls. Each public installation occupies a new space with different cross-sections of society. Thus, it is difficult to quantitatively factor context out of the equation in order to arrive at well-justified conclusions regarding the social behavior appropriate for a mobile robot.

In work aimed at overcoming this issue, Bruce et al.

describe factored experiments in which the same social robot, Vikia (Fig. 38), is placed in the same public environment repeatedly[37]. Each experimental instance inactivates some portion of Vikias social competencies (e.g. animated visual saccades; physical head panning, facial animation; speech) and measures the robots social efficacy, in this case its penetration rate at engaging passers-by for a brief, anonymous poll. This work demonstrates the practicality of using formal, psychological techniques to explore the interaction mechanisms at work when robot are tasked with establishing effective, short-term relationships with the public.

Future work in the various contexts of task-oriented robotics, from personal assistants and collaborators to public interaction systems, will doubtless lead to richer and more meaningful social relationships between robots and humans for years to come.

### 3.3 Entertainment, personal, and toys

Commercially viable robotic pursuits in the toy and entertainment markets are governed by several constraints. An entertaining robot must achieve a maximum of entertainment value at a minimum of cost, which means that sensors must be multi-purpose and effectors must be minimized. Thus it is generally true that toy robots are technologically sub-par as compared to industrial and research robot platforms, and furthermore the technology curve for toy robots will tend to be shallower.

But the toy market is most adept at applying play-pattern based design principles to the problem of toy-human interaction. For a given toy, designers identify a finite collection of ways in which the user is intended to interact with the toy. The toy is then designed with the explicit goal of enabling the desired list of play patterns.

#### 3.3.1 Animatronic children’s dolls

The children’s doll continues to be one of the best-selling toys in history, and as such, toy manufacturers continue to explore new avenues for distinguishing their product from those of their competition. One of many heuristics states that a high-volume



Fig. 21. My Real Baby (Hasbro and iRobot)

toy cannot be priced more than \$99 retail, which implies a manufacturing cost of approximately \$20. With the cost of low-end microprocessors, MEMS-based accelerometers, voice recognition chips and imaging chips continually decreasing, it has become possible to develop robotic dolls.

It was with these price trends in mind that Hasbro funded IS-Robotics (now known as iRobot) to design an animatronic children’s doll that provides palpable interactivity in place of the purely “pretend” interactivity of a conventional doll.

My Real Baby is the toy resulting from this endeavor (Fig. 21). The development process focused most closely on the doll’s face, using small actuators planted underneath the rubber face to distort the face along several degrees of freedom, producing smiling, laughing and grimacing expressions. In addition to expression, the robot uses a small speaker to produce a wide array of infant sounds. Sensors in My Real Baby include an accelerometer, an array of pressure switches on the body and a light sensor.

The operating principle driving this interactive robot is closely aligned with the concept of highly parallel Subsumption. Multiple sensor-effector processes are active at once, and these processes can combine in a variety of ways to results in overall physical expressions and vocalized sounds. Thus, although the number of individual phonemes and muscles is small, the total number of output trajectories is effectively limitless[110].

Robotic autonomy does enable one key feature:

that of an evolution of behavior over time. My Real Baby takes advantage of this quality, vocalizing single-syllable infant sounds when just purchased and then gradually emitted more lengthy and complex vocalizations after days and weeks of use, emulating an infant’s changing behavior over time.

Other toy companies responded quickly by producing their own animatronic, interactive dolls. For example, Amazing Babies (Playmates), My Dream Baby (MGA Entertainment) and Miracle Moves Baby (Mattel) also offer sensor-laden interactive robots that respond to hugging and touching.

As a post-script, sales of the animatronic doll category have not met early expectations, although fad-like early sales were strong. As a result most such robot toys are now out of production, including My Real Baby.

### 3.3.2 Mobile social companions: quadruped and wheeled personal robots

While the animatronic doll category comprises toy robots that are to be cared for by their human masters, a more technologically demanding category are toys that are companions to their human users. Such social companions must achieve sufficient autonomy to function well during both direct manipulation by the human and during times of passive human observation. Often modeled after the social niche filled by domestic pets, one distinguishing feature of such companion robots is that they will usually demonstrate some level of mobility.

Mobility is of significance for such companion robots because it is such a strong prerequisite to the ability of an artifact to demonstrate its personal autonomy, however limited this may be in reality. However, mobility is far more technologically challenging than simple animatronic expressiveness. Just as Hasbro’s funding of My Real Baby catalyzed a small revolution in animatronic dolls, so Sony’s funding of the AIBO project has catalyzed a revolution in quadruped robot companions.

The Sony AIBO is the first and also the most technologically advanced of the commercially available quadruped companion robots [89–91,117]. Modeled

after aspects of the human relationship with a pet dog, the AIBO was designed not only for direct interaction but also as an enjoyable source of entertainment; watching the robot stumble and gradually learn to walk, or watching the robot play with its red ball constitutes a relatively one-way watch-me play pattern that is usually avoided in interactive toys.

The original AIBO (Fig. 7, top) had an extreme level of mechanical sophistication, including 20 degrees of freedom and the ability to stand up and sit under its own power. Sony invested heavily in the design of motors and motor control schemes that would enable smooth and desirable overall body motion from AIBO, and this investment has clearly paid off in that a short interaction with AIBO tends to leave the user staring at the smooth and lifelike qualities of its motion.

A small CMOS-based vision chip enables AIBO to perform color segmentation and thus to detect and chase brightly colored objects. This, combined with accelerometers, pressure sensors and an infrared reflectance sensor enable the toy robot to wander and avoid obstacles, and to sense falling over or being picked up, and even to recover from falling down.

Anticipated play patterns for AIBO have increased in levels of sophistication, and so ensuing versions of the toy robot demonstrate appropriate sensory and effectory improvements (Fig. 22). The ERS-200 series AIBO embodies greatly improved walking performance as well as the ability to detect 75 voice commands and to record still pictures.

Toy manufacturers were quick to reproduce some of the AIBO's functionality at a fraction of the price. Tiger Electronics, the maker of Furby, sold both a low-end robot dog, Poo-Chi, and a higher-end robot, I-Cybie. The latter is able to perform many of the same kinematic motion demonstrations at AIBO at one-tenth the price (see Fig. 23). Me and My Shadow (MGA Entertainment) offers much the same functionality as Poo-Chi but packaged in fur, thus offering greatly improved tactile interaction (Fig. 24).

The AIBO toy has itself moved away from the canine metaphor, partially due to the expectations of



Fig. 22. Aibo ERS-200 (top) and ERS-300 series (Sony)

consumers when encountering a dog-like robot. In 2002 Omron corporation introduced the NeCoRo feline robot (Fig. 25). Omron is explicitly aiming to engender the affection of the robot's human owner[176,226]. The robot's pressure sensors, for instance, are placed to optimize sensing stroking, petting and other such physical displays of affection. A simple affective state machine enables this robot to respond with a changing emotional trajectory to positive and abusive attention as well as inattention.

The basic goal of the NeCoRo project is to create a toy robot that will attract the affection of its user, thus allowing it to function as a positive, personal companion. This nurturing social application is also the motivation behind NEC's effort to develop a robot originally known as the R100[167]. The newest version, PaPeRo (Partner-type Personal Robot) has a body reminiscent of



Fig. 23. I-Cybie (Tiger Electronics)



Fig. 25. NeCoRo (Omron)



Fig. 24. Me and My Shadow (MGA Entertainment)

R2D2 (Fig. 26). As with most companion robots, PaPeRo has both speech synthesis capabilities and command recognition (650 spoken phrases). This robot is equipped with pressure sensors, ranging sensors and even a floor drop-off detector in addition to the microphone.

One unusual aspect of NEC's goal is made clear



Fig. 26. PaPeRo (NEC)



Fig. 27. Roball (Université de Sherbrooke)

in literature regarding PaPeRo. The company believes that one way of improving human-machine interaction is by enabling humans to live with robots in the human. The suggestion is that interaction with robots over the long term will empower humans more effectively for interaction with various electronic media, thus improving the quality of their human-machine interactions in the large.

Roball is a spherical play-based robot (Fig. 27). In this case, the primary effectory output of the robot is, by definition, motion. Thus, Roball becomes a useful testbed for evaluating the efficacy of autonomous mobility itself in child-toy interactions[151,152]. Qualitative evaluations conclude that this robot can engage children as young as 2 years old in games that they invent rather than funneling the users into pre-ordained play patterns.

The authors of Roball also describe a potential therapeutic use for Roball in regards to autistic children. One of the stumbling blocks induced by autism involves repetitive behavioral patterns from which the child may have difficult escaping. Robot companions such as Roball may aid such children in breaking out of such repetitive behavior, both because they move (motion is a clear behavioral trigger in autism) and because they follow relatively unpredictable behavioral trajectories.



Fig. 28. Tama (Matsushita/Panasonic)

### 3.3.3 Interactive goal-directed tools

A final category of toy and entertainment robot is that of robots with a mission beyond that of engaging and entertaining the user.

Matsushita, best known for its Panasonic brand, has revealed a research program to design a robotic companion for the elderly [166]. Tama is offered as a robotic substitute for animal therapy according to Matsushita (Fig. 28). It has a 50-phrase vocabulary as well as speech recognition and pressure sensors.

Three goals motivate research and development of Tama. First, this robot can provide affordable companionship for the elderly, primarily using its speech generation capabilities. Second, the robot can provide information and reminders regularly. In its literature, Matsushita suggests that the local government can use the robot to provide daily bulletins of relevance to those who would otherwise be unable to receive important information. Finally, by checking on the human's responses to Tama, off-site health care professionals would be able to identify those who are suspiciously absent from interaction with their robot and thus may need medical attention.

In a rather different direction, the Personal Rover Project aims to develop a commercialized, toy robot that can be deployed into the domestic environment and that will help forge a community of create robot enthusiasts[82]. Such a personal rover is highly configurable by the end user, who is creatively governing the behavior of the rover



Fig. 29. Personal Rover (Carnegie Mellon University)

itself: a physical artifact with the same degree of programmability as the early personal computer combined with far richer and more palpable sensory and effectory capabilities. The researchers hypothesize that the right robot will catalyze a community of early adopters and will harness their inventive potential.

As in the toy industry, the first step towards designing a Personal Rover for the domestic niche is to conduct a User Experience Design study. The challenge in the case of the Personal Rover is to ensure that there will exist viable user experience trajectories in which the robot becomes a member of the household rather than a forgotten toy relegated to the closet. The user experience design results fed several key constraints into the Rover design process: the robot must have visual perceptual competence both so that navigation is simple and so that it can act as a videographer in the home; the rover must have the locomotory means to travel not only throughout the inside of a home but also to traverse steps to go outside so that it may explore the back

yard, for example; finally, the interaction software must enable the non-roboticist to shape and schedule the activities of the rover over minutes, hours, days and weeks (Fig. 29).

### 3.4 Therapy

Increasingly, robots are being used in rehabilitation and therapy. Robotic wheelchairs allow people to regain some of their mobility in everyday environments during, for example, recovery from a spinal injury[190]. Robotic devices can also assist in the rehabilitation of stroke patients who have lost particular motor control functions[128].

Social robots are slowly but steadily being investigated as remedial and therapeutic tools. A key ingredient that makes a therapeutic robot social is interactivity. Robotic wheelchairs or robots that are used for sensorimotor exercises very much have the appeal of “machines”, more or less autonomous, but provide a particular functionality similar to a bicycle or a bus, in that they are clearly tools rather than interaction partners. However, in scenarios where service robots and disabled people cooperate, where the strength and weaknesses of both parties are exploited towards forming a “relationship,” robots require certain social skills[242]. Using synergetic effects emerging from robot-human cooperative activity is one advantage of using social robots. Others important advantages are:

- Robots can provide a stimulating and motivating influence that make living conditions or particular treatments more pleasant and enduring, an effect that has particular potential for children or elderly people.
- By acknowledging and respecting the nature of the human patient as a social being, the social robot represents a humane technological contribution.
- In many areas of therapy, teaching social interaction skills is in itself a therapeutically central objective, an effect that is important in behavioral therapeutic programs, e.g. for autistic children, but that might potentially be used across a range of psychological, developmental or social behavioral disorders.



Fig. 30. Paro, the robotic seal pup, imitates aspects of the behavior and appearance of a baby harp seal[212].

To date, social robots have been studied in a variety of therapeutic application domains, ranging from using robots as exercise partners[97], using robots in pediatrics[188], robots as pets for children and elderly people[212,213,236,237], and robots in autism therapy[65,68,69,71,154,155,158,240].

For the past six years, Shibata and his colleagues have been pursuing research into using robots for robot assisted activities[212,213,236,237]. The group has been developing robots specifically built for physical interaction with humans, targeting children and elderly people.

Physical contact in particular, if combined with interactivity, usually provided in interaction with other humans or animal pets, can have a positive impact on people, including calming, relaxation, stimulation, feelings of companionship and other emotional and physiological effects.

Robots such as the robotic seal robot called “Paro” (see Fig. 30) are designed as emotional creatures that capitalize on these effects. Complementary to animal assisted therapy, robot assisted therapy can be used even in environments where animals are not allowed or cannot be used for other practical, legal or therapeutic purposes (e.g., allergies).

Autism therapy is a different, promising application domain of interactive social robots. People with autistic spectrum disorders have impairments in social interaction, communication and imagination.

In the Aurora project (AUtonomous RObotic platform as a Remedial tool for children with Autism), Dautenhahn and her colleagues have been studying how autonomous interactive robots can be used by children with autism[68,69,71,240]. Differing from early, encouraging studies with a remote-controlled Logo turtle and a single autistic child[239], employing multiple autonomous mobile robots allows one or two children at the same time to freely interact with the robotic toys in a playful scenario. This scenario allows the children to exercise therapeutically relevant behaviors such as turn taking, and use communicative skills to relate to children or adults that are part of the trial scenario.

The humanoid doll Robota has been tested recently in the context of eliciting imitative behavior in children with autism[65] (see Fig. 31). Quantitative and qualitative evaluation techniques are used in order to analyze the interactions[69,71].

Designing robots for autistic children poses a number of engineering problems. Many of these are investigated in student projects under the direction of Francois Michaud[154,158]. The robots show a variety of modalities for interacting with people, including movement, speech, music, color and visual cues, among others. The robots vary significantly in their appearance and behavior, ranging from spherical robotic “balls” to robots with arms and tails. The goal of this endeavor is to engineer robots that can most successfully engage different children with autism. Therefore, by exploring the design space of autonomous robots in autism therapy one can produce a “zoo” of social robots that might meet individual needs of children with autism.

Social robots can look forward to a bright future in education in general [161,77], as well as in various areas of therapy. However, a number of methodological issues still need to be addressed, e.g. the developing and application of appropriate evaluation techniques that must demonstrate that robots really have an impact and can make a difference compared to other means of therapy and education. Also, the design space of behavior and appearance need to be investigated systematically so that systems are tailored towards educational, therapeutic and individual needs of users.



Fig. 31. Autonomous robots used in the Aurora project. An autistic child playing with a mobile robot (top) and Robota (bottom).

### 3.5 Anthropomorphic

#### 3.5.1 Motivations

One basic motivation for anthropomorphic research stems from a desire to emulate, as closely as possible, natural human interaction. In [108,109] for instance there is a basic initial premise that humans must be able to interact with robots naturally, where naturally means that the humans should not behave differently than if they were interacting with other humans.

A more extreme extension of this philosophy, presented by [124,123], claims that any truly social intelligence must have an embodiment that is structurally and functionally similar to the human sensorimotor system. Although the argument for func-

tional similarity between social robots and humans is well accepted, Kozima and others are suggesting that the physical instantiation of that functionality must also be as human-like as possible.

Humanoid form can also be a purely pragmatic choice. For instance, [198] wish to design a robot that can be an effective member of a hybrid, robot-human team. As such, an important design constraint is that humans should interact with each robot without any special input devices or other physical connections to the system.

A complementary pragmatic reasoning process also justifies relatively fine reproduction of the human form. If robots are to be installed in our human world, replete with its artifice designed for human manipulation and interaction, then a natural form to enable interaction in the man-made world means human dexterity in hands and human locomotion in legs.

These various motivations are all valid in the pursuit of humanoid robots. There is, however, a useful if indistinct boundary that can be drawn between three types of research projects in the area of social, anthropomorphic robotics described below. In Section 3.5.2 below, we describe major achievements in the creation of anthropomorphic form.

#### 3.5.2 Engineering the anthropomorphic form

The most significant efforts in anthropomorphic form engineering have been undertaken by Sony Corp. and Honda Motor Corp. over the past decade. The creation of compelling anthropomorphic robots is a massive engineering challenge; yet, in the case of both Sony and Honda it is clear that the single largest hurdle involved actuation. Both companies designed small, powered joints that achieve power to weight ratios unheard of in commercial servomotors. These new “intelligent” servos provide not only strong actuation, but also compliant actuation by means of torque sensing and closed-loop control.

The Sony Dream Robot, model SDR-4X (Fig. 32), is the result of research begun in 1997 to develop motion entertainment and communication enter-



Fig. 32. SDR-4X (Sony)

tainment (i.e. dancing and singing). This 38-DOF robot has seven microphones for sound localization; image-based person recognition; on-board miniature stereo depth map reconstruction and limited speech recognition. Given the goal of fluid and entertaining motion, Sony spent considerable effort designing a motion prototyping application system to enable their own engineers to script dances in a straightforward manner. Note that SDR-4X is relatively small, standing 58cm and weighing only 6.5kg.

The Honda humanoid design project dates from 1986. Fig. 33 shows model P3, the eighth humanoid prototype and immediate predecessor to the Asimo robot (Advanced Step in Innovative MObility)[105,200]. In contrast to Sony, Honda's humanoid robots are being designed, not for entertainment purposes, but as human aids throughout society. Honda refers, for example, to Asimo's height as the minimum required for compatibility with human environments (e.g., control of light switches). Thus, the P3 is much larger than the



Fig. 33. P3 (Honda)

SDR-4X, at 120cm tall and 52 kg. This gives the robot practical mobility in the human world of stairs and ledges, while maintaining a non-threatening size and posture.

The level of competence achieved by these humanoid forms is already impressive. SDR-4X can fall down and raise itself unaided; ASIMO can manipulate a shopping cart. Yet the research efforts of both companies appear to continue unabated.

### 3.5.3 *The science of anthropomorphism: developmental and social learning*

Learning continues to pose an extremely difficult problem, yet many researchers insist that social robotics will only be successful if they are able to learn. One argument is presented in [123], in which the authors suggest that any engineered solution, although at first novel, will fail to preserve its identity with the public over the long-term. Eventually, one's knowledge that the robot was designed by

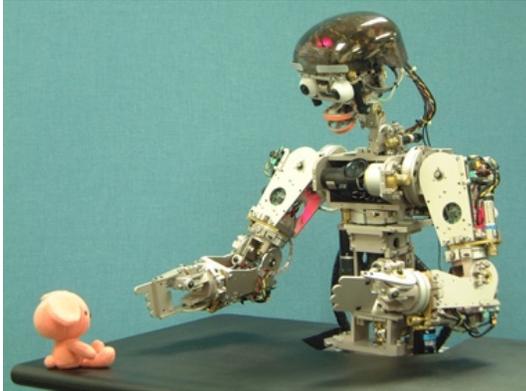


Fig. 34. Infanoid [121]

other humans reduces the robot to an engineered system, directly interfering with any hopes for social robot-human interaction. In contrast, consider a robot that continues to learn and evolve. The open nature of this robot's repertoire, combined with its ability to adapt to the humans behavior, will allow the robot to be viewed as a social being.

Reinforcement learning is often seen as the key to the robots continuing progression, where feedback is derived directly from human-robot interaction. Iida et al. argue that robots must not only interact with humans on the humans own terms, but must also learn from humans within the domain of natural human interaction[101,108,109]. They contend that directed instruction, whereby a human teaches a robot using a carefully engineered feedback and reward mechanism, is constraining and ultimately unable to scale. Instead, they propose the design of reinforcement learning mechanisms in which the robot does not measure explicit reward, but rather its ability to predict human responses and behavior over time.

The developmental approach suggests that the path to a mature social robot begins with an immature, childlike robot that employs the appropriate learning mechanisms. Often, in this work, the human is not a peer but rather a caregiver for the robot. For example [121,123] use the robot, Infanoid (Fig. 34), as a vehicle for developing mechanisms for shared focus of attention.

Infanoid has 23 degrees of freedom, including

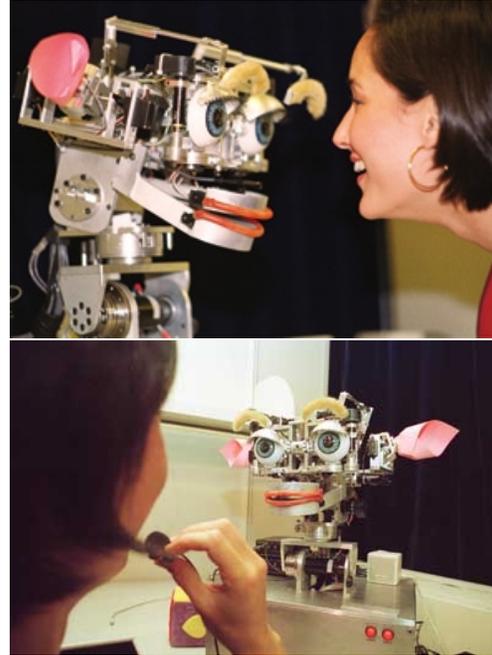


Fig. 35. Kismet (images by D. Coveney (MIT) and L. Poole (AP))

foveated stereo vision and an array of controllable facial expressions. Kozima and Yano demonstrate shared attention, thought to be a key prerequisite to social learning, between Infanoid and a human caregiver. A key aspect of this and other similar mechanisms involves projection: the projection of the caregivers attention onto oneself; the projection of the caregivers motor actions onto ones own motor system; and the projection of ones own state onto the caregiver.

Attention is perhaps the most studied aspect of human behavior in developmental android systems. Particularly in case of caregiver robot relationships, focus of attention and all of its secondary aspects form core functionalities for social interaction and, eventually, learning. The robot Kismet (Fig. 35) was built primarily for studying models of human attention and visual search[22,27].

This research proposes a minimal functionality research query: what is the minimal interaction functionality required for a robot to be capable of normal social interaction with its caregiver? Using a

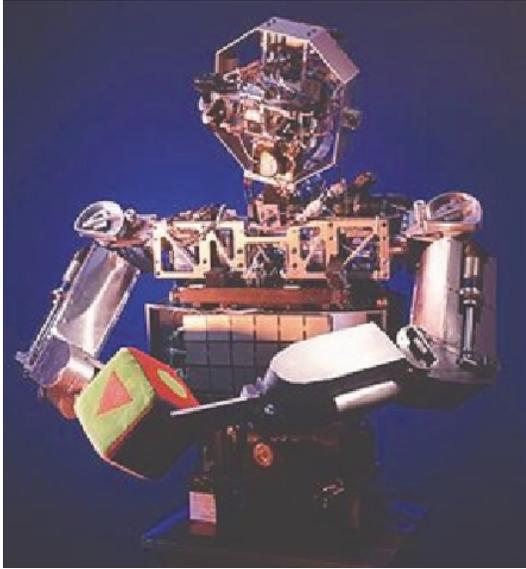


Fig. 36. Cog

behavior-based approach with activation thresholds varied over time based on state parameters, Kismet responds to cues while tending towards a homeostatic middle-ground. Thus the same user input, which triggers surprise at first may soon trigger annoyance when repeated ad nauseum.

The most well-known developmental study of social development revolves around the robot Cog, shown in Fig. 36 [1,36,204]. In this work, the explicit goal is the evaluation of models of human social behavior using robotics as a practical testbed. Four basic goals infuse the Cog research programs: emotional models for regulating social interaction; shared attention and learning. Cog has 22 degrees of freedom and is designed to emulate human motion as closely as possible.

Shared attention models are inspired directly by those of Baron-Cohen [10]. Separate modules enable theory-of-mind, intentionality, shared attention and eye-direction control. In implementing these modules with a physical robot, the challenges are two-fold: how will the primitive sensors of the robot enable the requisite perception (eye gaze direction, etc.); and how will the modules literally combine to result in an emergent behavior that is significantly richer than the composite parts (e.g.

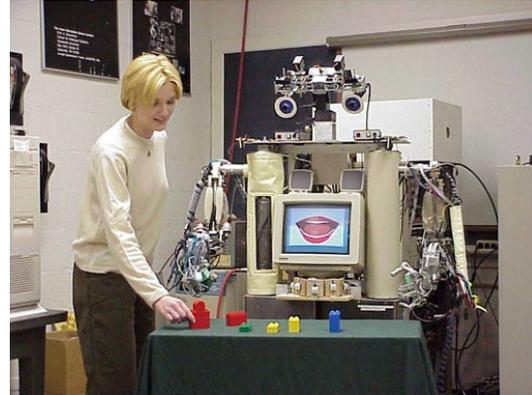


Fig. 37. ISAC (University of Tennessee)



Fig. 38. Vikia (CMU)

imperative pointing).

### 3.5.4 Designing for human-robot interaction

In [198], the goal of unfettered human-robot interaction in team settings leads to natural design decisions regarding the study of interaction. The physical embodiment of their robot, ISAC, is driven not by fidelity to the humanoid form but rather by those aspects of form that are most critical to natural communication. Thus, ISAC (Fig. 37) includes a screen-animated mouth, a color stereo vision system, affective eyebrows, passive-IR sensing and microphones and anthropomorphic arms for gesturing.

Vikia is another robot engineered for social interaction rather than for fidelity to the human form



Fig. 39. Robovie III (ATR)

(Fig. 38). A digitally rendered face enables a variety of facial implementations to be tested with human subjects to rate relative efficacy. Bruce et al. conducted a series of social tests in which various features of the robot were activated, measuring the factored impact of face rendering, robot motion and facial servoing on human-robot interaction.

Robovie is a third example of a selectively anthropomorphic robot[111]. Robovie (Fig. 39) is based on a commercial wheeled base and has two arms, an eye pair, and a decidedly un-anthropomorphic flat tactile panel. The principal thesis offered by this work is that emerged mutual gestures between robot and human aid both parties in comprehending and responding to their actions in a social setting.

### 3.6 Education

#### 3.6.1 The social role of robots in education

The role of robotic technologies in education is a broad subject. From the earliest Lego/LOGO tools, educators have been inspired to include robotic focused activities for pedagogic purposes. Today, there are at least 6 major robotics competitions for secondary level students, including Robot Sumo, Botball, US First, MicroMouse, Firefighters, and RoboCup Soccer.

In this section we focus more narrowly on the form of the relationship between robotics and education. More precisely, what social niches do robots occupy in the educational process? A useful classification can be based on the relationship of the robot, and robotics itself, to the subjects being learned. In one case, robotics is the explicit goal of the educational experience. Such a narrow focus does not preclude a breadth of learning, but rather provides direct motivation for the whole experience, for instance in the form of a robotics contest or robot programming challenge. Section 3.6.2 below addresses this Study of Robotics.

A second approach is to make deliberate use of robots as members of the students' social community. Sometimes, the robot is a social companion and educational catalyst. At other times, the robot is transparent, providing senses and motors that are otherwise unattainable to the student-explorer.

#### 3.6.2 Robots as educational foci

When a robot is the goal of a team project, then the student-robot relationship is one of creator and creation. As creators, the students must find constructive solutions to the problem of fashioning a desirable, robotic end-product. Often such goals are presented in series, as part of a challenge-based and project-based curriculum. Such approaches provide motivation to the students without didactically teaching solutions. The process of exploration and solution creation is left to the students themselves, much as in Constructionism, which is often exemplified by Lego/LOGO[178].

Lessons learned vary, but common themes throughout the study of robotics include the following:

*Interest in science and engineering.* Especially in younger educational settings, the study of robotics can be sufficiently rewarding as to generate enthusiasm for science and technology fields.

*Empowerment towards technology.* Qualitative results often demonstrate that students who have low technological self-esteem can often leave a robotics course feeling technologically empowered. Through such empowerment, fear or shyness towards technology can be transformed dramatically into interest in exploring technology and even altering its course.

*Teamwork.* Even at undergraduate and graduate educational levels, an important aspect of project-based work in general and robotics in particular is its team-building quality. Industry demands teamwork, and robotics projects provide opportunities for interdisciplinary integration.

*Problem-solving techniques.* Studying robot diagnosis and problem-solving brings together the best physical and software debugging skills in the scope of a single activity.

*Research and integration skills.* Due to its relative youth, robotics has a fast-moving and diverse knowledge frontier. Thus students pursuing robotic creations must demonstrate the ability to research that knowledge frontier and integrate information across multiple fields: mathematics, physics, cognitive psychology, artificial intelligence and others.

Botball is a challenge-based program for both educators and students in middle and high schools[222]. Students work in teams to build Lego-based robots that perform autonomously, guided by on-board microprocessors (68HC11 and the Lego Mindstorms™ programmable brick). Educators, in turn, are provided with resources and knowledge to enable teaching robot building and programming skills to future students in their class.

In the case of programs such as Botball, the robot is nothing more than the students' creation (Fig. 40). The contest challenge is the social glue that brings the student team members together for the com-

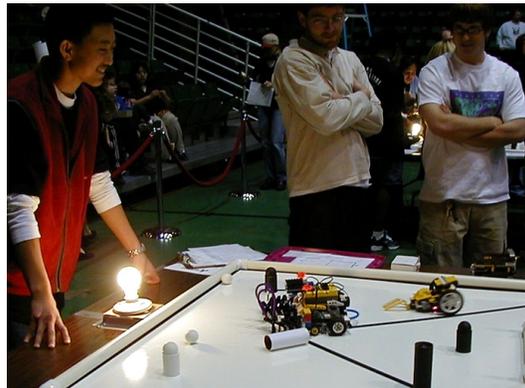


Fig. 40. The Botball Competition

mon purpose of robot creation.

This same general relationship between student teams and robot creation is also valid with respect to older students at undergraduate and graduate levels of education. In such cases, the robot hardware may be fixed- often purchased from a commercial research robotics corporation. The student challenge may be one of creating robot behavior. For example, at Carnegie Mellon University a course on mobile robot programming brings student teams together with an off-the-shelf robot platform. The teams' goal is to surmount obstacle avoidance, navigation, communication and cooperation challenges to eventually demonstrate intelligent game-playing in a cardboard maze-world[172]. In this and other undergraduate courses elsewhere, robotic projects serve to capture student interest and provide a forum for the development of skills essential to scientific inquiry[50].

Robot contests held as part of technical conferences can also be highly motivating to student teams. Although most contests have emphasized robot autonomy, recently there has been increased interest in exploring human-robot interaction. For example, [148] and [157] describe the experience of student teams at the AAAI *hors d'oeuvres* event. One interesting aspect is that, unlike purely robot-focused contests, these teams involved computer science majors as well as art and theater majors to not only design the behavior of a butler-robot, but also to create an engaging external appearance (e.g., a tuxedo-wearing penguin, Fig. 41).



Fig. 41. Alfred the tuxedo-wearing penguin (Swarthmore University)



Fig. 42. Robota (Didel SA)

In one especially sophisticated example, the Robota series of robots is shown in pilot studies to demonstrate efficacy as a learning tool for students acting as the robot's behavior creators[14]. Robota serves both as a vessel for students to program, and as a programmed robotic companion that guides children through games (Fig. 42).

In the study of Robota the robot, students must

design human-computer interaction software for natural exercises such as role-playing and conversation between Robota and humans. Students cover subjects as diverse as computer vision, natural language processing and motor control, all with the aim of creating a compelling, highly interactive doll.

### 3.6.3 Robots as educational collaborators

In this section we examine the role of robots that are fully developed members of the learning system. Students are not in the position of modifying robot behavior nor robot appearance directly. Rather, the robot is a sometime peer, sometime companion, sometime collaborator in a greater educational enterprise.

Social robots are particularly well-suited to inhabit such a role. First, robot artifacts continue to be novel. As a result, there is little or no established background bias regarding the expected behavior of a robot tutor. As a novel, animated artifact, a robot is able to easily attract the initial attention of a student and, given interesting behavior, retain that interest over some time.

As compared to a software agent, the physical robot artifact demonstrates not only far higher levels of attention-grabbing novelty, but has a functionally useful physical presence[214]. Through local movement or through general mobility, a robot can draw the viewer's attention to a desired location. For instance, a fixed doll can gesture at a region of interest, as demonstrated by Mel the Robot Host[214]. While teaching best practices for the operation of a gas turbine, this on-screen tutorial is augmented by a sessile robot, Mel, that can move its beak and can gesture at interface details using its arms (Fig. 43).

Another multi-modal robot communicator with a specific educational charter is the Sage (also known as "Chips") robot, which operated in the Carnegie Museum of Natural History for five years (Fig. 20). This mobile robot used mobility itself, engaging museum-goers then taking them to rarely viewed exhibits, in order to broaden the educational impact on visitors. Educational efficacy measurements indicated a strong correlation between im-



Fig. 43. Mel (Mitsubishi Electric Research Labs)



Fig. 44. Insect Telepresence: User kiosk (left), 3-DOF raster arm (top right), camera view (bottom right)

provements on subject matter tests and interaction with the robot's educational material[171].

In addition to explicit physical presence, a robotic educational collaborator can also play an augmentative role. Robots have access to sensory measurements and effectory degrees that may be literally beyond the reach of the student. Thus the robot may be a bionic or tele-present extension of the human. A simple example of such an educational robot is Insect Telepresence, a robotic kiosk operating at the Carnegie's Entomology Division (Fig. 44)[3].

In this exhibit, students explore the micro-world of Madagascan Hissing Roaches using an equivalently scaled miniature camera controlled by a 3DOF raster arm. By controlling the motions of this robot in the small-scale world, visitors learn to appreciate small-scale natural structure and roach social behavior with a clarity that is otherwise im-

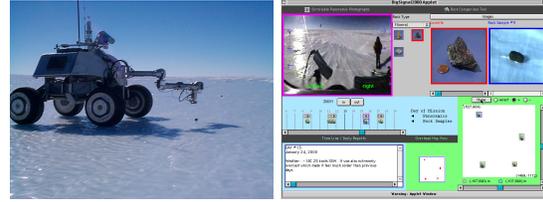


Fig. 45. The BigSignal Telepresence Project: Nomad (left), user interface (right)

possible.

The BigSignal project demonstrated the use of a mobile robot as a remotely operated tool for exploration and learning (Fig. 45). Although a number of similar projects have occurred since, BigSignal is relatively unique in the completeness of the long-distance exploration interface. The goal of this mission was to bring the sense of exploration, along with closely accompanying science data and goals, to a large segment of the public at the same time[51,52]. The robotic target was Nomad during a meteorite search in Antarctica.

By creating a broad website around the robot, the educators were able to create a site which empowered each individual user with the feeling of robot exploration, sensor review and science study. Techniques such as data abstraction, daily data downloads and robotic first-person diaries all enabled the relationship between one robot and thousands of viewers to be transformed into individual one-on-one relationships to as complete a degree as is feasible.

## 4 Discussion

### 4.1 Human perception of social robots

A key difference between conventional and socially interactive robots is that the way in which a human perceives a robot establishes expectations that guide his interaction with it. This perception, especially of the robot's intelligence, autonomy, and capabilities is influenced by numerous factors, both intrinsic and extrinsic.

Clearly, the human's preconceptions, knowledge,

and prior exposure to the robot (or similar robots) have a strong influence. Additionally, aspects of the robot’s design (embodiment, dialogue, etc.) may play a significant role. Finally, the human’s experience over time will undoubtedly shape his judgment, i.e., initial impressions will change as he gains familiarity with the robot.

In the following, we briefly present studies that have examined how these factors affect human-robot interaction, particularly the way in which the humans relate to, and work with, social robots.

#### *4.1.1 Attitudes towards robots*

In [38], Bumby and Dautenhahn describe a study designed to identify how people, specifically children, perceive robots and what type of behavior they may exhibit when interacting with robots. They performed three sub-studies on a sample of thirty-eight school children. In the first two, observations were made as each child drew a picture of a robot and then wrote a story about the robot they had drawn. In the third study, the children interacted with two Fischertechnik robots operating with Braitenberg behaviors and were questioned through an informal, but guided interview.

Bumby and Dautenhahn found that children tend to conceive of robots as geometric forms with human features (i.e, their is a strong pre-disposition towards anthropomorphism). Moreover, in their stories, the children tend to attribute free will to the robots and to place them in familiar, social contexts. Finally, most of the children attributed preferences, emotion, and male gender to the robots, even without explicit cues to prompt this response.

In [115], Khan describes a survey to investigate people’s attitudes towards an intelligent service robot in domestic settings. Among the questions the survey sought to answer were: “How are robots perceived by humans in general?”, “What should the robot look like?” and “How should the communication between a human and robot be conducted?” A review of robots in literature and film, followed by an interview study, were used to design the survey questionnaire.

A total of 134 participants (54% female, 21-60 years of age, well educated, varied occupations) completed the questionnaire. The survey revealed that people’s attitudes towards service robots is strongly influenced by science fiction. When asked to sketch a picture of their preferred robot, respondents drew robots that were either strongly anthropomorphic or mechanistic in appearance. Two significant findings were: (1) a robot with machine-like appearance, serious personality, and round-shaped is preferred; and (2) verbal communication (voice recognition and synthesized speech) using a human-like voice (neutral with respect to gender and age) is highly desired.

#### *4.1.2 Field studies*

Thus far, few studies have investigated people’s willingness to closely interact with social robots. Given that we expect social robots to play increasingly larger roles in daily life, there is a strong need for field studies to examine how people behave when robots are introduced into their activities.

Scheeff et al. conducted two studies to observe how people interact with a creature-like social robot[207]. In the first study, thirty subjects worked with the robot in controlled laboratory conditions. In the second study, the robot was placed in a public area without explanation and observations were made about how passers-by interacted with it. In these studies, children were observed to be more engaged than adults, with responses that varied with gender and age. Also, a friendly personality was reported to have prompted qualitatively better interaction than an angry personality.

In [208], Schulte et al. discuss short-term and spontaneous interaction between Minerva, a tour-guide robot and crowds of people. Minerva performed 201 attraction interaction experiments and learned, over time, how to more successfully attract people. They found that there was a clear tendency for friendlier behavior (sounds and facial expressions) to better engage users. To measure Minerva’s believability, Schulte et al. asked a sampling of 60 museum visitors to answer a questionnaire. One finding was that young children (less than 10 years of

age) were more likely to attribute human-like intelligence to the robot, than were older visitors.

In [107], Huttenrauch and Severinson-Eklundh describe a long-term usage study of CERO, a service robot that assists motion-impaired people in an office environment (Fig. 10). The study was designed to observe interaction over time, after the user had fully integrated the robot into his work routine. A key finding was that whenever robots operate around people, they need to be capable of social interaction and aware of social context.

In [69], Dautenhahn and Werry describe a quantitative method for evaluating robot-human interactions, which is similar to the way ethologists use observation to evaluate animal behaviour. This method has been used to study differences in interaction style when children play with a socially interactive robotic toy versus a non-robotic toy. Complementing this approach, Dautenhahn et al. have also proposed qualitative techniques (based on conversation analysis) that focus on social context[71].

#### 4.1.3 *Effects of emotion*

Cañamero and Fredslund performed a study to evaluate how well humans can recognize facial expressions displayed by Felix (Fig. 11), a robot constructed with LEGO Mindstorms<sup>TM</sup> parts[42]. In this study, they asked test subjects (45 adults and 41 children) to make subjective judgments of the emotions displayed on Felix's face and in pictures of humans. The results were very similar to those reported in other studies of facial expression recognition. Additionally, Cañamero and Fredslund concluded that the "core" emotions of anger, happiness, and sadness are easily recognized, even with embodiment as simple as Felix's.

Bruce, Nourbakhsh and Simmons conducted a 2x2 full factorial experiment to explore how emotion expression and indication of attention affect a robot's ability to engage humans[37]. Of primary concern was answering the question "Would people find interaction with a robot that had a human face more appealing than a robot with no face?". In the study, the robot exhibited different emotions based on its

success at engaging and leading a person through a poll-taking task. The results suggest that having an expressive face and indicating attention with movement can help make a robot more compelling to interact with.

#### 4.1.4 *Effects of appearance and dialogue*

One problem with dialogue is that it can lead to biased perceptions. For example, associations of stereotyped behavior can be created, which may lead users to attribute qualities to the robot that are inaccurate. Users may also form incorrect models, or make poor assumptions, about how the robot actually works. This can lead to serious consequences, the least of which is user error[85].

Kiesler and Goetz conducted a series of studies to understand the influence of a robot's appearance and dialogue on how people think about the robot and act towards it[116]. A primary contribution of this work are measures for characterizing the mental models people use when interacting with robots. The measures consist of: scales for rating anthropomorphic and mechanistic dimensions; measures of model richness or certainty; and measures of compliance with a robot's requests. One significant study finding was that neither ratings, nor behavioral observations alone are sufficient to fully describe human responses to robots. In addition, Kiesler and Goetz concluded that dialogue more strongly influences development and change of mental models than differences in appearance.

DiSalvo et al. investigated how the features and size of humanoid robot faces contribute to the perception of humanness[76]. In this study, they analyzed 48 robots and conducted surveys to measure people's perception. Statistical analysis showed that the presence of certain features, the dimensions of the head, and the number of facial features greatly influence the perception of humanness.

#### 4.1.5 *Effects of personality*

When a robot exhibits personality (whether intended by the designer or not), a number of effects occur. First, personality can serve as an affordance

for interaction. A growing number of commercial products targeting the toy and entertainment markets, such as Tiger Electronic’s Furby (a creature-like robot), Hasbro’s My Real Baby (a robot doll), and Sony’s Aibo (robot dog) focus on personality as a way to entice and foster effective interaction[27].

Personality can also impact task performance, in either a negative or positive sense. For example, Goetz and Kiesler examined the influence of two different robot personalities on user compliance with an exercise routine[97]. In their study, they found some evidence that simply creating a charming personality will not necessarily engender the best cooperation with a robotic assistant.

#### 4.2 Open issues and questions

When we engage in social interaction, there is no guarantee that it will be meaningful or worthwhile. Sometimes, in spite of our best intentions and attention, the interaction fails. Relationships, especially long-term ones, involve myriad factors and making them succeed requires concerted effort.

In [244], Woods writes:

It seems paradoxical, but studies of the impact of automation reveal that design of automated systems is really the design of a new human-machine cooperative system. The design of automated systems is really the design of a team and requires provisions for the coordination between machine agents and practitioners.

In other words, humans and robots must be able to coordinate their actions so that they interact productively with each other, rather than just sharing the same space. It is not appropriate, or perhaps even necessary, for the the robot to be as socially competent as possible. Rather, it is more important that the robot be compatible with the human’s needs, that it be understandable and believable, and that it provide the interactional support the human expects.

In research and engineering, it is common that the system designer is also user interface designer. As a result, interfaces tend to reflect the underlying

system design. However, unless the designer is the only user, which is rarely the case, this can be a source of trouble. The reason is that the designer usually has different goals than the end-user, i.e., the designer wants to control or debug the system, whereas the end-user wants to complete a task [96].

With social robots, the “task” to be accomplished may simply be social interaction between human and robot. Even when social interaction is not the robot’s primary function, interaction is still central to task performance. Thus, the ideal interface is one that enables the human and robot to focus on the content of the interaction (i.e., what is being said or exchanged), rather than semantics or manipulation of interface controls.

As we have seen, building a social robot involves numerous design issues. Although much progress has already been made to solving these problems, much work remains. This is due, in part, to the broad range of applications for which social robots are being developed. Additionally, however, is the fact that there many research questions that remain to be answered, including:

*What are the minimal criteria for a robot to be social?* Social behavior includes such a wide range of phenomena that it is not evident which features a robot must have in order to show social awareness or intelligence. Clearly, a robot’s design depends on its intended use, the complexity of the social environment and the sophistication of the interaction. However, in general, we should still be able to answer: Does a social robot have to be modeled after a living creature or can it be an entirely new social species? To what extent does social robot design need to reflect theories of human social intelligence?

*How do we evaluate social robots?* Many researchers contend that adding social interaction capabilities will improve robot performance, e.g., by increasing usability. Thus far, however, little experimental evidence exists to support this claim. What is needed is a systematic study of how “social features” impact human-robot interaction in the context of different application domains[62]. The problem is that it difficult to determine which metrics are most appropriate for evaluating social “effectiveness”. Should we use human performance met-

rics? Should we apply psychological, sociological or HCI measures? How do we account for cross-cultural differences and individual needs?

*What differentiates social robots from robots that exhibit good human-robot interaction?* Although conventional HRI design does not directly address the issues presented in Section 2.2, it does involve techniques that indirectly support social interaction. For example, HCI methods (e.g., contextual inquiry) are often used to ensure that the interaction will match user needs. The question is: Are social robots so different from traditional robots that we need different interactional design techniques?

*What underlying social issues may influence future technical development?* An interesting observation made by Restivo is that “robotics engineers seem to be driven to program out aspects of being human that for one reason or another they don’t like or that make them personally uncomfortable” [196]. If this is true, does that mean that social robots will always be “benign” by design? If our goal is for social robots to eventually have a place in human society, should we not investigate what could be the negative consequences of introducing social robots into society?

*Are there ethical issues that we need to be concerned with?* For social robots to become more and more sophisticated, they will need increasingly better computational models of humans, if not of individuals. Detailed user modeling, however, may not be socially acceptable, especially if it involves privacy concerns (e.g., recording of certain user habits). A related question is that of user monitoring. If a social robot has a model of an individual, should it be capable of recognizing when a person is acting erratically and taking action?

*How do we design for long-term interaction?* To date, research in social robot has focused exclusively on short duration interaction, ranging from periods of several minutes (e.g., tour-guiding) to several weeks, such as in [107]. Little is known about interaction over longer periods. To remain engaging and empowering for months, or years, will social robots need to be capable of long-term adaptiveness, associations, and memory? Also, how can we determine whether long-term human-

robot relationships may cause ill-effects?

### 4.3 Summary

As we look ahead, it seems clear that social robots will play an ever larger role in our world, working for and in cooperation with humans. Social robots will assist in health care, rehabilitation, and therapy. Social robots will work in close proximity to humans, serving as tour guides, office assistants, and household staff. Social robots will engage us, entertain us, and enlighten us.

Central to the success of social robots will be close and effective interaction between humans and robots. Thus, although it is important to continue enhancing autonomous capabilities, we must not neglect improving the human-robot relationship. The challenge is not merely to develop techniques that allow social robots to succeed in limited tasks, but also to find ways that social robots can participate in the full richness of human society.

### Acknowledgments

We would like to thank the participants of the *Robot as Partner: An Exploration of Social Robots* workshop (2002 IEEE International Conference on Intelligent Robots and Systems) for inspiring this paper. We would also like to thank Cynthia Breazeal, Lola Cañamero, and Sara Kiesler for their insightful comments. This work was partially supported by EPSRC grant (GR/M62648).

### References

- [1] B. Adams et al., Humanoid robots: a new kind of tool, *IEEE Intelligent Systems* 15 (4), (2000).
- [2] J. Aggarwal and Q. Cai, Human motion analysis: a review. *Computer Vision and Image Understanding* 73(3) (1999).
- [3] S. All and I. Nourbakhsh, Insect Telepresence: Using robotic tele-embodiment to bring insects

- face-to-face with humans, Special issue on Personal Robotics, *Autonomous Robots* 10 (2001).
- [4] P. Andry et al. Learning and communication via imitation: an autonomous robot perspective, *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans* 31 (5) (2001).
- [5] T. Aoki et al., An animal psychological approach for personal robot design—interaction between a rat and a rat-robot, in: *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, 2000.
- [6] R. Arkin et al., An ethological and emotional basis for human-robot interaction, *Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems* 42 (3-4) (2003).
- [7] C. Armon-Jones, The social functions of emotions, in: R. Harré, ed., *The Social Construction of Emotions*, Oxford, Basil Blackwell.
- [8] R. Aylett and L. Cañamero, eds., *Animating Expressive Characters for Social Interactions, Papers from the AISB'02 Symposium*, SSAISB Press, 2002.
- [9] T. Balch and R. Arkin, Communication in reactive multiagent robotic systems, *Autonomous Robots* 1 (1994).
- [10] S. Baron-Cohen, *Mindblindness: an essay on autism and theory of mind*, Cambridge, MIT Press, 1995.
- [11] C. Bartneck and M. Okada, Robotic user interfaces, in: *Proceedings of the Human and Computer Conference*, 2001.
- [12] C. Bartneck, *eMuu - An Emotional Embodied Character for the Ambient Intelligent Home*, Ph.D. thesis, Technical University of Eindhoven, The Netherlands, 2002.
- [13] R. Beckers et al., From local actions to global tasks: stigmergy and collective robotics, in: R. Brooks and P. Maes, eds., *Proceedings Artificial Life IV*, MIT Press, 1996.
- [14] A. Billard, *Robota, clever toy and educational tool*, *Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems* 42 (3-4) (2003).
- [15] A. Billard and K. Dautenhahn, Grounding communication in situated, social robots, in: *Proceedings of Towards Intelligent Mobile Robots Conference*, Report UMCS-97-9-1, Department of Computer Science, Manchester University, 1997.
- [16] A. Billard and K. Dautenhahn, Grounding communication in autonomous robots: an experimental study, *Robotics and Autonomous Systems* 24 (1-2) (1998).
- [17] A. Billard and K. Dautenhahn, Experiments in learning by imitation: grounding and use of communication in robotic agents, *Adaptive Behavior* 7 (3-4) (1999).
- [18] A. Billard and G. Hayes, Learning to communicate through imitation in autonomous robots, in: *Proceedings of the 7th International Conference on Artificial Neural Networks*, 1997.
- [19] E. Bonabeau, M. Dorigo, and G. Theraulaz, *Swarm Intelligence: From Natural to Artificial Systems*, New York, Oxford University Press, 1999.
- [20] V. Braitenberg, *Vehicles-experiments in synthetic psychology*, Cambridge, MIT Press.
- [21] C. Breazeal, A motivation system for regulating human-robot interaction, in: *Proceedings of the National Conference on Artificial Intelligence*, 1998.
- [22] C. Breazeal, *Sociable machines: expressive social exchange between humans and robots*, Sc.D. dissertation, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 2000.
- [23] C. Breazeal, Believability and readability of robot faces, in: *Proceedings of the Eighth International Symposium on Intelligent Robotic Systems*, 2000.
- [24] C. Breazeal, Proto-conversations with an anthropomorphic robot, in: *Proceedings of the Ninth IEEE International Workshop on Robot and Human Interactive Communication*, 2000.
- [25] C. Breazeal, Affective interaction between humans and robots”, in: *Proceedings of the European Conference on Artificial Life*, 2001.
- [26] C. Breazeal, Emotive qualities in robot speech, in: *Proceedings of the International Conference on Intelligent Robotics and Systems*, 2001.

- [27] C. Breazeal, *Designing sociable robots*, Cambridge, MIT Press, 2002.
- [28] C. Breazeal, Towards sociable robots, *Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems* 42 (3-4) (2003).
- [29] C. Breazeal, Designing sociable robots: lessons learned, in: K. Dautenhahn et al., *Socially Intelligent Agents: Creating Relationships with Computers and Robots*, Kluwer, 2002.
- [30] C. Breazeal, Emotion and sociable humanoid robots, *International Journal of Human Computer Interaction*, (in press), 2002.
- [31] C. Breazeal and P. Fitzpatrick, That certain look: social amplification of animate vision, in: *Proceedings of the AAAI Fall Symposium on Socially Intelligent Agents—The Human in the Loop*, 2000.
- [32] C. Breazeal and B. Scassellati, How to build robots that make friends and influence people, in: *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, 1999.
- [33] C. Breazeal and B. Scassellati, A context-dependent attention system for a social robot, in: *Proceedings of the Sixteenth International Joint Conference on Artificial Intelligence*, 1999.
- [34] C. Breazeal and B. Scassellati, Challenges in building robots that imitate people, in: K. Dautenhahn and C. Nehaniv, eds., *Imitation in Animals and Artifacts*, MIT Press, 2001.
- [35] C. Breazeal et al., Active vision for sociable robots, *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans* 31(5) (2001).
- [36] R. Brooks et al., *The Cog Project: building a humanoid robot, Computation for Metaphors, Analogy, and Agents*, (C. Nehaniv, ed.), *Lecture Notes in Artificial Intelligence* 1562, Springer, 1998.
- [37] A. Bruce, I. Nourbakhsh, and R. Simmons, The role of expressiveness and attention in human-robot interaction, in: *Proceedings of the AAAI Fall Symposium on Emotional and Intelligent II: The Tangled Knot of Social Cognition*, 2001.
- [38] K. Bumby and K. Dautenhahn, Investigating children’s attitudes towards robots: a case study, in: *Proceedings of the Third Cognitive Technology Conference*, 1999.
- [39] J. Cahn, The generation of affect in synthesized speech, *Journal of American Voice I/O Society* 8 (1990).
- [40] L. Cañamero, Modeling motivations and emotions as a basis for intelligent behavior, in: W. Johnson, ed., *Proceedings of the International Conference on Autonomous Agents*, 1997.
- [41] L. Cañamero, Emotional and Intelligent: the tangled knot of cognition, *Technical Report FS-98-03*, Menlo Park, AAAI Press, 1998.
- [42] L. Cañamero, and J. Fredslund, I show you how I like you—can you read it in my face?, *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans* 31 (5) (2001).
- [43] L. Cañamero, ed. *Emotional and Intelligent II: the tangled knot of social cognition*, *Technical Report FS-01-02*, Menlo Park, AAAI Press, 2001.
- [44] L. Cañamero and P. Petta, eds., *Grounding Emotions in Adaptive Systems. Volumes I and II. Special Issue of Cybernetics and Systems: An International Journal*, 32 (5) and 32(6) (2001).
- [45] L. Cañamero, Designing emotions for activity selection in autonomous agents, in R. Trappl, P. Petta, S. Payr, eds., *Emotions in Humans and Artifacts*, Cambridge, MIT Press, 2003.
- [46] J. Cassell, Nudge, nudge, wink, wink: elements of face-to-face conversation for embodied conversational agents, in: J. Cassell et al., eds., *Embodied conversational agents*, Cambridge: MIT Press, 1999.
- [47] J. Cassell et al., eds., *Embodied conversational agents*, Cambridge, MIT Press.
- [48] R. Chellappa et al., Human and machine recognition of faces: a survey, in: *Proceedings of the IEEE* 83 (5), 1995.
- [49] R. Collins et al., A system for video surveillance and monitoring, *Technical Report CMU-RI-TR-00-12*, Robotics Institute, Carnegie Mellon University, 2000.

- [50] M. Cooper et al., Robots in the classroom—tools for accessible education, in: Proceedings of the 5th European Conference for the Advancement of Assistive Technology, 1999.
- [51] P. Coppin et al., Big Signal: information interaction for public telerobotic exploration, in: Proceedings of the Workshop on Current Challenges in Internet Robotics, IEEE International Conference on Robotics and Automation, 1999.
- [52] P. Coppin et al., EventScope: a telepresence interface for internet-based education, in: Proceedings of the Workshop on Telepresence for Education, IEEE International Conference on Robotics and Automation, 2002.
- [53] M. Coulson, Expressing emotion through body movement: a component process approach, in: R. Aylett and L. Cañamero, eds., Animating Expressive Characters for Social Interactions, SSAISB Press, 2002.
- [54] J. Crowley, Vision for man-machine interaction, Robotics and Autonomous Systems 19 (1997).
- [55] C. Darwin, The expression of emotions in man and animals, Oxford University Press, Oxford, 1998.
- [56] K. Dautenhahn, Getting to know each other—artificial social intelligence for autonomous robots, Robotics and Autonomous Systems 16 (1995).
- [57] K. Dautenhahn, I could be you - the phenomenological dimension of social understanding, Cybernetics and Systems Journal 28 (5) (1997).
- [58] K. Dautenhahn, The art of designing Socially Intelligent Agents - science, fiction, and the human in the loop, Special Issue on “Socially Intelligent Agents”, Applied Artificial Intelligence Journal 12 (7-8) (1998).
- [59] K. Dautenhahn, Embodiment and interaction in socially intelligent life-like agents, in: C. Nehaniv, ed., Lecture Notes in Artificial Intelligence 1562, Springer 1999.
- [60] K. Dautenhahn, Socially intelligent agents and the primate social brain—Towards a science of social minds, in: Proceedings of the AAAI Fall Symposium on Socially Intelligent Agents—The Human in the Loop, 2000.
- [61] K. Dautenhahn, Roles and functions of robots in human society - implications from research in autism therapy, in: D. McFarland, ed. (guest), Special issue on Biological Robotics, Robotica (2003).
- [62] K. Dautenhahn, Design spaces and niche spaces of believable social robots, in: Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication, 2002.
- [63] K. Dautenhahn and A. Billard, Bringing up robots or - the psychology of socially intelligent robots: from theory to implementation, in: Proceedings of Autonomous Agents, 1999.
- [64] K. Dautenhahn and A. Billard, Studying robot social cognition within a developmental psychology framework, in: Proceedings of the Third European Workshop on Advanced Mobile Robots, 1999.
- [65] K. Dautenhahn and A. Billard, Games Children with Autism Can Play With Robota, a Humanoid Robotic Doll, Proceedings of the 1st Cambridge Workshop on Universal Access and Assistive Technology, in: S. Keates et al., eds., Universal Access and Assistive Technology, Springer-Verlag, London, 2002.
- [66] K. Dautenhahn and C. Nehaniv, Living with socially intelligent agents: a cognitive technology view, in: K. Dautenhahn, ed., Human Cognition and Social Agent Technology, John Benjamins Publishing Company, 2000.
- [67] K. Dautenhahn and C. Nehaniv, eds., Imitation in Animals and Artifacts, MIT Press, 2001.
- [68] K. Dautenhahn and I. Werry, Issues of Robot-Human Interaction Dynamics in the Rehabilitation of Children with Autism, in: Proceedings of From Animals to Animats, The Sixth International Conference on the Simulation of Adaptive Behavior, 2000.
- [69] K. Dautenhahn and I. Werry, A quantitative technique for analysing robot-human interactions, in: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, 2002.
- [70] K. Dautenhahn, B. Ogden, and T. Quick, From embodied to socially embedded agents - implications for interaction-aware robots, Special

- issue on Situated and Embodied Cognition, *Cognitive Systems Research* 3 (3) (2002).
- [71] K. Dautenhahn, I. Werry, J. Rae, P. Dickerson, P. Stribling, and B. Odgen, Robotic playmates: Analysing interactive competencies of children with autism playing with a mobile robot, in: K. Dautenhahn et al, *Socially Intelligent Agents: Creating Relationships with Computers and Robots*, Kluwer Academic Publishers, 2002.
- [72] D. Dennett, *The Intentional Stance*, Cambridge, Massachusetts, MIT Press, 1987.
- [73] J. Demiris and G. Hayes, Imitative learning mechanisms in robots and humans, in: *Proceedings of the 5th European Workshop on Learning Robots*, 1996.
- [74] J. Demiris and G. Hayes, Active and passive routes to imitation, in: *Proceedings of the AISB Symposium on Imitation in Animals and Artifacts*, 1999.
- [75] J.-L. Deneubourg et al., The dynamic of collective sorting robot-like ants and ant-like robots, in: *Proceedings of From Animals to Animats, The Fifth International Conference on the Simulation of Adaptive Behavior*, 2000.
- [76] C. DiSalvo et al., All robots are not equal: The design and perception of humanoid robot heads, in: *Proceedings of the Conference on Designing Interactive Systems*, 2002.
- [77] A. Druin and J. Hendler, Robots for kids: exploring new technologies for learning, *The Morgan Kaufmann Series in Interactive Technologies*, Morgan Kaufmann, 2000.
- [78] B. Duffy, Anthropomorphism and the social robot, *Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems* 42 (3-4) (2003).
- [79] P. Ekman and W. Friesen, Measuring facial movement with the Facial Action Coding System, In *Emotion in the Human Face*, Cambridge University Press, 1982.
- [80] P. Ekman, Basic emotions, in: T. Dalgleish and M. Power, eds., *Handbook of Cognition and Emotion*, New York, Wiley, 1999.
- [81] C. Elliot, *The Affective Reasoner: A Process Model of Emotions in a Multi-Agent System*. Ph.D. thesis, The Institute for the Learning Sciences Technical Report No. 32, Northwestern University, 1992.
- [82] E. Falcone et al., The personal rover project, *Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems* 42 (3-4) (2003).
- [83] B. Fogg, Introduction: persuasive technologies, *Communications of the ACM* 42 (5) (1999).
- [84] T. Fong, C. Thorpe, and C. Baur, Collaboration, dialogue, and human-robot interaction, in: *Proceedings of the 10th International Symposium on Robotics Research*, Springer, 2001.
- [85] T. Fong, C. Thorpe, and C. Baur, Robot, asker of questions, *Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems* 42 (3-4) (2003).
- [86] N. Frijda, *The Emotions*, Cambridge, Cambridge University Press, 1968.
- [87] N. Frijda, Recognition of emotion, *Advances in Experimental Social Psychology* 4 (1969).
- [88] T. Fromherz, P. Stucki, and M. Bichsel, A survey of face recognition, *MML Technical Report 97.01*, Department of Computer Science, University of Zurich, 1997.
- [89] M. Fujita and H. Kitano Development of an autonomous quadruped robot for robot entertainment, *Autonomous Robots* 5 (1998).
- [90] M. Fujita, S. Zrehen, and H. Kitano, A quadruped robot for RoboCup legged robot challenge in Paris '98, *Lecture Notes in Computer Science* 1604, Springer-Verlag, 1999.
- [91] M. Fujita et al., Experimental results of an emotionally grounded symbol acquisition by four-legged robot, in: J. Muller, ed., *Proceedings of Autonomous Agents*, 2001.
- [92] S. Gadanho and J. Hallam, Emotion-triggered learning in autonomous robot control, *Cybernetics and Systems* 32 (5) (2001).
- [93] B. Galef, Imitation in animals: history, definition, and interpretation of data from the psychological

- laboratory, in: *Social Learning: Psychological and Biological Perspectives*, Hillsdale, New Jersey, Lawrence Erlbaum Associates, 1988.
- [94] P. Gaussier et al., From perception-action loops to imitation processes: a bottom-up approach of learning by imitation, *Applied Artificial Intelligence Journal* 12 (7-8), (1998)
- [95] D. Gavrilla, The visual analysis of human movement: A survey. *Computer Vision and Image Understanding* 73 (1) (1999).
- [96] D. Gentner and J. Grudin, Why good engineers (sometimes) create bad interfaces, in: *Proceedings of CHI '90: Empowering People*, 1990.
- [97] J. Goetz and S. Kiesler, Cooperation with a robotic assistant, in: *Proceedings of Computer-Human Interaction*, 2002.
- [98] D. Goldberg and M. Mataric, interference as a tool for designing and evaluating multi-robot controllers, in: *Proceedings AAAI*, 1997.
- [99] D. Goren-Bar. Designing model-based intelligent dialogue systems. In Rossi, M., and Siau, K., eds. *Information Modeling in the New Millennium*, London, Idea Group, 2001.
- [100] E. Hall, *The hidden dimension: man's use of space in public and private*, London, The Bodley Head Ltd, 1966.
- [101] F. Hara, Personality characterization of animate face robot through interactive communication with human, in: *Proceedings of the 1998 International Advanced Robotics Program*, 1998.
- [102] C. Heyes and B. Galef, *Social learning in animals: the roots of culture*, Academic Press, 1996.
- [103] G. Hayes and J. Demiris, A robot controller using learning by imitation, in: *Proceedings of the Second International Symposium of Intelligent Robotic Systems*, 1994.
- [104] O. Holland, Grey Walter: the pioneer of real artificial life, in: C. Langton, K. Shimohara, eds., *Proceedings of the 5th International Workshop on Artificial Life*, Cambridge, MIT Press.
- [105] Honda, Honda debuts new humanoid robot: Asimo, Press release, 20 November 2000, Honda Corporation, 2000.
- [106] E. Hudlicka, Increasing SIA architecture realism by modeling and adapting to affect and personality. In K. Dautenhahn et al., eds., *Socially Intelligent Agents: Creating Relationships with Computers and Robots*, Kluwer, 2002.
- [107] H. Huttenrauch and K. Severinson-Eklund, Fetch-and-carry with CERO: observations from a long-term user study, in: *Proceedings of the IEEE International Workshop on Robot and Human Communication*, 2002.
- [108] F. Iida et al., Generating Personality Character in a Face Robot through Interaction with Human, in: *Proceedings of 7th IEEE International Workshop on Robot and Human Communication*, 1998.
- [109] F. Iida et al., Behavior learning of Face Robot using human natural instruction, in: *Proceedings of the IEEE International Workshop on Robot and Human Communication*, 1999.
- [110] iRobot, Hasbros MY REAL BABY arrives at retail, Press Release, 20 November 2000, iRobot Corporation, 2000.
- [111] H. Ishiguro et al. Robovie: an interactive humanoid robot, *Int. J. Industrial Robotics*, 28 (6) (2001).
- [112] O. John, The 'Big Five' factor taxonomy: dimensions of personality in the natural language and in questionnaires, in: L. Pervin, ed., *Handbook of personality: theory and research*, New York, Guilford, 1990.
- [113] F. Kaplan et al., Taming robots with clicker training: a solution for teaching complex behaviors, in: *Proceedings of the 9th European Workshop on Learning Robots*, 2001.
- [114] T. Kemper, Social Models in the explanation of emotions, in: M. Lewis and J. Haviland-Jones, eds., *The Handbook of Emotions* (2nd ed.), New York, The Guilford Press, 2000.
- [115] Z. Khan, Attitudes towards intelligent service robots, Technical report TRITA-NA-P9821, NADA, KTH, Stockholm, Sweden, 1998.
- [116] S. Kiesler and J. Goetz, Mental models and cooperation with robotic assistants, in: *Proceedings of Computer-Human Interaction*, 2002.

- [117] H. Kitano et al., Sony legged robot for RoboCup challenge, in: Proceedings of the IEEE International Conference on Robotics and Automation, 1998.
- [118] R. Kjeldsen and J. Hartman, Design issues for vision-based computer interaction systems, in: Proceedings of ACM Perceptual User Interfaces, 2001.
- [119] V. Klingspor, J. Demiris and M. Kaiser, Human-Robot-Communication and Machine Learning, Applied Artificial Intelligence Journal 11 (1997).
- [120] H. Kobayashi, F. Hara, and A. Tange, A basic study on dynamic control of facial expressions for face robot, in: Proceedings of the IEEE International Workshop on Robot and Human Communication, 1994.
- [121] H. Kozima, Infanoid: an experimental tool for developmental psycho-robotics, in: Proceedings of the International Workshop on Developmental Study, 2000.
- [122] H. Kozima and H. Yano, In search of otogenetic prerequisites for embodied social intelligence, in: Proceedings of the Workshop on Emergence and Development of Embodied Cognition, International Conference on Cognitive Science, 2001.
- [123] H. Kozima and H. Yano, A robot that learns to communicate with human caregivers, in: Proceedings of the International Workshop on Epigenetic Robotics, 2001.
- [124] H. Kozima and J. Zlatev, An epigenetic approach to human-robot communication, in: Proceedings of the International Workshop on Robot and Human Interactive Communication, 2000.
- [125] Kopp and Gardenfors, Attention as a Minimal Criterion of Intentionality in Robots, Lund University Cognitive Studies 89, 2001.
- [126] D. Kortenkamp, E. Huber, and P. Bonasso, Recognizing and interpreting gestures on a mobile robot, in: Proceedings of AAAI, 1996.
- [127] R. Krauss, P. Morrel-Samuels, and C. Colasante. Do conversational hand gestures communicate? Journal of personality and social psychology 61 (1991).
- [128] H. Krebs, B. Volpe, M. Aisen, N. Hogan, Increasing productivity and quality of care: robot-aided neurorehabilitation, Journal of Rehabilitation Research and Development 37 (6) (2000).
- [129] M. Krieger, J.-B. Billeter, and L. Keller, Ant-like task allocation and recruitment in cooperative robots, Nature 406 (6799) (2000).
- [130] C. Kube and E. Bonabeau, Cooperative transport by ants and robots, Robotics and Autonomous Systems 30 (1-2) 2000.
- [131] Y. Kuniyoshi et al., Learning by watching: extracting reusable task knowledge from visual observation of human performance, IEEE Transactions on Robotics and Automation 10(6) (1994).
- [132] M. Lansdale and T. Ormerod. Understanding Interfaces, London, Academic Press, 1994.
- [133] S. Lauria et al., Mobile robot programming using natural language, Robotics and Autonomous Systems 38 (3-4) (2002).
- [134] V. Lee and P. Gupta, Children's cognitive and language development, Blackwell, 1995.
- [135] H. Lim, A. Ishii, and A. Takanishi, Basic emotional walking using a biped humanoid robot, in: Proceedings of IEEE SMC, 1999.
- [136] C. Lisetti and D. Schiano, Automatic facial expression interpretation: where human-computer interaction, artificial intelligence, and cognitive science intersect, 2000.
- [137] K. Lorenz, The foundations of ethology, Springer-Verlag, 1981.
- [138] C. Lueg, Information seeking as socially situated activity, in: Proceedings of the Workshop Research Directions in Situated Computing, ACM SIGCHI Conference on Human Factors in Computing Systems, 2000.
- [139] Y. Marom and G. Hayes, Preliminary approaches to attention for social learning, Informatics Research Report EDI-INF-RR-0084, University of Edinburgh, 1999.
- [140] Y. Marom and G. Hayes, Attention and social situatedness for skill acquisition, Informatics Research Report EDI-INF-RR-0069, University of Edinburgh, 2001.

- [141] Y. Marom and G. Hayes, Interacting with a robot to enhance its perceptual attention, Informatics Research Report EDI-INF-RR-0085, University of Edinburgh, 2001.
- [142] D. Massaro, Perceiving talking faces: from speech perception to behavioural principles, MIT Press, 1998.
- [143] M. Mataric, Learning to behave socially, in: Proceedings of the Third International Conference on Simulation of Adaptive Behavior, 1994.
- [144] M. Mataric, Issues and approaches in design of collective autonomous agents, Robotics and Autonomous Systems 16 (1995).
- [145] M. Mataric et al., Behavior-based primitives for articulated control, in: Proceedings of the International Conference on Simulation of Adaptive Behavior, 1998.
- [146] T. Matsui et al., Integrated natural spoken dialogue system of Jijo-2 mobile robot for office services, in: Proceedings of AAAI, 1999.
- [147] Y. Matsusaka and T. Kobayashi, Human interface of humanoid robot realizing group communication in real space, in: Proceedings of the Second International Symposium on Humanoid Robots, 1999.
- [148] B. Maxwell and L. Meeden, Integrating Robotics Research with Undergraduate Education, IEEE Intelligent Systems November/December (2000).
- [149] D. McNeill, Hand and mind: What gestures reveal about thought, Chicago: University of Chicago, 1992.
- [150] C. Melhuish, O. Holland and S. Hoddell, Collective sorting and segregation in robots with minimal sensing, in: R. Pfeifer et al., eds., Proceedings From Animals to Animats 5, MIT Press, 1998.
- [151] F. Michaud, Social intelligence and robotics, in: Proceedings of AAAI Fall Symposium on Social Intelligent Agents: The Human in the Loop, 2000.
- [152] F. Michaud and S. Caron, Roball – An autonomous toy-rolling robot, in: Proceedings of the Workshop Interactive Robot Entertainment, 2000.
- [153] F. Michaud et al., Artificial emotion and social robotics, in: Proceedings of the International Symposium on Distributed Autonomous Robotic Systems, 2000.
- [154] F. Michaud et al., Mobile robotic toys for autistic children, in: Proceedings PRECARN-IRIS International Symposium on Robotics (ISR), 2000.
- [155] F. Michaud et al., Designing robot toys to help autistic children – An open design project for Electrical and Computer Engineering education, in: Proceedings of the American Society for Engineering Education Conference, 2000.
- [156] F. Michaud et al., Dynamic robot formations using directional visual perception, in: Proceedings of the International Conference on Intelligent Robots and Systems, 2002.
- [157] . F. Michaud, D. Gutfason, The Hors d'Oeuvres Event at the AAAI-2001 Mobile Robot Competition, AI Magazine, 23 (1) (2002).
- [158] F. Michaud and C. Theberge-Turmel, Mobile robotic toys and autism: observation and interaction, in: K. Dautenhahn et al, Socially Intelligent Agents: Creating Relationships with Computers and Robots, Kluwer Academic Publishers, 2002.
- [159] H. Miwa et al., Robot personality based on the equations of emotion defined in the 3D mental space, in: Proceedings of the International Conference on Intelligent Robots and Systems, 2001.
- [160] H. Mizoguchi et al., Realization of expressive mobile robot, in: Proceedings of the International Conference on Robotics and Automation, 1997.
- [161] J. Montemayor, A. Druin, and J. Hendler, From Pets to Storyrooms: Constructive storytelling systems designed with children, for children, in: K. Dautenhahn et al, Socially Intelligent Agents: Creating Relationships with Computers and Robots, Kluwer Academic Publishers, 2002.
- [162] I Murray and J. Arnott, Towards the simulation of emotion in synthetic speech: A review of the literature on human vocal emotion, Journal of the Acoustic Society of America 93 (2) (1993).
- [163] I. Myers, Introduction to Type, Consulting Psychologists Press, Palo Alto, 1998.

- [164] T. Nakata et al., Expression of emotion and intention by robot body movement, in: Proceedings of International Autonomous Systems 5 (1998).
- [165] Y. Nakauchi and R. Simmons, A social robot that stands in line, in: Proceedings of the International Conference on Robots and Systems, 2000.
- [166] National/Panasonic, Matsushita develops robotic pet to aid senior citizens with communication, Press Release, 24 March 1999, Matsushita Corporation, 1999.
- [167] NEC, NEC develops friendly walkin talkin personal robot with human-like characteristics and expressions, Press Release, 21 March 2001, NEC Corporation, 2001.
- [168] W. Newman and M. Lamming, Interactive System Design, Addison-Wesley, 1995.
- [169] M. Nicolescu and M. Mataric, Learning and interacting in human-robot domains, IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans 31 (5) (2001).
- [170] D. Norman and S. Draper, eds.. User Centered System Design. Hillsdale, New Jersey, Lawrence Erlbaum Associates, 1986.
- [171] I. Nourbakhsh et al., An affective mobile robot educator with a full-time job. Artificial Intelligence 114 (1-2) (1999).
- [172] I. Nourbakhsh, Robotics and education in the classroom and in the museum: On the study of robots, and robots for study, in: Proceedings of the Workshop for Personal Robotics for Education, IEEE International Conference on Robotics and Automation, 2000.
- [173] T. Ogata and S. Sugano, Emotional communication robot: WAMOEB-2R - emotion model and evaluation experiments, in: Proceedings of the IEEE International Conference on Humanoid Robotics, 2000.
- [174] H. Okuno et al., Human-robot interaction through real-time auditory and visual multiple-talker tracking, in: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, 2001.
- [175] N. Oliver, B. Rosaroi and A. Pentland, A Bayesian computer vision system for modeling human interactions, Technical Report 459, Media Lab, MIT, 1999.
- [176] Omron, Is this a real cat? A robot cat you can bond with like a real pet – NeCoRo is born, News Release 16 October 2001, Omron Corporation, 2001.
- [177] A. Ortony, G. Clore, and A. Collins, The cognitive structure of emotions, Cambridge, Cambridge University Press, 1988.
- [178] S. Papert and I. Harel, Situating Constructionism, in: Constructionism, Ablex Publishing Corp., 1991.
- [179] A. Paiva, ed., Affective interactions: towards a new generation of computer interfaces, LNCS/LNAI 1914, Springer-Verlag, 2000.
- [180] J. Panksepp, Affective Neuroscience, Oxford University Press, 1998.
- [181] E. Paulos and J. Canny, Designing personal tele-embodiment, Autonomous Robots 11 (1) (2001).
- [182] V. Pavlovic, R. Sharma, and T. Huang, Visual interpretation of hand gestures for human-computer interaction: a review, IEEE Transactions on Pattern Analysis and Machine Intelligence 19 (7) (1997).
- [183] P. Persson et al., Understanding socially intelligent agents—a multilayered phenomenon, IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans 31 (5) (2001).
- [184] R. Pfeifer, On the role of embodiment in the emergence of cognition and emotion, in: Proceedings of the 13th Toyota Conference on Affective Minds, 1999.
- [185] S. Picault and A. Drogoul, Robots as social species: the MICRobES project, in: K. Dautenhahn, Ed., Socially Intelligent Agents: The Human in the Loop, Technical Report FS-00-04, AAAI Press, 2000.
- [186] R. Piccard, Affective computation, Cambridge, MIT Press, 1997.

- [187] J. Pineau et al., Towards robotic assistants in nursing homes: challenges and results, Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems 42 (3-4) (2003).
- [188] C. Plaisant, A. Druin, C. Lathan, K. K. Dakhane, Edwards, J. Vice, and J. Montemayor, A storytelling robot for pediatric rehabilitation, in: Proceedings of ASSETS, 2000.
- [189] R. Plutchik, Emotions: a general psychoevolutionary theory, in K. Scherer and P. Ekman, eds., Approaches to Emotion, Hillsboro, New Jersey, Lawrence Erlbaum Associates, 1984.
- [190] E. Prassler, J. Scholz, and P. Fiorini, A robotics wheelchair for crowded public environments, IEEE Robotics and Automation Magazine 8 (1) (2001).
- [191] L. Rabiner and B. Juang, Fundamentals of speech recognition, Englewood Cliffs, Prentice-Hall, 1993.
- [192] B. Reeves and C. Nass, The Media Equation, Stanford: CSLI Publications, 1996.
- [193] J. Reichard. Robots: fact, fiction, and prediction, New York, Viking Press, 1978.
- [194] W. Reilly, Believable social and emotional agents, Ph.D. Thesis, Computer Science, Carnegie Mellon University, 1996.
- [195] S. Restivo, Bringing up and booting up: social theory and the emergence of socially intelligent robots, in: Proceedings of the IEEE Conference on Systems, Man, and Cybernetics, 2001.
- [196] S. Restivo, Romancing the robots: social robots and society, in: Proceedings of Robot as Partner: An Exploration of Social Robots Workshop, International Conference on Intelligent Robots and Systems, 2002.
- [197] A. Rowe, C. Rosenberg, I. Nourbakhsh, CMUcam: a low-overhead vision system, in: Proc. Intl. Conf. Intel. Rob. Sys., 2002.
- [198] T. Rogers and M. Wilkes, The Human Agent: a work in progress toward human-humanoid interaction, in: Proceedings of the International Conference on Systems, Man, and Cybernetics, 2000.
- [199] A. Sage, Systems Engineering, New York, J. Wiley and Sons, 1992.
- [200] Y. Sakagami et al., The intelligent ASIMO: System overview and integration, in: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, 2002.
- [201] A. Samal and P. Iyengar, Automatic recognition and analysis of human faces and facial expressions: a survey, Pattern Recognition 25 (1992).
- [202] H. Schlossberg, Three dimensions of emotion. Psychological Review 61 (1954).
- [203] J. Searle, Minds, Brains and Science, Cambridge, Harvard University Press, 1984.
- [204] B. Scassellati, Investigating models of social development using a humanoid robot, in: Barbara Webb and Thomas Consi, eds., Biorobotics, Cambridge, MIT Press, 2000.
- [205] B. Scassellati, Foundations for a theory of mind for a humanoid robot, Ph.D. Thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 2001.
- [206] S. Schall, Robot learning from demonstration, in: Proceedings of the International Conference on Machine Learning, 1997.
- [207] M. Scheeff et al., Experiences with Sparky: a social robot, in: Proceedings of the Workshop Interactive Robot Entertainment, 2000.
- [208] J. Schulte et al., Spontaneous, short-term interaction with mobile robots in public places, in: Proceedings of the IEEE International Conference on Robotics and Automation, 1999.
- [209] K. Severinson-Eklund et al., Social and collaborative aspects of interaction with a service robot, Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems 42 (3-4) (2003).
- [210] T. Sheridan, Eight ultimate challenges of human-robot communication, in: Proceedings of the IEEE International Workshop on Robot and Human Communication, 1997.
- [211] T. Shibata et al., Emergence of emotional behavior through physical interaction between human and robot, in: Proceedings of the International Conference on Robotics and Automation, 1999.
- [212] T. Shibata et al., Mental commit robot and its application to therapy of children, in: Proceedings of the International Conference on AIM, 2001.

- [213] T. Shibata, K. Wada, and K. Tanie, Tabulation and analysis of questionnaire results of subjective evaluation of seal robot at science museum in London, in: Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication, 2002.
- [214] C. Sidner and M. Dzikovska, Hosting Activities: Experience with and Future Directions for a Robot Agent Host, Technical Report TR-2002-03, Mitsubishi Electric Research Laboratories, Cambridge, MA, 2002.
- [215] R. Siegwart et. al., RoboX @ Expo.02: A large scale installation of personal robots, Special Issue on Socially Interactive Robots, Robotics and Autonomous Systems 42 (3-4) (2003).
- [216] C. Smith and H. Scott, A componential approach to the meaning of facial expressions, in: J. Russell and J. Fernandez-Dols, eds., The Psychology of Facial Expression, Cambridge University Press, 1997.
- [217] R. Smith and S. Eppinger, A predictive model of sequential iteration in engineering design, Management Science, 43 (8) (1997).
- [218] D. Spiliotopoulos et al., Human-robot interaction based on spoken natural language dialogue, in: Proceedings of the European Workshop on Service and Humanoid Robots, 2001.
- [219] L. Steels, Emergent adaptive lexicons, in: Proceedings of the International Conference on Simulation of Adaptive Behavior, 1996.
- [220] L. Steels, AIBO's first words. The social learning of language and meaning, in: H. Gouzoules, ed., Evolution of Communication 4(1), Amsterdam, John Benjamins Publishing Company, 2001.
- [221] L. Steels, Language games for autonomous robots, IEEE Intelligent Systems 16 (5) (2001).
- [222] C. Stein, Botball: Autonomous students engineering autonomous robots, in: Proceedings of the ASEE Conference, 2002.
- [223] R. Stiefelhagen, J. Yang and A. Waibel, Tracking focus of attention for human-robot communication, in: Proceedings of the IEEE-RAS International Conference on Humanoid Robots, 2001.
- [224] K. Suzuki et al., Intelligent agent system for human-robot interaction through artificial emotion, in: Proceedings of the IEEE SMC, 1998.
- [225] R. Tanawongsuwan et al., Robust tracking of people by a mobile robotic agent, Technical Report GIT-GVU-99-19, Georgia Institute of Technology, Atlanta, Georgia, 1999.
- [226] T. Tashima et al., Interactive pet robot with emotion model, in: Proceedings of the 16th Annual Conference of the Robot Society of Japan, 1998.
- [227] L. Terveen. An overview of human-computer collaboration, Knowledge-Based Systems 8 (2-3) (1994).
- [228] F. Thomas and O. Johnston, Disney animation: the illusion of life, New York, Abbeville Press, 1981.
- [229] W. Thorpe, Learning and instinct in animals, London, Methuen, 1963.
- [230] S. Thrun et al., Probabilistic algorithms and the interactive museum tour-guide robot Minerva, International Journal of Robotics Research 19 (11) (2000).
- [231] K. Toyama, Look, Ma - No Hands! Hands-free cursor control with real-time 3D face tracking, in: Proceedings of the Workshop on Perceptual User Interfaces, 1998.
- [232] M. Trivedi, K. Huang and I. Miki, Intelligent environments and active camera networks, IEEE Systems, Man and Cybernetics, 2000.
- [233] R. Vaughan, K. Stoey, G. Sukhatme, and M. Mataric, Go ahead, make my day: robot conflict resolution by aggressive competition, in: Proceedings of From Animals to Animats, The Sixth International Conference on the Simulation of Adaptive Behavior, 2000.
- [234] J. Velasquez, Modeling emotions and other motivations in synthetic agents, in: Proceedings of the Fourteenth National Conference on Artificial Intelligence, 1997.
- [235] J. Velasquez, A computational framework for emotion-based control, in: Proceedings of the workshop on grounding emotions in adaptive systems, Conference on Simulation of Adaptive Behavior, 1998.

- [236] K. Wada, T. Shibata, T. Saito, and K. Tanie, Analysis of Factors that Bring Mental Effects to Elderly People in Robot Assisted Activity, in: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, 2002.
- [237] K. Wada, T. Shibata, T. Saito, and K. Tanie, Robot Assisted Activity for Elderly People and Nurses at a Day Service Center, in: Proceedings of the IEEE International Conference on Robotics and Automation, 2002.
- [238] S. Waldherr, R. Romero and S. Thrun, A gesture-based interface for human-robot interaction, *Autonomous Robots* 9 (2000).
- [239] S. Weir and R. Emanuel, Using Logo to catalyse communication in an autistic child, DAI Research Report No. 15, University of Edinburgh, 1976.
- [240] I. Werry et al., Can social interaction skills be taught by a social agent? The role of a robotic mediator in autism therapy, in: Proceedings of the Fourth International Conference on Cognitive Technology, 2001.
- [241] A. Whiten, *Natural theories of mind*, Oxford, Basil Blackwell, 1991.
- [242] D. Wilkes, A. Alford, R. Pack, T. Rogers, R. Peters II, and K. Kawamura, Toward socially intelligent service robots, *Applied Artificial Intelligence* 12 (7-8) (1998).
- [243] T. Willeke et al., The history of the mobot museum robot series: an evolutionary study, in: Proceedings of FLAIRS, 2001.
- [244] D. Woods, Decomposing automation: apparent simplicity, real complexity, in: *Automation and Human Performance: Theory and Applications*, R. Parasuraman and M. Mouloua, eds. Mahwah, New Jersey, Lawrence Erlbaum Associates 1996.
- [245] Y. Wu and T. Huang, Vision-based gesture recognition: a review, *Lecture Notes in Computer Science* 1739, *Gesture-Based Communication in Human-Computer Interaction*, 1999.
- [246] G. Xu et al., Toward robot guidance by hand gestures using monocular vision, in: Proceedings of the IEEE Hong Kong Symposium on Robotics and Control, 1999.
- [247] S. Yoon et al., Motivation driven learning for interactive synthetic characters, in: Proceedings of the Fourth International Conference on Autonomous Agents, 2000.
- [248] J. Zlatev, The epigenesis of meaning in human beings and possibly in robots, *Lund University Cognitive Studies* 79, Lund, University, 1999.



Terrence Fong is a joint postdoctoral fellow at Carnegie Mellon University (CMU) and the Swiss Federal Institute of Technology / Lausanne (EPFL). He received his Ph.D. (2001) in Robotics from CMU. From 1990 to 1994, he worked at the NASA Ames Research Center, where he was co-investigator for virtual environment telerobotic field experiments. His research interests include human-robot interaction, PDA and Web-based interfaces, and field mobile robots.



Illah Nourbakhsh is an Assistant Professor of Robotics at Carnegie Mellon University (CMU) and is co-founder of the Toy Robots Initiative at The Robotics Institute. He received his Ph.D. (1996) degree in computer science from Stanford. He is a founder and chief scientist of Blue Pumpkin Software, Inc. and Mobot, Inc. His current research projects include robot learning, believable robot personality, visual navigation and robot locomotion.



Kerstin Dautenhahn is a Reader in Artificial Intelligence in the Computer Science Department at University of Hertfordshire, where she also serves as coordinator of the Adaptive Systems Research Group. She received her doctoral degree in natural sciences from the University of Bielefeld. Her research lies in the areas of socially intelligent agents and HCI, including virtual and robotic agents. She has served as guest editor for numerous special journal issues in AI, cybernetics, artificial life, and recently co-edited the book “Socially Intelligent Agents – Creating relationships with Computers and Robots”.