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# KASPAR – a minimally expressive humanoid robot for human–robot interaction research

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This paper provides a comprehensive introduction to the design of the minimally expressive robot KASPAR, which is particularly suitable for human–robot interaction studies. A low-cost design with off-the-shelf components has been used in a novel design inspired from a multi-disciplinary viewpoint, including comics design and Japanese Noh theatre. The design rationale of the robot and its technical features are described in detail. Three research studies will be presented that have been using KASPAR extensively. Firstly, we present its application in robot-assisted play and therapy for children with autism. Secondly, we illustrate its use in human–robot interaction studies investigating the role of interaction kinesics and gestures. Lastly, we describe a study in the field of developmental robotics into computational architectures based on interaction histories for robot ontogeny. The three areas differ in the way as to how the robot is being operated and its role in social interaction scenarios. Each will be introduced briefly and examples of the results will be presented. Reflections on the specific design features of KASPAR that were important in these studies and lessons learnt from these studies concerning the design of humanoid robots for social interaction will also be discussed. An assessment of the robot in terms of utility of the design for human–robot interaction experiments concludes the paper.

**Keywords:** humanoid robots; minimally expressive robot; human–robot interaction; social interaction

## 1. Introduction

A key interest in our research group concerns human–robot interaction research; see Fong et al. (2003), Dautenhahn (2007), Goodrich and Schultz (2008) for introductory material of this research field. One of the most challenging open issues is how to design a robot that is suitable for human–robot interaction research, whereby suitability not only concerns the technical abilities and characteristics of the robot but, importantly, its perception by people who are interacting with it. Their acceptance of the robot and willingness to engage with the robot will not only fundamentally influence the outcome of human–robot interaction experiments but will also impact the acceptance of any robots designed for use in human society as companions or assistants (Dautenhahn et al. 2005; Dautenhahn 2007). Will people find a machine with a human appearance or the one that interacts in a human-like manner engaging or frightening? If a face is humanoid, what level of realism is suitable? Different studies have independently shown the impact of robot appearance on people's behaviour towards robots, expectation from and opinions about robots; see Walters (2008a) and Walters et al. (2008b) for in-depth discussions. Lessons learnt from the literature indicate that a humanoid appearance can support enjoyable and successful human–robot interaction; however, the degree of human-likeness required for a certain task/context etc. remains unclear.

In contrast to various approaches trying to build robots as visual copies of humans, so-called 'android' research (MacDorman and Ishiguro 2006), or research into designing versatile high-tech humanoid robots with dozens of degrees of freedom (DoFs) in movement and expression (cf. the iCub humanoid robot, Sandini et al. 2004), the approach we adopted is that of a humanoid, but minimally expressive, robot called KASPAR[1] that we built in 2005 and have modified and upgraded since then (see Figure 1). Our key aim was to build a robot that is suitable for different human–robot interaction studies. This paper describes the design and use of the robot.

In order to clarify concepts that are important to the research field of human–robot interaction, the following definitions of terms that are being employed frequently in this paper will be used[2]:

*Socially interactive robots* (Fong et al. 2003): Robots for which social interaction plays a key role, different from other robots in human–robot interaction that involve teleoperation scenarios.

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[1]KASPAR: Kinesics and Synchronization in Personal Assistant Robotics.
[2]Other related definitions relevant to the field of human–robot interaction and social robotics are discussed in Dautenhahn (2007).

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Figure 1. The minimally expressive humanoid robot KASPAR designed for social interaction.

*Humanoid robots, humanoids* (based on Gong and Nass 2007): "A robot which is not realistically human-like in appearance and is readily perceived as a robot by human interactants. However, it will possess some human-like features, which are usually stylised, simplified or cartoon-like versions of the human equivalents, including some or all of the following: a head, facial features, eyes, ears, eyebrows, arms, hands and legs. It may have wheels for locomotion or use legs for walking" (Walters et al. 2008b, p. 164).

Of specific interest to the present paper are humanoid robots with faces. Generally these can range from abstract/cartoon-like to near-to-realistic human-like faces. Section 2.2.2 discusses in more detail the design space of robot faces and Section 3 motivates our decision for a *minimally expressive* face.

This paper has been structured as follows: Section 2 provides an introduction to important issues in the design of robots and robot faces, in particular with respect to the design space of robots and how people perceive and respond to faces. Related work and design issues discussed in the literature are critically reflected upon. Section 3 describes the issues and rationale behind the design of minimally expressive humanoids in general and KASPAR in particular, and provides construction details regarding the current versions of the robot used in research. Section 4 illustrates its use in a variety of projects covering the spectrum from basic research to more application-oriented research in assistive technology. Human–robot interaction studies with KASPAR are summarised and discussed in the light of KASPAR's design features. The conclusion (Section 5) reflects upon our achievements and provides a conceptual assessment of KASPAR's strengths and weaknesses.

## 2. Robot design for interaction

This section reflects in more detail on issues regarding the appearance of a robot in the context of human–robot interaction and how people perceive faces (robotic or human). Related work on designing socially interactive research platforms will be discussed. Note, we do not discuss in detail the design of commercially available robots since usually little or nothing is made public about the details or rationale of the design. An example of such robots is the Wakamaru (Mitsubishi Heavy Industries), which has been designed to 'live with humans'. Unfortunately only brief, online information has been provided about the design rationale, hinting at the importance of expressiveness in the eyes, mouth and eyebrows (Wakamaru 2009).

Thus, for a more detailed comparison of the design rationale of KASPAR with other robots, we focus our discussion of related work on other *research* platforms.

### *2.1. The design space of humanoid robots*

The effect of the aesthetic design of a robot is an area that has often been neglected, and only in visual science fiction media or recently with the advent of commercial household robots has it been paid much attention. A notable exception is the 'uncanny valley' proposed by Masahiro Mori (Mori

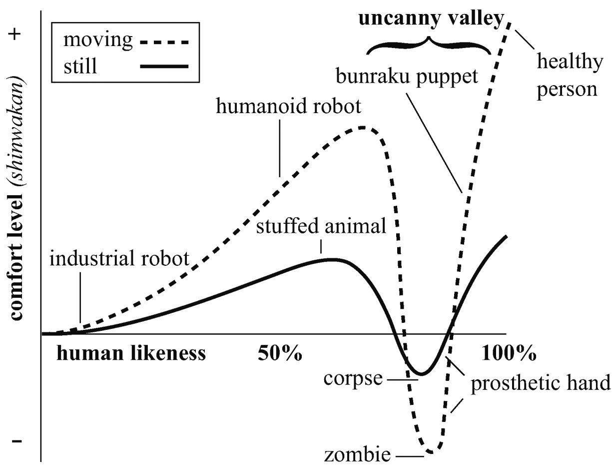


Figure 2. The uncanny valley (MacDorman et al. 2009).

1970). Mori proposed that the acceptance of a humanoid robot increases as realism increases, up to a point where, as the robot approaches perfect realism, the effect becomes instead very disturbing and acceptance decreases sharply because the robot starts to look not quite human or at worst like a moving corpse (see Figure 2 to illustrate the 'uncanny valley'). In theory the realism of both appearance and movement can give rise to this effect, with movement evoking the stronger response. It is possible that there may also be 'behavioural uncanniness' affecting perception of a robot during social interaction and governed by (among other things) the appropriateness and timing of its responses to social cues. However, little empirical data exists to support Mori's theory and opinions vary as to the strength of the effect and its longevity; see MacDorman (2005a) and MacDorman et al. (2005b) for recent works on the uncanny valley.

Previous work has identified a number of issues that are important in the design of robots meant to socially interact with people (Dautenhahn 2004). A full review of the technical and theoretical aspects of different robot designs in the field of humanoid robotics would go beyond the scope of this paper; therefore we discuss in the following paragraphs in more detail the key design features of the robot Kismet. Both Kismet and KASPAR have been specifically designed for human–robot interaction and, importantly, detailed information about the design rationale of Kismet is available in the research literature.

When Breazeal (2002) designed Kismet, which '... is designed to have an infant-like appearance of a fanciful robotic creature' (p. 51), with a youthful and appealing appearance, her intention was not to rival but rather to connect to the social competence of people. Furthermore, she incorporated key features in the robot that are known to elicit nurturing responses, as well as other non-humanoid features (e.g. articulated ears), in conjunction with exaggerated, cartoon-like, believable expressions. The overall cartoon-like appearance of the robot took advantage of people's liking and familiarity with cartoon characters. The overall design has been very successful: 'As a result, people tend to intuitively treat Kismet as a very young creature and modify their behavior in characteristic baby-directed ways' (Breazeal 2002, p. 51). However, it should be noted that the robot has never been used in any task-oriented scenarios that involve the manipulation of objects due to the fact that it does not have any manipulation abilities. The overall design is based on the assumption that people *are eager* to interact with the robot in the role of a caretaker. We contend that while this may be an appropriate approach for entertainment purposes, it is unclear how this design approach of a 'robotic pet/baby' would apply to work that is oriented towards robots as assistants or companions (see a detailed discussion of these two different approaches in Dautenhahn 2007). Note, Kismet was an expensive laboratory prototype, and to run its sophisticated perception and control software required more than 10 networked PCs.

In Breazeal and Foerst (1999) several of Kismet's design guidelines are presented for achieving human–infant like interactions with a humanoid robot; however, the underlying basic assumption here is 'the human as a caretaker', so some, but not all, of these guidelines are relevant for this paper. We now discuss these guidelines in relation to the specific approach that we took with the design of our humanoid robot KASPAR.

*Issue I*: 'The robot should have a cute face to trigger the 'baby-scheme' and motivate people to interact with it, to treat it like an infant, and to modify their own behavior to play the role of the caregiver (e.g. using motherese, exaggerated expressions and gestures)'.

Cuteness of the robot is not a key issue in the design rationale of our robot KASPAR because we did not envisage human–infant caretaker interactions. On the contrary, our goal was to have a robot that people may relate to in different ways, depending on the particular context of use and application domain.

*Issue II*: 'The robot's face needs several degrees of freedom to have a variety of different expressions, which must be understood by most people. Its sensing modalities should allow a person to interact with it using natural communication channels'.

Our approach partly agrees with the view on this issue; however, we focused on what we call a *minimally expressive face* with few expressions and few sensors in order to emphasise the most *salient* human-like cues of the robot. Rather than trying to make a robot very human-like, our goal was to concentrate on a few salient behaviours, gestures and facial expressions in order to run experiments that systematically study the influence of each of these cues on the interaction with people. Note, while Kismet also includes some cues that are zoomorphic but not anthropomorphic (e.g. articulated ears), the design of KASPAR's face focused on human-like features alone in order not to violate the aesthetic consistency.

*Issue III*: 'The robot should be pre-programmed with the basic behavioral and proto-social responses of infants. This includes giving the robot the ability to dynamically engage a human in social [interaction]. Specifically, the robot must be able to engage a human in proto-dialogue exchanges'.

Our approach uses an emphasis on non-verbal interaction without any explicit verbal 'dialogue'. We are interested in the *emergence* of gesture communication from human–robot interaction dynamics. Also, rather than solely building a research prototype for the laboratory, our aim was to have a robot that can be used in different application areas, including its use in schools, and under different methods of control (remote control of the robot as well as autonomous behaviour).

*Issue IV*: 'The robot must convey intentionality to bootstrap meaningful social exchanges with the human. If the human can perceive the robot as a being "like-me", the human can apply her social understanding of others to predict and explain the robot's behavior. This imposes social constraints upon the caregiver, which encourages her to respond to the robot in a consistent manner. The consistency of these exchanges allows the human to learn how to better predict and influence the robot's behavior, and it allows the robot to learn how to better predict and influence the human's behavior'.

The above is again very specific to the infant–caretaker relationship that Kismet's design is based upon. Rather than a 'like-me' perception of the robot we targeted a design that allows a variety of interpretations of character and personality on the robot (which might be termed 'it could be me' – see Dautenhahn 1997). Below we discuss this issue in more detail in the context of the design space of faces.

*Issue V*: 'The robot needs regulatory responses so that it can avoid interactions that are either too intense or not intense enough. The robot should be able to work with the human to mutually regulate the intensity of interaction so that it is appropriate for the robot at all times'.

*Issue VI*: 'The robot must be programmed with a set of learning mechanisms that allow it to acquire more sophisticated social skills as it interacts with its caregiver'.

Issues V and VI as discussed by Breazeal and Foerst relate specifically to the programming of the robot. For KASPAR we did not aim at a 'pre-programmed' robot but intended to build an open platform that would allow the development of a variety of different controllers and algorithms.

Other related work on humanoid robots includes the Lego robot Feelix (Cañamero 2002) that reacts to tactile stimulation by changing its facial expression. Feelix follows a similar design approach as Kismet, i.e. using exaggerated features, but a low-cost approach with commercially available Lego components. The humanoid robot Robota (Billard et al. 2006) has been designed as a toy for children and used in various projects involving imitation, interaction and assistive technology (Robins et al. 2004a, 2004b, 2005b). The key movements of this robot in these studies include turning of the head (left and right movements) and lifting of arms and legs (up and down movements of the whole limbs). Facial expressiveness or the generation of more complex gestures was not possible. The design considerations of Robota (see Figure 3) addressed in (Billard et al. 2006) include the following:

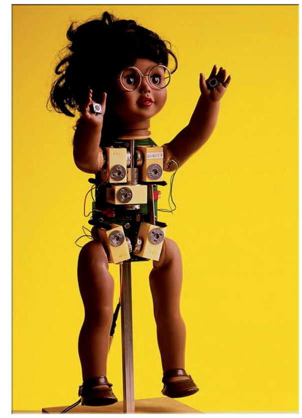

Figure 3. Robota (Billard et al. 2006).

1. *Ease of Set-up*: This concerns the ease of setting up sessions, e.g., in schools, and favours a light-weight, small-sized and low-cost robot with on-board processing and battery power.

Note, the above design consideration applies generally to all robots that are meant to be used in different locations where they have to be brought 'in and out' quickly, different from a robot that relies on a sophisticated laboratory set-up (such as above-mentioned Kismet). Since the robot whose design we were undertaking was also meant to be suitable for school applications, it was important for us, too, to keep the costs down. We decided that the price of the robot should be comparable to that of a laptop.

2. *Appearance and behaviour*: This criterion concerns the human-likeness in the appearance of the robot. Robota had a static face (from a toy doll), so it included some human-like features. A doll-like appearance was also considered to be 'child-friendly'. Billard et al. (2006) argued that taking a doll as a basis would help to integrate the robot in natural play environments.

The above design considerations are consistent with our approach to the design of KASPAR, where we used a mannequin as the basis of the 'body' of the robot; however, we replaced the head (including the neck) and designed a minimally expressive robot. Thus, while the design of KASPAR started before Billard et al.'s publication of design guidelines (2006), several key aspects are common.

Other research groups have studied the design of robots for 'child's play', including Michaud et al. (2003) who discuss design guidelines for children with autism but with an emphasis on mobile robots and playful interactions as related to the robot's behaviour, focusing primarily on non-humanoid robots. This work indicates that the design space of robots is vast, and, depending on the actual user groups and requirements as well as individual needs and preferences, different designs may be favourable. Different from this work, in the context of this paper we focus on minimally expressive humanoid robots, suitable for human–robot interaction experiments in assistive technology as well as developmental robotics research. Please note, in Section 4.1 we discuss in more detail design issues of robots for the particular application area of autism therapy.

Since the key component of KASPAR is its minimally expressive face and head, the next sections provide more background information on the perception of faces.

### 2.2. *Perceptions of faces*

In this section we discuss some important issues to how people perceive human or robot faces.

#### 2.2.1. *Managing perceptions*

DiSalvo et al. (2002) performed a study into how facial features and dimensions affect the perception of robot heads as human-like. Factors that increased the perceived humanness of a robot head were a 'portrait' aspect ratio (i.e. the head is taller than its width), the presence of multiple facial features and, specifically, the presence of nose, mouth and eyelids. Heads with a 'landscape' aspect ratio and minimal features were seen as robotic. They suggest that robot head design should balance three considerations: 'human-ness' (for intuitive social interaction), 'robot-ness' (to manage expectations of the robot's cognitive abilities) and 'product-ness' (so that the human sees the robot as an appliance). The idea of designing a robot to be perceived as a consumer item is noteworthy for the fact that people's *a priori* knowledge of electronic appliances can be utilised in avoiding the uncanny valley; the implication is that the robot is non-threatening and under the user's control. To fulfil their design criteria, they present six suggestions: a robot should have a wide head, features that dominate the face, detailed eyes, four or more features, skin or some kind of covering and an organic, curved form.

#### 2.2.2. *The design space of faces*

Faces help humans to communicate, regulate interaction, display (or betray) our emotions, elicit protective instincts, attract others and give clues about our health or age. Several studies have been carried out into the attractiveness of human faces, suggesting that symmetry, youthfulness and skin condition (Jones et al. 2004) are all important factors. Famously, Langlois and Roggman (1990) proposed that an average face – that is, a composite face made up of the arithmetic mean of several individuals' features – is fundamentally and maximally attractive (although there are claims to the contrary, see Perrett et al. 1994), and that attractiveness has a social effect on the way we judge and treat others (Langlois et al. 2000).

Human infants seem to have a preference for faces, and it appears that even newborns possess an 'innate' ability to spot basic facial features, such as a pair of round blobs situated over a horizontal line which is characteristic of two eyes located above a mouth. It has been debated whether this is due to special face recognition capability or due to sensory-based preferences for general perceptual features such as broad visual cues and properties of figures such as symmetry, rounded contours etc., which then, in turn, form the basis for learning to recognise faces (Johnson and Morton 1991). The nature and development of face recognition in humans is still controversial. Interestingly, while the baby develops, its preference for certain perceptual features changes until a system develops that allows it to rapidly recognise familiar human faces. Evidence suggests that exposure to faces in the first few years of life provides the necessary input to the developing face recognition system (see Pascalis et al. 2005). The specific nature of the face stimuli during the first year of life appears to impact the development of the face-processing system. While young infants (up to about six months of age) can discriminate among a variety of faces belonging to different species or races, children at around nine months (and likewise adults) demonstrate a face-representation system that has become more restricted to familiar faces. The social environment, i.e. the 'kinds of faces' an infant is exposed to, influences the child's preferences for certain faces and abilities to discriminate among them. Not only time of exposure but also other factors, including emotional saliency, are likely to influence the tuning of the face recognition systems towards more precision (Pascalis et al. 2005).

In terms of perception of emotions based on faces, it is interesting to note that people can perceive a variety emotions based on rigid and static displays, as exemplified in the perception of Noh masks that are used in traditional Japanese Noh theatre. Slight changes in the position of the head of an actor wearing such a mask lead to different types of emotional expressions as perceived by the audience. This effect is due to the specific design of the masks where changes in angle and lighting seemingly 'animate' the face. Lyons et al. (2000) scientifically studied this effect (see Figure 4) and also pointed out cultural differences when studying Japanese as well as British participants. We are not aware if this Noh mask effect has

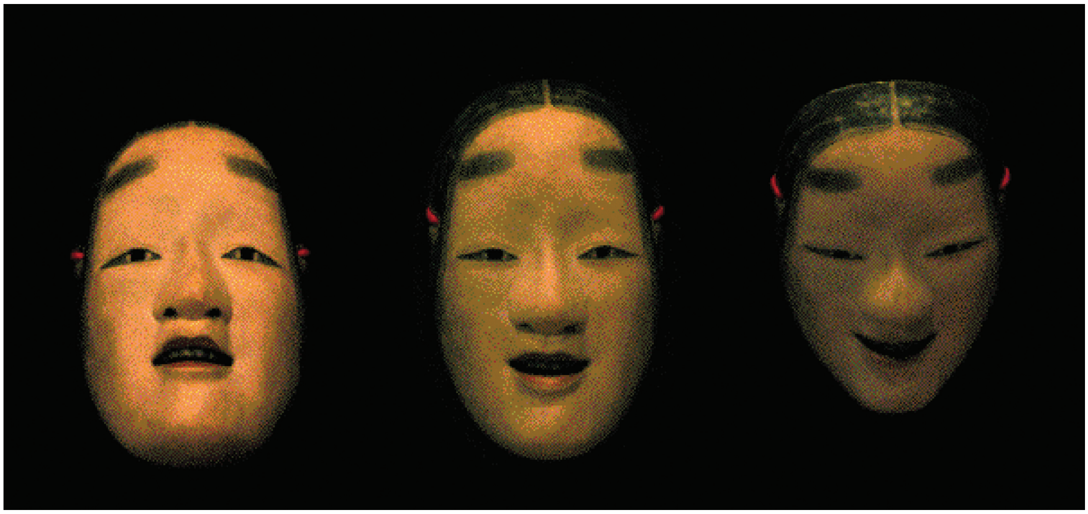

Figure 4. The Noh mask effect. Photo used with permission (Lyons et al. 2000).

been exploited deliberately in the design of humanoid robot expressions.

In his book *Understanding Comics* (McCloud 1993) on narrative art, Scott McCloud introduces a triangular design space for cartoon faces (Figure 5). The left apex is realistic, i.e. a perfect representation of reality, for example a photograph, or realistic art such as that by Ingres. Travelling to the right faces becomes more iconic, that is, the details of the face are stripped away to emphasise the expressive features; emoticons such as ':)' are a perfect example in the 21st century zeitgeist. The simplification has two effects. Firstly, it allows us to amplify the meaning of the face, and to concentrate on the message rather than the medium. Secondly, the more iconic a face appears the more people it can represent. Dautenhahn (2002) points out that iconography can aid the believability of a cartoon character. We are more likely to identify with Charlie Brown than we are with Marilyn Monroe, as a realistic or known face can only represent a limited set of people, whereas the iconic representation has a much broader range – to the extent of allowing us to project some aspects of ourselves onto the character. Towards the top apex representations become *abstract*, where the focus of attention moves from the meaning of the representation to the representation itself. Examples in art would be (to a degree) Picasso's cubist portraits or the art of Mondrian.

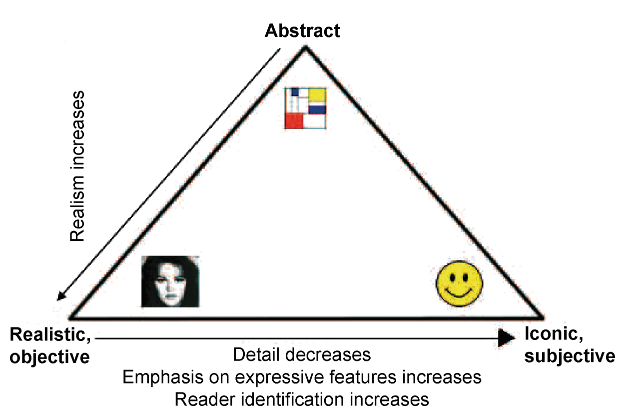


Figure 5. The design space of comics (Blow et al. 2006), modified from McCloud (1993). Note, similar principles are also relevant to animation and cartoons.

We can use this design space, and the accumulated knowledge of comic's artists, to inform the appearance of our robots. Figure 6 shows some robot faces and their (subjective) places on the design triangle. Most are 'real-life' robots although several fictional robots have been included, as functionality has no bearing on our classification in this context. At the three extremes are NEC's Papero (iconic), a small companion robot which is relatively simple and cheap to make and allows easy user-identification; Hanson's K-bot (realistic), complex and theoretically deep in the uncanny valley but allowing a large amount of expressive feedback and Dalek (abstract), potentially difficult to identify with but not as susceptible to the uncanny valley due to its non-human appearance.

Of course, the design space only addresses the static appearance of the robot. The nature of most robot faces is that they encompass a set of temporal behaviours that greatly affect our perception of them. For example, as these issues are so important in human–human interaction (Hall 1983), it seems well worthwhile investigating the rhythm and timing of verbal and, especially, non-verbal behavioural interaction and dynamics of robots interacting with humans, an area referred to as *interaction kinesics* (Robins et al. 2005a). An extension of McCloud's design space to investigate

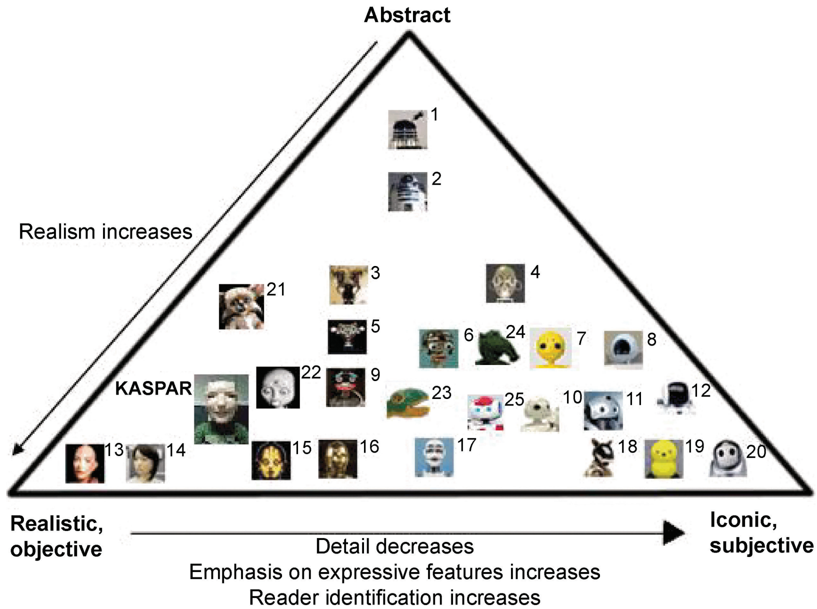


Figure 6. Robot faces mapped into McCloud's design space, updated version of Blow et al. (2006). (1) Dalek (© the British Broadcasting Corporation/Terry Nation); (2) R2D2, fictional robot from 'Star Wars' (© Lucas Film Ltd.); (3) DB (© ATR Institute Kyoto); (4) MIT humanoid face project (© MIT); (5) Kismet (© MIT/Cynthia Breazeal); (6) Infanoid (© Hideki Kozima); (7) Wakamaru communication robot (© Mitsubishi Heavy Industries); (8) HOAP-2 (© Fujitsu Automation); (9) Minerva tour-guide robot (© Carnegie Mellon University); (10) Toshiba partner robot (© Toshiba); (11) QRIO (© Sony); (12) ASIMO (© Honda); (13) K-Bot, extremely realistic 24 DoF head built by David Hanson (© Human Emulation Robotics); (14) Repliee-Q1 (© Osaka University/Kokoro Inc.); (15) False Maria, fictional robot from Fritz Lang's 1927 film 'Metropolis'; (16) C3PO, fictional robot from 'Star Wars' (© Lucas Film Ltd.); (17) WE-4R robot (© WASEDA University); (18) AIBO robotic dog (© Sony); (19) Keepon, minimal DoF HRI robot (© Hideki Kozima); (20) Papero household robot (© NEC); (21) Leonardo HRI research robot (© MIT Personal Robots Group); (22) Nexi HRI research robot (© MIT Personal Robots Group); (23) Pleo commercial companion robot (© Ugobe Inc.); (24) Probo medical companion robot for children (© Vrije Universiteit Brussel); (25) Nao personal robot (© Aldebaran Robotics).

behavioural aspects would be a worthwhile study, specifically how a robot's behaviour affects its perception as iconic, realistic or abstract, and the effect of social behaviour on the uncanny valley and user identification with the robot.

As one moves in the design space of faces from realism towards iconicity, a human is more likely to identify themselves with the face due to the decrease in specific features, and the distinction between *other* and *self* becomes less and less pronounced. Could this idea be useful in robot design? If a robot is to be designed to extend humans' abilities or carry out tasks on their behalf, iconic features may possibly allow the user to project their own identity onto the robot more easily. In contrast, realistic face designs will be seen objectively as *someone else*, and abstract designs often as *something else*. In this case the interaction partner's identification with the robot will be discouraged by the non-iconic nature of the design. Some robot roles (such as security guards) might benefit from reinforcing this perception. While the idea of the robot as an extension of self remains speculative at this point, future work in this area needs to shed more light on these issues.

## 3. Design of KASPAR

This section details the technical design of KASPAR. We start with general considerations for the design-space of minimal expressive humanoids, particular initial design requirements for KASPAR and then present the technical design and construction details.

### *3.1. Robot design and construction details*

#### *3.1.1. General considerations for the design-space of minimal expressive humanoids*

First we discuss some key considerations on the expressive face/head and general appearance and expression in minimal expressive humanoids for human–robot social interaction. In the next section the requirements for KASPAR are introduced.

#### *3.1.2. Balanced design*

- If face, body and hands are of very different complexities, this might create an unpleasant impression for humans interacting with the robot. Aesthetic coherence also requires balance in the physical design and

in turn also the behavioural and interactional design of the robot and its control.
- DoFs and design should be appropriate for the actual capabilities that the robot will possess and use (otherwise inappropriate expectations are created in the human). (cf. Dautenhahn and Nehaniv 2000).

*3.1.3. Expressive features for creating the impression of autonomy*

- Attention: Visible changes in direction of head, neck and eye gaze direction (i.e. with independent DoFs within eyes) are the most important expressive features in creating the impression of autonomy. In a humanoid, this entails actuation of the neck in some combination of pan, tilt and roll.
- Emotional state: Expressive components in face (eyes, eyebrows, mouth, possibly others) are at the next level of importance (see point 3 below).
- Contingency: The human interaction partner should see *contingency* of the robot's attentional and expressive states as it responds to interaction – this entails behavioural design on appropriate hardware (see below for minimal 6+ DoF systems).

Conveying attention (indication of arousal and direction of attention) and the impression of autonomy has been illustrated in the elegant design of the very minimal, non-humanoid robot Keepon by Hideki Kozima (Kozima et al. 2005).

*3.1.4. Minimal facial expressive features*

One can make use of the Noh mask-like effects discussed above. This may be compared to Y. Miyake's concept of *co-creation* in man–machine interaction, namely that a human's subjective experience of a technological artifact, such as a robot or *karakuri* (traditional Japanese clockwork automaton), lies in the situated real-time interaction between observer, artifact and the environmental situation (Miyake 2003; see also Dautenhahn 1999). Therefore, we propose that a largely still, mask-like face (or even other body parts) that is dynamically oriented and tilted at different angles can be designed and used to induce various perceptions of the robot's state in the interaction with a human participant.

Unlike extreme minimal robots (such as Keepon) or robots with complex facial actuation expressiveness in the head (e.g. Kismet) in conjunction with the Noh-like elements of design, a few DoFs within the head may provide additional expressiveness (e.g. smiling, blinking, frowning, mouth movement etc.). Human-like robots with such minimal degrees of face actuation include Feelix by Lola Cañamero at University of Hertfordshire (Cañamero 2002) and Mertz by Lijin Aryananda at MIT-CSAIL (Aryananda 2004).

Possibilities for this additional facial actuation (approximately 6+ DoFs) are included:

- Eyebrows: 270° rotary 1 DoF/eyebrow (× 2), RC servo; if an additional DoF is to be used, then it could be used for raising/lowering the eyebrow in the vertical direction. (Eventually, directly actuated eyebrows were dropped from the first design of KASPAR in order to maintain aesthetic coherence. The adopted design leads to indirect expressiveness via the eyebrows of the face mask under deformations due to mouth and smile actuation.)
- Eyes: Pan and tilt, possibly supporting mutual gaze and joint attention.
- Eyelids: Blinking (full or partial, at various rates).
- Lips/mouth: Actuators for lips to change shape of mouth, e.g. from horizon lips to open mouth, possibly more DoFs a right and left edge to lift/lower mouth (smile/frown); also opening/closing of mouth.

In a minimally expressive robot, some subset of the above features could be selected (e.g. direct actuation of emotional expression could be omitted completely, while retaining the capacity to show direct attention, or, if included, any combination of eyebrows, eyelids or mouth actuation etc., could be omitted).[3]

*3.1.5. Specific requirements for a minimally expressive humanoid suitable for different human–robot interaction studies: KASPAR*

The overall minimally expressive facial expressions of KASPAR have been designed in order not to 'overwhelm' the observer/interaction partner with social cues but to allow him or her to individually interpret the expressions as 'happy', 'neutral', 'surprised' etc. Thus, only as few motors were used that were absolutely necessary to produce certain *salient* features.

- Similar to Kismet, as discussed above, KASPAR was meant to have a youthful and aesthetically pleasing design. Different from Kismet, we did not want to explicitly elicit nurturing responses in people, but instead support the function of KASPAR as a playmate or companion. So we refrained from exaggerated facial features and decided on a *minimally* expressive face.
- It was considered important that the robot has the size of a small child, in order not to appear threatening.
    - KASPAR sits on a table in a relaxed playful way with the legs bent towards each other (the way children often sit when playing).

[3]We thank H. Kozima for discussions on the design of Keepon and A. Edsinger-Gonzales for technical discussions on the implementation of Mertz.

  - The head is slightly larger in proportion to the rest of the body, inspired by comic's design as discussed above (in order not to appear threatening).

- Unlike Kismet which requires a suite of computers to run its software, we decided to have KASPAR's software running either on-board the robot or from a laptop. The reason for this was that we envisaged KASPAR to be used in various human–robot interaction studies, including studies outside the laboratory, so the robot had to be easily transportable, easy to set up etc.
- A low-cost approach was also considered practical in case future research or commercial versions were planned (e.g. to use KASPAR as a toy, or educational/therapeutic tool in schools or at home).
- In order to have a 'natural' shape, a child-sized mannequin was used as a basis. The legs, torso and the hands were kept. The hands were not replaced by articulated fingers in order to keep the design simple, and in order to invite children to touch the hands (which is more like touching a doll).
- Arms were considered necessary for the study of gesture communication, and they also allow the manipulation of objects which is important for task-based scenarios, e.g. those inspired by children's play. It was decided to build low-cost arms with off-the-shelf components that are not very robust and do not allow precise trajectory planning etc, but can nevertheless be 'powerful' in interaction for producing gestures such as waving, peek-a-boo etc.
- The neck was designed to allow a large variety of movements, not only nodding and shaking the head, but also socially powerful movements such as slightly tilting the head (important for expressing more subtle emotions/personality traits such as shyness, cheekiness etc.).
- KASPAR has eyelids that can open and close. Blinking can provide important cues in human–human interaction, so we decided that this was a salient feature to be added.

### 3.1.6. *Technical design considerations*

A main criteria for KASPAR emphasised the desirability of low cost. The budget for KASPAR allowed up to 1500 Euros for material costs. Therefore, the following decisions were made at the initial design specification stage:

A shop window dummy modelled after an approximately two-year-old girl was available at reasonable cost. It already possessed the overall shape and texture required for the body of the robot and could be readily adapted to provide the mainframe and enclosure for the robot system's components. Therefore, it was decided that KASPAR would be stationary and would not have moving or articulated legs.

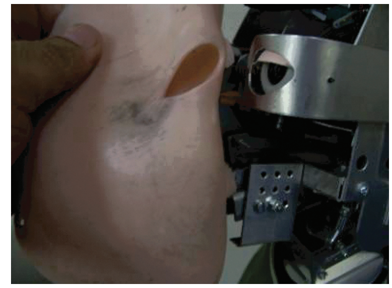

Figure 7. Detailed view of face mask attachment points.

In line with our discussion of identification and projection (as for Noh masks), it was also decided that the silicon rubber face mask from a child resuscitation practice dummy would be used for the face of the robot. These masks were flesh coloured and readily available as spare parts (to facilitate hygienic operation of the dummy). The masks were also sufficiently flexible to be deformed by suitable actuators to provide the simple expression capabilities that would be required, and also provided simplified human features which did not exhibit an unnerving appearance while static (cf. the 'uncanny valley' mentioned above, Mori 1970). See Figure 7 for the attachment of the mask to the robot's head.

It was decided that all joint actuation would be achieved by using radio control (RC) model servos. These were originally made for actuating RC models, but as they have been commercially available to the mass hobby market at low cost, they are also commonly used as joint actuators for small-scale robots. Interface boards are also available which allow them to be interfaced and controlled by a computer.

The main moving parts of the robot were head, neck and arms; hence, the original head, neck and arms were removed from the shop dummy to allow replacement with the respective new robot systems. The batteries and power and control components were fitted internally. KASPAR's main systems are described in more detail in the following sub-sections.

Further details of the design and construction of head and arms, as well as details of the robot's control and power supply are provided in Appendix A.

### 3.1.7. *KASPAR II*

About a year after completing KASPAR we built a second version called 'KASPAR II', and both robots are currently used extensively in different research projects. KASPAR II had been used in experiments on learning and interaction histories as reported in Section 4.3 (all other studies mentioned in this paper used the original KASPAR robot). KASPAR II's design is very similar to the original (KASPAR I), with a few modifications primarily in terms of upgrades. Details of KASPAR II are given in Appendix B, which also provides information on upgrades, changes and planned future improvements of KASPAR.

*3.1.8. Remote control of the robot*

In applications involving children with autism (see Section 4.1), a remote control was used to operate KASPAR. It is made of a standard wireless keypad (size 8 cm × 12 cm) with 20 keys. Different keys were programmed to activate different behaviours in KASPAR, i.e left/right arm drumming, waving, different postures etc. These are dynamic expressive behaviours released via single key press. The programmed keys had stickers on them with simple drawings representing the behaviour, e.g. a drum for drumming (two keys – right and left), a smiley for a 'happy' posture, a hand for hand-waving etc. The remote control allowed the introduction of collaborative games and role switch, with a view to use the robot as a social mediator, as will be explained in more detail in Section 4.1.

### 3.2. Software

The software development of KASPAR is not the focus of this paper and will thus only be mentioned briefly. The robot can be used in two modes: remotely controlled as well as autonomous operation. Unskilled operators can easily run and develop programmes for the robot using the novel user-friendly KWOZ (KASPAR Wizard of OZ) graphic user interface (GUI) software which runs on any Windows or Linux PC. This interface has been used in human–robot interaction scenarios when an experimenter (usually hidden from the participants) remotely controlled the robot from a laptop (see Section 4.1). This type of control is different from the remote control device that was specifically introduced to openly introduce collaborative games (see Section 3.1.8).

In a variety of projects KASPAR operates autonomously, see examples in Sections 4.2 and 4.3. An applications programming interface (API) provides access for programmers to develop custom programmes and access to open source robot software produced under the Yet Another Robot Programme (YARP) initiative (Yarp 2008).

### 3.3. Aesthetics of the face

As mentioned above, a child resuscitation mask was used.[4] The mask is produced by the Norwegian company Laerdal, which specialises in medical simulators and first produced 'Resusci-Anne', as a life-like training aid for mouth-to-mouth ventilation. Anne's face mask had been inspired by the 'peaceful-looking and yet mysterious death mask' (Laerdal Products Catalogue 2008–2009) of a girl who is said to have drowned herself in the Seine. The death mask is said to have first appeared in modellers' shops in Paris around the 1880s. In a 1926 catalogue of death masks it is called 'L'Inconnue de la Seine' (the unknown woman of the Seine). Replicas of the mask became fashionable as a decorative item in France and Germany. The mask and as yet unconfirmed stories surrounding its origin then sparked the imagination of many poets and other artists, such as Rilke, for the next few decades and led to numerous literary art works (The Guardian Weekend, 2007). The mysterious and beautiful, 'timeless' quality of the mask may contribute to its appeal to participants in human–robot interaction studies. In our view, the mask itself has a 'neutral expression' in terms of gender as well as age. It has a skin colour, without facial hair or any additional colouring, and we left it unchanged in order to allow viewers/interaction partners to impose different interpretations of personality/gender etc. on the robot.

Interestingly, the specific design and material that the rubber mask is made of, in conjunction with the attachment of the mask to the actuators, creates KASPAR's unique smile, which is minimal but naturalistic and similar to the so-called 'genuine smile' or 'true smile' shown by people. Ekman et al. (1990) describe the Duchenne smile (the genuine smile) that is characterised by movements of the muscles around the mouth and also the eyes. Humans show a true smile typically involuntarily. This smile is perceived as pleasant and has positive emotions associated to it, in contrast to other smiles in which the muscle orbiting the eye is not active. A variety of other smiles can be observed and they occur, e.g. when people voluntarily try to conceal negative experience (masking smiles), feign enjoyment (false smiles) or signal that they are willing to endure a negative situation (miserable smiles).

KASPAR's smile causes a very slight change in the mask around the eyes. This change is based on passive forces pulling on the mask when the mouth moves. Thus, this 'true' smile is possible due to particular way in which the smile was designed, how the mask is attached and the material properties of the mask.

As a consequence, KASPAR's smile is very appealing (Figure 8), and similar to a genuine smile shown by people. This is a novel feature that is different from many other robot (head) designs where smiles often appear 'false' since they either only operate the mouth or different parts of the face but not in the naturally smooth and dynamic fashion it occurs in KASPAR's face mask.

Note that the *dynamic* transition of the facial expressions (i.e. from neutral to a smile, cf. Figure 8) plays an important part in how people perceive KASPAR's facial expressions. Experimental results of an online survey with 51 participants (Blow et al. 2006) have shown that natural transitions (taking about two seconds from neutral expression to smile) are seen as more appealing than sudden (artificially created) transitions. Also, the larger the smile, the greater the participants' judgement of 'happiness'. However, while smiles with a natural transition are seen as more appealing than static pictures of the smiles, those with a sudden

[4]Thanks to Guillaume Alinier of the Hertfordshire Intensive Care & Emergency Simulation Centre at University of Hertfordshire for his generous donation of the face mask.

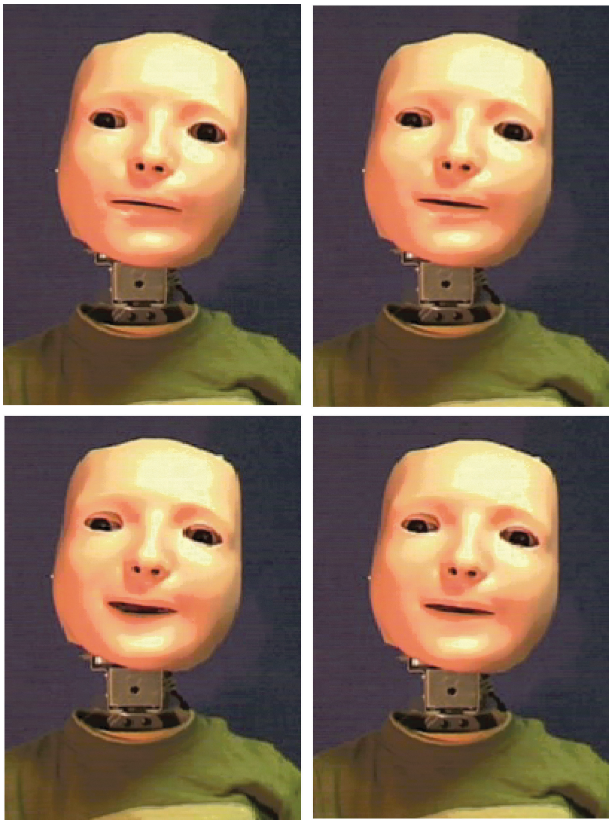

Figure 8. KASPAR's minimally expressive face illustrating four expressions designed for human–robot interaction. Clockwise from top left: neutral, small, medium and large smiles.

transition are not (Blow et al. 2006). This emphasises the need for consistency of appearance (in this case a humanoid face with a natural smile) and behaviour (the transition time of facial expressions). Further results of this study show that all four of KASPAR's expressions (Figure 8) shown to the participants were found appealing or very appealing. Note, our primary research interest is in human–robot interaction, not in facial design or emotion modelling, but these results give encouragement to participants' ratings of KASPAR's facial expressions. Other researchers might use KASPAR for a further investigation of these issues concerning the perception of robot facial expressions.

### *3.4. Contextual features*

Contextual features are an important ingredient of interaction design (Preece et al. 2002). In order to help people relate to the robot socially we used various contextual features in terms of the robot's clothing. We dressed the robot in children's clothing (shirt, trousers and socks). We utilised children's used clothing which appear more natural than newly purchased clothing. We did not try to hide the fact that KASPAR is a robot, on the contrary we left the neck and wrists uncovered so that cables and pieces of metal can be seen.

For the applications of the robot in autism therapy (see Section 4.1) where we mainly work with boys, we wanted to give the robot a boyish appearance and added a baseball cap and a wig in order to emphasise the child-sized and playful nature of the robot. We tried different hair colours, but the dark-coloured wig gave the most consistent appearance. The cap can also serve as a prop and invites children to remove and replace it etc. Moreover, in several research projects where we study human–humanoid interaction games, we place a toy tambourine in the robot's lap, which the robot is able to drum on. This feature adds to the robot's perceived playfulness and allows the study of task-based interaction (e.g. drumming).

### *3.5. Gestures*

As discussed above, our initial requirements were to have arms that allow simple gestures. During the course of using KASPAR in different research projects a number of dynamic gestural expressions were defined (Figure 9).

Note, while within our human–robot interaction research group we did not systematically study how different user groups perceive KASPAR's appearance and behaviours, we have been using the robot in multiple experiments, demonstration and public engagement events involving children and adults of different age ranges, gender, background etc. In total, more than 600 children have been exposed to the robot (either watching its live demonstrations or participating in an interaction experiment) along with about 300 adults. These encounters were part of interaction experiments carried out in schools or in the laboratory, or were part of public engagement events taking place either in schools, museums or conference venues, or on university premises. While feedback from the public events was very informal in nature, we nevertheless have gained anecdotal evidence that can be described as follows:

- Children of various ages (typically developing children as well as children with special needs, including children with autism; cf. Section 4.1) generally show a very positive reaction towards KASPAR, attempting spontaneously to play and interact with the robot, often touching it etc. The minimal facial expressions and gestures appear particularly appealing, the child-like appearance and size of the robot seems to elicit play behaviour similar to what children may show towards other interactive toys. Once children discover (through play and inquiry from the researchers) that KASPAR has a wider range of abilities than conventional interactive toys that can be bought in toy shops, their curiosity appears to get reinforced and they continue to engage with KASPAR more systematically, e.g. exploring its eyes etc. For typically developing children the minimal/subtle expressiveness in KASPAR seems to encourage them to reply

Figure 9. Some of KASPAR's expressions. Children usually interpret these expressions as 'good bye' (top, left), 'happy' (top, middle), 'surprised' (top, right), 'sad' (bottom, left) and 'thinking' (bottom, right). Note, our goal was not to create scientifically plausible emotional and other expressions (compare FEELIX, Kismet), but to create a robot with – from a user-centred perspective – appealing and interactional salient features.

with emphasised or bigger expressions in return, i.e. with a bigger smile, and bigger hand movements in imitation games etc.

- Adults show in general a more cautious and less playful attitude towards KASPAR, sometimes commenting on specific design features, e.g. noticing that the head is disproportionately larger than the rest of its body (as has been explained, this was a deliberate cartoon-inspired design choice). It appears (from explicit comments given to the researchers) that adults tend to spontaneously compare KASPAR with very realistically human-like robots they have seen in movies or on television. Their expectations towards the robot's capabilities are similarly high, so overall, adults tend to have a more critical attitude towards the robot. For these reasons, in our experiments involving adult participants we took care to introduce the robot and its capabilities before the start of the experiment.

Psychologists may further investigate the above issues, which go beyond the scope of our research, in future systematic studies.

## 4. Applications of KASPAR in research

Since 2005 our research team has been using KASPAR extensively in various research projects in the area of robot-assisted play, developmental robotics, gesture communication and development and learning. This section illustrates the experiments and the results that were obtained from some of these studies. We discuss these studies in the light of KASPAR's interaction abilities that afford a great variety of different human–robot interaction experiments. Note, a detailed description of the motivation, research questions, experiments and results would go beyond the scope of this paper. Instead, the following sections aim to *illustrate* the different usages of the robot in different interaction scenarios and applications where different methodological approaches have been used in the research and to document the experiments. Case study I illustrates work in a project in assistive technology based on case study evaluations whereby a narrative format has been chosen to describe the work. Case study II is situated in the context of human–robot interaction studies whereby a more experimental approach has been taken that takes into account not only the evaluation of the performance of the human–robot dyad (pair) but also the subjective evaluations of the experiment participants. Finally, case study III reports on research in developmental robotics whereby the emphasis is on the development and evaluation of cognitive architectures for robot development that relies on human interaction. Each case study will provide pointers to published work on these experiments so that the reader is able to find detailed information about the different methodological approaches, experiments and results.

### 4.1. Case study I: robot-assisted play and therapy

This case study discusses the use of KASPAR in robot-assisted play, in the specific application context of therapy for children with autism.

#### 4.1.1. Motivation

Our research group has been involved for more than 10 years in studies that investigate the potential use of robots in autism therapy (Dautenhahn and Werry 2004) as part of the Aurora project (Aurora 2008). Different humanoid as well as non-humanoid robots have been used. The use of robots in robot-assisted play (with therapeutic and/or educational goals) is a very active area of research and a variety of special-purpose robots have been developed in this area (Michaud et al. 2003; Kozima et al. 2005; Saldien et al. 2008). Other work is exploring available research platforms (Kanda and Ishiguro 2005; Billard et al. 2006) or commercially available robots in an educational context (Tanaka et al. 2007). While in the area of assistive technology a variety of special requirements and needs need to be considered (cf. Robins et al. 2007 which reports on the IROMEC project that specifically designs a novel robot for the purpose of robot-assisted play for children who cannot play), KASPAR originally had not been designed only for this specific application area. However, as discussed above, the design of KASPAR included lessons learnt from the use of robots in autism therapy. And not surprisingly, KASPAR turned out to be a very engaging tool for children with autism and has been used extensively as an experimental platform in this area over the past few years.

This section presents some case study examples that highlight the use of KASPAR in the application area of autism therapy. Autism here refers to Autistic Spectrum Disorders, a range of manifestations of a disorder that can occur to different degrees in a variety of forms (Jordan 1999). The main impairments that are characteristic of people with autism, according to the National Autistic Society (NAS 2008), are impairments in social interaction, social communication and social imagination. This can manifest itself in difficulties in understanding gesture and facial expressions, difficulties in forming social relationships, the inability to understand others' intentions, feelings and mental states etc. They also usually show little reciprocal use of eye contact. As people's social behaviour can be very complex and subtle, for a person with deficits in mind-reading skills (as with autism), this social interaction can appear widely unpredictable and very difficult to understand and interpret.

KASPAR, which was designed as a minimally expressive humanoid robot, can address some of these difficulties by providing a simplified, safe, predictable and reliable environment. The robot was found to be very attractive to children with autism and a suitable tool to be used in education and therapy. As autism can manifest itself to different degrees and in a variety of forms, not only children in different schools might have different needs but also children in the same school might show completely different patterns of behaviour from one another and might have different or even some contradictory needs. Importantly, interaction with KASPAR provides multi-modal embodied interaction where the complexity of interaction can be controlled and tailored to the needs of the individual child and can be increased gradually.

#### 4.1.2. Illustration of trials

The following examples show the potential use of KASPAR in education and therapy of children with autism. They present a varied range of settings (e.g. schools, therapy sessions etc.) and children who vary widely in their abilities and needs (from very low functioning children to high functioning and those with Asperger syndrome). KASPAR was found to be very attractive to all these children regardless of their ability. Children who were usually not able to tolerate playing with other children initially used KASPAR in solitary play and closely explored its behaviour, postures and facial features and expressions. Later, assuming the role of a social mediator (Robins et al. 2004b; Marti et al. 2005) and an object of shared attention, KASPAR helped these children (and others) in fostering basic social interaction skills (using turn-taking and imitation games), encouraging interaction with other children and adults. All trials took place in schools for children with special needs (Examples I–V) or health centres (Example VI). The experimenter was part of and actively involved in all of the trials; compare with Robins and Dautenhahn (2006) for a detailed discussion on the role of the experimenter in robot-assisted play.

The examples in school are part of a long-term study where children repeatedly interact with KASPAR over several months. More details about trials and analysis of the results can be found in Robins et al. (2009).

*Example I. KASPAR promotes body awareness and sense of self*

KASPAR encourages tactile exploration of its body by children of different age groups irespective of their gender (Figure 10). All children with autism who first met KASPAR were drawn into exploring him in a very physical way. This tactile exploration is important to increase body awareness and sense of self in children with autism.

*Example II. KASPAR evokes excitement, enjoyment and sharing – mediates child/adult interaction*

We observed situations when children with severe autism who have very limited or no language at all got excited in their interaction with KASPAR and sought to share this experience with their teachers and therapists. These

Figure 10. Tactile exploration of KASPAR by children from different age groups and gender.

human contacts may give significance and meaning to the experiences with the robot (Figure 11).

*Example III. KASPAR helps to break the isolation*

Liam is a child with severe autism. Although in his home he interacts regularly with other family members, in school he is withdrawn to his own world, not initiating any interaction with other people (neither with other children nor with the teachers). After playing with KASPAR once a week for several weeks, Liam started to share his experience with his teacher (Figure 11, left), exploring the environment and communicating (in a non-verbal manner) with adults around him (both with the teacher and the experimenter) as can be seen in Figures 12 and 13.

*Example IV. KASPAR helps children with autism to manage collaborative play*

KASPAR's minimal expressiveness, simple operation and the use of a remote control encourage children not only to play with it but also to initiate, control and manage collaborative play with other children and adults (see Figures 14 and 15).

*Example V. KASPAR as a tool in the hands of a therapist*

As stated above, interaction with KASPAR is a multi-modal embodied interaction where the complexity of interaction can be controlled, tailored and gradually increased to the needs of the individual child. Figure 16 shows how a therapist is using KASPAR to teach a child with severe autism turn-taking skills. Adam is a teenager who does not tolerate any other children, usually his focus and attention lasts only for very short time, he can be violent towards others and can also cause self-injury. However, after he was first introduced to KASPAR, he was completely relaxed, handled KASPAR very gently and kept his attention focused on it for as long as he was allowed (approximately 15 minutes). The therapist used his keen interest in KASPAR to teach him turn-taking skills with another person. Initially, Adam insisted on being in control all the time and refused to share KASPAR with anyone else, but after a while he allowed the therapist to take control, and slowly they progressed into full turn-taking and imitation games.

*Example VI. KASPAR as a teaching tool for social skills*

KASPAR was used in a pilot scheme to teach children with autism social skills during their family group therapy sessions run by the local child and adolescent mental health centre. During these sessions children practise how to approach other children to befriend them in the playground and in school. Children learnt how to ask precise questions by approaching KASPAR (as a mediator between them and other children), asking the robot a question and interpreting its response. KASPAR was operated by another child who gave the answer indirectly via the robot's gestures and facial expressions (Figure 17).

Figure 11. Liam seeks to share his excitement with his teacher (left); Derek shares his enjoyment with his therapists (right).

Figure 12. Liam is exploring KASPAR's facial features very closely (in this snapshot it concerns the eyes) and then turns to his teacher and explores her face in similar way.

*Example VII. Use of a remote control by children with autism to operate KASPAR*

In Examples IV and VI children used the remote control (Figure 18) to facilitate collaborative play. They were given the remote control and shown how to operate it. Most children got excited once they discovered and explored the use of its keypad, and asked for it every time they came to play with KASPAR.

The objectives for the children to use the remote control were varied. For those children who always wanted to be in control (a typical behaviour in autism), the remote control was a tool for learning turn-taking skills. It was a 'reward' once they learnt to 'let go' of the control, and not only gave it to another person but also participated in an imitation game where the other person was controlling the robot. For children who are usually passive and follow any instruction given, the use of the remote control encouraged taking initiative, discovering cause and effect and realising that they could also do actions on their own (e.g. they can change the robot's posture).

Moreover, whenever possible, the experimenter and a child, or two children were encouraged to play together (e.g. an imitation game), with the robot assuming the role of a social mediator. In this scenario the remote control is a key object that facilitates the acquisition of new skills that are *vital* for children with autism, i.e. they no longer merely follow instructions of games given to them by adults (which is often the case in classroom settings) but are also actually allowed *to take control of a collaborative game* to initiate, follow, take turns and even have the opportunity to give instructions to their peers.

Figure 13. Liam communicates with the experimenter.

Figure 14. Billy controls an imitation game (using a remote control) in a triadic interaction with the robot and the experimenter.

Figure 15. KASPAR mediates child–child interaction in a turn-taking and imitation game: one child controls KASPAR via remote control, the other imitates KASPAR. The children then switch roles.

#### *4.1.3. Reflections on KASPAR's design*

As has been mentioned, the Aurora research team has been using a variety of different robots in robot-assisted play for children with autism, including non-humanoid mobile robots, a humanoid robotic doll as well as a zoomorphic (in this case dog-like) robot (see Figure 19).

All three approaches with different robots used have in common that the child's control of the robot is indirect, i.e. through interaction – the robot and the child are active participants in the interaction, and enjoyment of the child is a key aim. Also, in all three studies the child can influence whatever game is being played. Table 1 shows in boldface the specific features of KASPAR that have turned out to be very successful during interactions with children with autism, as demonstrated in the above-mentioned case studies.

To summarise, following are the key features of KASPAR that turned out to be very important in the robot-assisted therapy with children with autism:

- A variety of facial/head and gestural expressions that allow a spectrum of social interaction and communicative as well as collaborative games.
- A remote control to operate the robot that can be operated by the experimenter or therapist as well as by children themselves. This control forms the basis of a variety of different games, e.g. imitation and turn-taking games.
- The remote control-facilitated collaborative games among children on their own initiative.

Note, after reviewing the literature (see discussion in Dautenhahn and Werry 2004) and discussions with psychologists we suggest that some of the attractiveness of KASPAR to children with autism is its minimal expressiveness, i.e. possessing simple facial features with less details – a face that appears less overwhelming and thus less threatening to children (in comparison to a person's face with numerous facial details and expressions that often are overwhelming to children with autism causing information overload). Also, KASPAR's limited amount of facial expressions makes its behaviours more predictable, which again suits the cognitive needs of children with autism. The generally very positive reactions from children (some verbal but most non-verbal due to limited language abilities) further support the view that KASPAR can provide a safe and enjoyable interactive learning environment for children with autism as motivated in Section 4.1.1.

### ***4.2. Case study II: drumming with KASPAR – studying human–humanoid gesture communication***

This second case study concerns the use of KASPAR in the European project 'Robotic Open-Architecture Technology for Cognition, Understanding, and Behaviours' (Robotcub; Sandini et al. 2004; Robotcub 2008) in the field of developmental robotics.

#### *4.2.1. Motivation*

'[I]nterpersonal coordination is present in nearly all aspects of our social lives, helping us to negotiate our daily face-to-face encounters . . . We also coordinate our nonverbal behavior with others to communicate that we are listening to them and want to hear more' (Bernieri and Rosenthal 1991, p. 401).

Figure 16. A therapist is using KASPAR to teach turn-taking skills to a child with autism.

Figure 17. KASPAR as part of family group therapy sessions to mediate between children and teach social skills.

Over the past two years KASPAR has been used extensively in our *drum-mate* studies, which investigate the playful interaction of people with KASPAR in the context of drumming games as a tool for the study of non-verbal communication (Kose-Bagci et al. 2007, 2008a, 2008b). This work forms part of our studies on gesture communication as part of the EU 6th framework project Robotcub. Drumming is a very suitable tool to study human–humanoid non-verbal communication because it includes issues such as social interaction, synchronisation, and turn-taking which are important in human–human interaction (Kendon 1970; Hall 1983; Bernieri and Rosenthal 1991; Goldin-Meadow and Wagner 2005). In robotics, different works have used robot drumming as a test bed for robot controllers (Kotosaka and Schaal 2001; Degallier et al. 2006). Other approaches focus on the development of a robot drummer that is able to play collaboratively with professional musicians (Weinberg et al. 2005; Weinberg and Driscoll 2007) or in concert with human drummers and at the direction of a human conductor (Crick et al. 2006). Our work uses drumming as a test bed for the study of human–humanoid non-verbal interaction and gesture communication.

From a practical viewpoint, drumming is relatively straightforward to implement and test, and can be applied technically without special actuators like fingers or special skills or abilities specific to drumming. So we could implement it with the current design of KASPAR, without additional need for fingers, or extra joints. With just the addition of external microphones for sound detection, it was able to perform drumming with tambourine style toy drums (Figure 20). Note, we did not need an additional drumstick, as due to its specific design KASPAR's hands are able to perform the drumming. In these experiments only one hand (the left one) was used for the drumming.

Figure 18. The remote control used in scenarios with children with autism.

#### 4.2.2. *Drumming experiments with KASPAR*

KASPAR, in our experiments, has the role of an autonomous 'drumming companion' in call-and-response games, where its goal is to imitate the human partner's drumming (Figure 20). In the drum-mate studies, the human partner plays a rhythm, which KASPAR tries to replicate,

Figure 19. Top row: Non-humanoid, mobile robots used in the Aurora project – Aibo (left, Sony), Labo-1 (right, AAI Canada, Inc.). Bottom row: Different appearances of Robota, the humanoid doll–robot that has been used with children with autism. The 'robot-like' appearance on the right has been shown to be more engaging in first encounters of children with autism compared to Robota, the doll-robot (Robins et al. 2006).

Figure 20. A screen shot from the experiments where KASPAR is a drum-mate of human interaction partners.

in a simple form of imitation (mirroring[5]). KASPAR has two modes: listening and playing. In the listening mode, it records and analyses the played rhythm, and in the playing mode, it plays the rhythm back by hitting the drum positioned in its lap. Then the human partner plays again. This turn taking will continue for the fixed duration of the game. KASPAR does not imitate the strength of the beats but only the number of beats and duration between beats, due to its limited motor skills. It tailors the beats beyond its skills to those values allowed by its joints. KASPAR needs a small time duration (e.g. at least 0.3 seconds in the experiments) between each beat to get its joints 'ready', so that even if the human plays faster, KASPAR's imitations will be slower using durations of at least 0.3 seconds between beats. It also needs to wait for a few seconds before playing any rhythm in order to get its joints into correct reference positions.

In the first set of experiments (Kose-Bagci et al. 2007), head gestures accompanied the drumming of KASPAR. Here KASPAR just repeated the beats produced by the human partner, and made simple fixed head gestures accompanying its drumming (we used very simple gestures, without overt affective components like smiling or frowning in order not to overly distract the participants during the experiments). The participants, in return, perceived these simple behaviours as more complex and meaningful and adapted their behaviour to the robot's gestures. In this part of the study, we used deterministic turn-taking skills, simply mirroring the human's playing, which caused problems in terms of timing and negatively affected human participants' enjoyment. In the second part of the study (Kose-Bagci et al. 2008a), we developed novel turn-taking methods that appear more natural and engage the human participants more positively in the interaction games. Here, computational probabilistic models were used to regulate turn-taking skills of KASPAR emerging from the dynamics of social interaction between the robot and the human partner. Although we used very simple computational models, and this work is a first step in this domain, we were able to observe some very 'natural' games in terms of coordinated turn-taking games, and some of the participants even compared the game to a game they might play with children.

From the first set of experiments and our public demonstrations where we used gestures as social cues, we got positive feedback from the participants (48 adults and 68 primary school children). Especially at the public demonstrations where we used more complex gestures (e.g. smiles when KASPAR imitated human drumming, frowns when KASPAR could not detect human drumming or waving 'good bye' with a big frown when it had to finish the game), we got very positive feedback and public attention.

The reason behind KASPAR's successful head and face gestures is hidden in its face design. KASPAR's facial expressions and head and arm gestures seemed to influence the way human participants perceive the robot and the interaction. Even blinking and nodding and other head movements affect significantly human participants' evaluations of the robot and the games. Besides, the size of KASPAR makes it appear more 'child-like' which affects people's evaluations. Some of the adult participants compared the drumming experience they had with KASPAR with the experiences they had with their two to three-year-old children.

It is important to note that while KASPAR's drum playing did not change over time, and stayed the same in different games, the participants learned the limits of KASPAR and the rules of the game. Participants seemed to adapt themselves to the game better and the success rate improved over time. Humans, as shown here, were not passive subjects in this game, but adapted themselves to the capabilities of the robot. In order to facilitate and motivate such an adaptation, aspects of the interaction that are not directly related to the task itself, such as interactional gestures – like KASPAR's simple head/face gestures and blinking – may play an important role. A variety of research questions have been addressed using KASPAR in human–robot drumming experiments. A detailed discussion and results pertaining to these questions would go beyond the scope of this paper but can be found in Kose-Bagci et al. (2007, 2008a, 2008b). The next section illustrates some of the results.

#### *4.2.3. Results and discussion*

The following is a brief summary of results of some of the key points resulting from experiments presented in Kose-Bagci et al. (2007, 2008a, 2008b).

[5]Here we use 'mirroring' to refer to generalised matching of aspects of behaviour in interaction, e.g. number and timing of beats in a drumming interaction. In particular, it does not refer here to ipsilateral vs. contralateral imitation. Mirroring plays an important part in communicative interactions and the social development of children. For further discussion of mirroring and imitation, see Nehaniv and Dautenhahn (2007) and Nadel and Butterworth (1999).

Table 1. Design space of robots explored in the Aurora project: a comparison of three approaches with different robots. Also see related comparisons in Davis et al. (2005).

| | **Labo-1** (Werry and Dautenhahn 2007; Dautenhahn 2007) | **Robota** (Robins et al. 2004a, 2004b, 2006; Dautenhahn and Billard 2002) | **KASPAR** (see case studies) |
|---|---|---|---|
| Appearance | Mechanical-looking | Doll or plain appearance | Humanoid |
| Mode of operation | Autonomous | Remote-controlled | Remote-controlled |
| Mobility | Movements in 2-D on the floor (translational and rotational movements) | Movements of head (left, right), lifting of arms and legs (up, down) | **Different movements of the head/neck, different facial expressions (e.g. 'surprised', 'happy', 'sad' etc.), variety of arm gestures (e.g. waving, peek-a-boo etc.)** |
| Tasks with objects | Indirectly (obstacle avoidance) | None | Drumming (playing a toy tambourine) |
| Spatial dimensions of interaction | 3-D, the child can approach and interact with the robot from any direction, child can also pick robot up etc. | 3-D, but the child must be positioned in front of the robot to interact with it | 3-D, but the child must be positioned in front of the robot to interact with it |
| Systems behaviours used | 1. Few predetermined behaviours and simple action–selection architecture based on the robot's sensory input and internal states<br>2. Emergent, i.e. behaviours emerge from the interaction of the robot with the environment | Few predetermined behaviours elicited under control of a puppeteer who selects the robot's actions based on his perception of the situation and knowledge about the child, the interaction history/context etc. | Few predetermined behaviours elicited under control of a puppeteer who selects the robot's actions based on his perception of the situation and knowledge about the child, the interaction history/context etc. |
| Stance and movement of child during interaction with the robot | Child is free to run around the room, sit or crawl on the floor, approach, follow, avoid or pick up the robot | Child is free to sit, stand, move towards or away from the robot and touch it | Child is free to sit, stand, move towards or away from the robot and touch it |
| Control over the robot by child | Indirectly, through interaction | Indirectly, through interaction | 1. Indirectly, through interaction<br>**2. Child can use a remote control to operate the robot** |
| Nature of the interaction | Free, playful, unstructured, basic turn-taking and approach/avoidance routines lead to games such as following, chasing etc. | Free interaction, but guided by experimenter, e.g. 'look at what the robot/the other child is doing' | 1. Free interaction, but guided by experimenter, e.g. 'look at what the robot/the other child is doing'<br>**2. By controlling the robot via a remote control, the child can *manage* a collaborative game with another child on his/her own initiative** |
| Targeted therapeutic behaviours | Turn-taking, joint attention, proactive behaviour, initiative taking, mediation between child and other persons via the robot | Turn-taking, joint attention, imitation of limb movements, proactive behaviour, initiative taking, mediation between child and other persons via the robot | Turn-taking, joint attention, collaborative activities, imitation of hand gestures and head and facial expressions, proactive behaviour, initiative taking, mediation between child and other persons via the robot, body awareness & sense of self |
| Tailoring to needs of individual children | No individual adaptation was used | Manual adaptation by puppeteering | Manual adaptation by puppeteering |

- A trade-off between the subjective evaluation of the drumming experience from the perspective of the participants and the objective evaluation of the drumming performance. Participants preferred a certain amount of robot gestures as a motivating factor in the drumming games that provided an experience of social interaction. However, the sample was divided in terms of what degrees of gestures were appropriate.
- The more games participants played with the robot the more familiar they became with the robot; however, boredom was also mentioned by some participants which indicates the essential role of research into how to maintain a user's interest in the interaction with a robot.
- The more participants played with the robot the more they synchronised their own drumming behaviour with the robot's. The different probabilistic models that controlled the robot's interaction dynamics led to different subjective evaluations of the participants and different performances of the games. Participants preferred models that enable the robot and humans to interact more and provide turn-taking skills closer to 'natural' human–human conversations, despite differences in objective measures of drumming behaviour. Overall, results from our studies are consistent with the *temporal behaviour-matching hypothesis* previously proposed in the literature (Robins et al. 2008), which concerns the effect that participants adapt their own interaction dynamics to that of the robot's.

#### 4.2.4. *Reflections on KASPAR's design*

How suitable has been KASPAR in the interaction experiments using drumming games? KASPAR's movements do not have the precision or speed of industrial robots or some other humanoid robots that have been developed specifically for manipulation etc. One example of a high-specification robot is the iCub that has been developed within the European project Robotcub at a cost of €200,000 (Figure 21). The iCub has the size of a 3.5-year-old child, is 104 cm tall and weighs 22 kg. It has 53 joints mainly distributed in the upper part of the body. While KASPAR has been designed from off-the-shelf components, every component of the iCub has been specifically designed or customised for the robot in order to represent cutting edge robotic technology.

Also, special purpose robotic percussionists have been designed specifically for the purpose of *efficient* drumming, e.g. Haile (Weinberg et al. 2005). The design rationale of Haile, a robot with an anthropomorphic, yet abstract shape that can achieve drumming speeds of up to 15 Hz, was very different from KASPAR: 'The design was purely functional and did not communicate the idea that it could interact with humans by listening, analyzing, and reacting' (Weinberg and Driscoll 2007). Haile is a special purpose drumming robot that can join and improvise with live professional players. Unlike Haile, which was specifically designed for performing drumming, KASPAR is using drumming as a *tool for social interaction*. Detailed technical comparisons of KASPAR with Haile or the iCub are not useful because these all serve very different purposes. For example, the iCub has been designed for tasks such as crawling and manipulation, and Haile can achieve impressive drumming performances in terms of speed and precision.

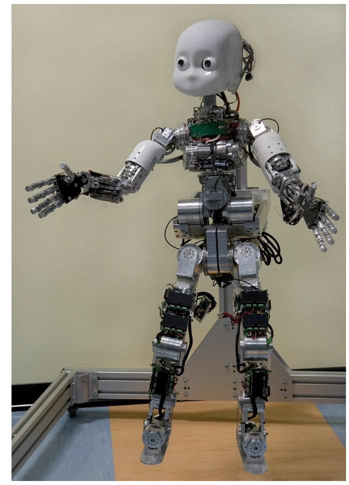

Figure 21. The iCub robot.

However, despite KASPAR's low-precision design, our studies have shown that it is very suitable for human–robot interaction studies where speed, precision or complex movement patterns are not of primary importance, as is the case in our experiments on drumming games that were successful in terms of social interaction, imitation and turn-taking. And it is in such cases that the low-cost robot KASPAR, which can easily be built and maintained by robotics researchers, is *socially* effective and suitable as a tool for interaction experiments. Also, compared with the iCub, KASPAR is safer to use in interactions even when involving children and tactile interactions with people (cf. Section 4.1.2 where, in the case of children with autism interacting with KASPAR they often touched the robot, e.g. stroking or squeezing the cheeks, tapping the chin etc.). KASPAR moves relatively slowly and cannot exhibit strong forces, which limits the risks involved in human–robot interaction[6]. Even small children can easily stop, e.g. KASPAR's arm movements by simply grabbing its hands/arms, and the coverage of metal parts

[6]We believe that any device or toy used in interactions with people can potentially provide a safety risk, e.g. children can choke on CE-certified commercially available toys. Thus, it is a matter of reducing risks as much as possible.

with clothing (or parts of the original mannequin used for the hands) prevents cuts and bruises.

### 4.3. *Case study III: 'peekaboo' – studying cognition and learning with KASPAR*

This last case study illustrates the use of KASPAR II, as part of the above-mentioned project Robotcub, for the investigation of cognition and learning. In this section we provide a brief summary of this research illustrating the use of KASPAR II. More details about this particular experiment can be found in Mirza et al. (2008).

#### 4.3.1. *Motivation*

Why use a robot to study cognition? The answer to this question defines modern research into Artificial Intelligence and the mechanisms and processes that contribute to the cognitive capabilities of humans and many other animals. Increasingly, the importance of embodiment and situatedness within complex and rich environments are becoming recognised as crucially important factors in engendering intelligence in an artifact (see for example Clancey 1997; Pfeifer and Bongard 2007) and the philosophical position regarding 'structural coupling' of Maturana and Varela (1987). The 'embodied cognition' hypothesis argues that 'cognition is a highly embodied or situated activity and suggests that thinking beings ought therefore be considered first and foremost as acting beings' (Anderson 2003).

That many aspects of cognition are grounded in embodiment is not the whole story though. We want to take a further step and ask 'why use a humanoid robot with expressive capabilities to study cognition?' In this case, two other aspects come into play. Firstly, having a human-like body allows the robot to participate in a social context, and secondly, in the absence of a language, being able to evoke emotional responses in a human interaction partner through facial expressions, the communicative capability of the robot is greatly enhanced.

In this section we describe research work that uses the early-communicative interaction game 'peekaboo' as a scenario through which aspects of ontogenetic development (i.e., development over a lifetime through accumulation of experience) can be studied. The research is focused on understanding how an *interaction history* (Mirza et al. 2007), developed continually over time from the sensorimotor experience of a robot, can be used in the selection of actions in playing the 'peekaboo' game.

'Peekaboo' is a well-known interaction game between infant and caregiver where, classically, the caregiver, having established mutual engagement through eye contact, hides their face momentarily. On revealing their face again the caregiver cries 'peekaboo!', or something similar usually resulting in pleasure for the infant and cyclic continuation of the game. Bruner and Sherwood (1975) studied the game in terms of its communicative aspects showing that timing is crucial. Moreover, research shows that such games can serve as scaffolding for the development of primary intersubjectivity and the co-regulation of emotional expressions with others (Rochat et al. 1999).

#### 4.3.2. *'Peekaboo' experiments with KASPAR*

In order to better understand the experiments, we first provide brief details on the robot's interaction history architecture and its socially interactive behaviour. More information about the experiments and results are provided in Mirza et al. (2008).

*4.3.2.1. Interaction history architecture.* The interaction history architecture has at its heart a mechanism for relating the continuous sensorimotor experiences of a robot in terms of their information-theoretic similarity to one another. At any time the robot's current experience (in terms of the sum of its sensorimotor values for a given period of time, the time-horizon $h$) can be compared to those in its history of interaction. The most similar one from the past can then be used to extract an action policy that was earlier successful. The feedback from the environment acts to enhance those experiences that result in high reward for the robot. By bootstrapping the history, by exploring interaction possibilities, by executing any action from its repertoire, the robot can rapidly develop the capability to act appropriately in a given situation. See Mirza et al. (2007) for further details.

*4.3.2.2. Actions, feedback and reward.* A total of 17 actions were available to the robot, and these can be considered in three groups: movement actions (e.g head-right, wave-right-arm or hide-head), facial expressions (e.g. smile – see Figure 22) and resetting actions (e.g. reset)[7]. The facially expressive actions convey the response of the robot in terms of the reward it receives. This provides instantaneous feedback for the interaction partner. Reward is given as an integral part of the interaction. The human partner encourages the robot with calls of 'peekaboo'. Such an increase in sound level combined with the detection of a face by the robot's camera-eyes, results in a high reward.

*4.3.2.3. Experimental method.* The robot faces the human partner and the interaction history started, initially empty of any previous experience. Interaction then commences with the robot executing various actions and the human offering vocal encouragement when thought appropriate, which continues for about three minutes. Three

[7]The actions that can be executed at any time are restricted for reasons of practical safety of the robot.

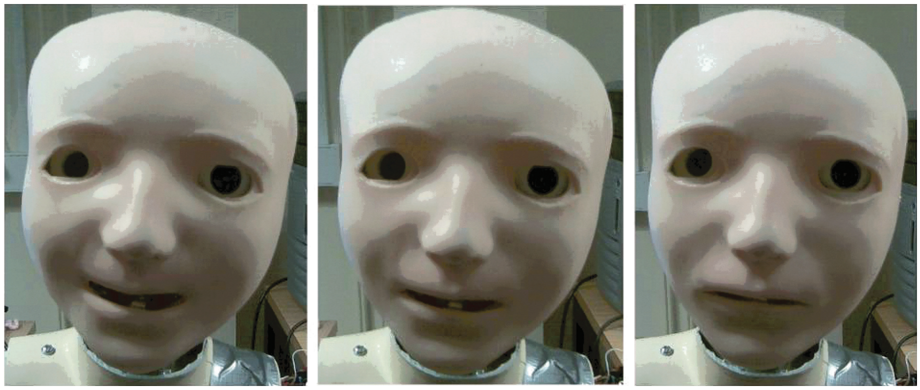

Figure 22. Facial expressions of KASPAR II. From left –to right: smile, neutral, frown.

different conditions were tried. Firstly, the hid-face behaviour was encouraged with a call of ‘peekaboo’ when the robot revealed its face again. The second condition encouraged an alternative action (such as turn-head-left) and the final condition was to offer no vocal encouragement at all during the interaction.

### *4.3.3. Results and discussion*

A total of 22 runs were completed. Sixteen of these for the first condition (encouraging the hiding action), three for the second one and three for the no-encouragement condition. In 67% of the cases where reward was given (‘peekaboo’ or otherwise), the robot repeated the encouraged behaviour. In the cases where no encouragement was given no repeated action took place.

Figure 23 shows for the first run (d0032), how the motivational variables (face, sound and resultant reward) vary with time, along with the actions being executed. The interaction partner encourages the first ‘peekaboo’ sequence (‘hide-face’ on the diagram). Note that the ‘peekaboo’ behaviour is actually a combination of actions to hide

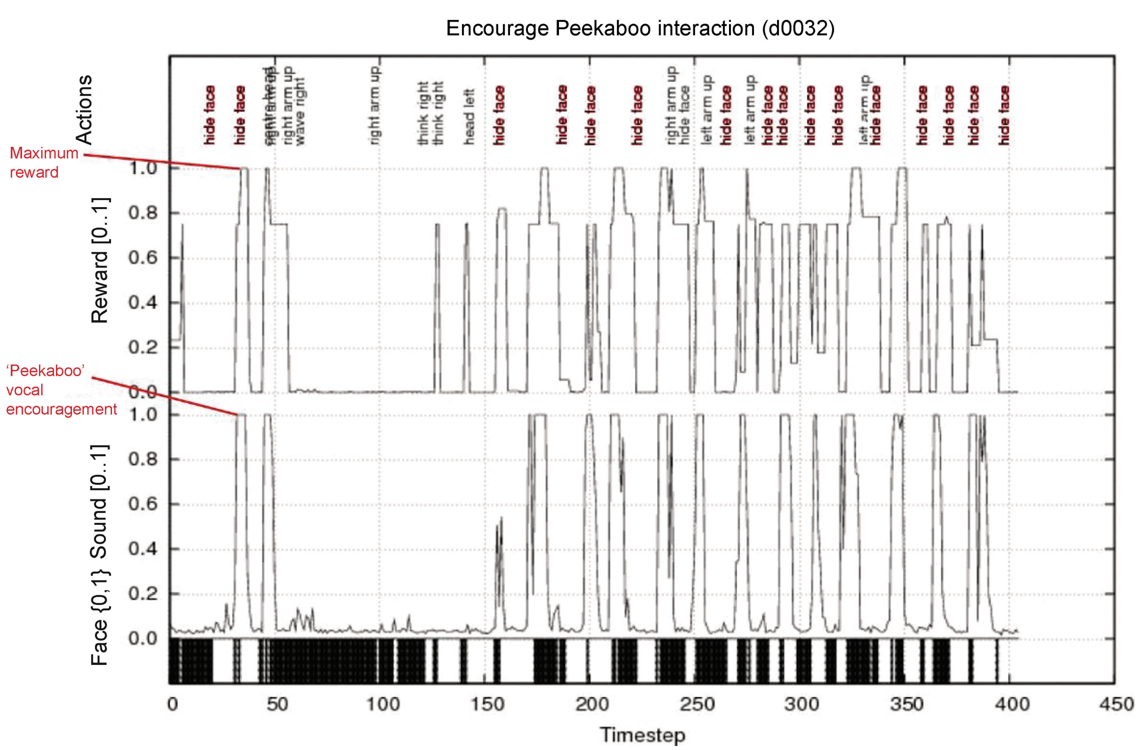


Figure 23. Illustration of results: Example of ‘peekaboo’ encouragement condition. The trace shows, against time, the detection of the face and audio encouragement as well as the resulting reward. Along the top are shown the actions executed.

the face (action 6), any number of ‘no-action’ actions (action 7) and an action to return to the forward resting position (action 0) (for clarity only the primary action is shown on the trace). This results in a maximal reward shortly after the hide-face action, and as the interaction partner continues to reinforce the ‘peekaboo’ behaviour with vocal reward, this pattern can be seen repeated throughout the trace.

The results supported the hypothesis that by encouraging the behaviour the interaction history of the robot would cause combinations of actions to be repeated in search of more reward. Furthermore, the exact combination of actions necessary is not hard coded as other action combinations can be similarly encouraged. Finally, not providing encouragement results in random, non-interactive behaviour. It was also found that the timings of the feedback and thus the interaction were important – too early or too late and alternative actions were encouraged.

#### *4.3.4. Reflections on KASPAR’s design*

Any embodied agent engaging in temporally extended interaction with its environment can make use of an interaction history; however, the particular embodiment plays an important role in managing both the types of interactions that are possible as well as the expectations of such possibilities in an interaction partner. As such, the particular design of the KASPAR series of robots plays an important role. For instance, bearing a physical similarity to that of a human infant means that complex speech will not be expected, but that attention to a human face and sounds might be expected. Probably, the most important aspect of the physical design of KASPAR is its expressive face that provides a mechanism for the robot’s actuators to influence a human interaction partner just as a robotic arm might influence the position of an object. However, in terms of the interaction history, it is also important that the embodiment provides not only suitable actuators and appearance but also well-engaged sensory surfaces. These are crucial for providing information about how the environment is changing with respect to the actions of the robot. As such, the KASPAR robots provide both visual and auditory sensors as well as (in KASPAR II) proprioceptive sensors that feed back information about the positions of its joints over and above the controlled position. Overall, this experiment illustrated the suitability of the robot for quantitative experiments in cognitive and developmental robotics for research involving human–robot interaction scenarios where accuracy and speed of movements is not of primary importance.

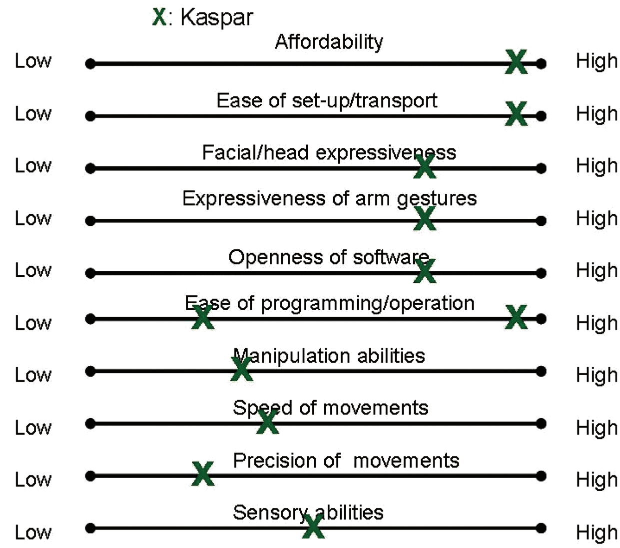


Figure 24. Assessment of the minimally expressive robot KASPAR. The continuous scales ranging from low to high provide a conceptual (not quantitative) assessment. Please note, for the ‘ease of programming’ category two estimations can be made, depending on whether one chooses to operate the robot in remote controlled mode/using the keypad (very easy to operate even by children), or whether the robot is used by researchers to develop new software (requires computer science knowledge).

## 5. Conclusion

This paper has described the development of a minimally expressive humanoid robot – KASPAR. The design rationale, guidelines and requirements, as well as the design of the robot itself were described in detail. We also discussed our approach in the context of related research work on socially interactive robots. While a detailed comparison of KASPAR with other robots, as well as experimental investigation comparing the suitability of those robots in human–robot interaction studies, go beyond the scope of this paper, in the following part we conceptually assess KASPAR (see Figure 24) according to different continuous scales ranging from high to low. We propose these dimensions as relevant assessment criteria for the design of humanoid (or other) robots used for multiple purposes involving interaction with people.

KASPAR affords a variety of usages for human–robot interaction studies in the laboratory or in schools, in being able to provide a high degree of expressiveness and ability to carry out interaction games. Disadvantages of KASPAR concern the technical constraints on its movements in terms of speed, precision etc.; however, these issues are usually not crucial in more socially oriented human–robot interaction research. Note that the ‘mobility’ of KASPAR (i.e. ease of transport) and suitability for a variety of interaction scenarios (see section 4) and application areas are important to the field of human–robot interaction, as most existing robotic platforms are still limited to usage in the laboratory and need to be set up and operated by highly trained staff. KASPAR belongs to a new category of more ‘user friendly’ and (relatively) inexpensive robots that can be constructed by robotic students and researchers with no specific expert knowledge in humanoid robotics.

Generally, any robot designed for human–robot interaction scenarios is likely to have strengths and weaknesses depending on the particular requirements given by their application context. However, the assessment criteria proposed here may also be applicable to other robotic platforms and thus allow a matching of requirements posed by application contexts and robot abilities.

We hope that this paper has served multiple purposes:

- A detailed account of the design of a minimally expressive humanoid research platform that will inform other researchers interested in such designs.
- An introduction of key issues relevant in the design of socially interactive robots.
- An illustration of the use of the robot KASPAR in a variety of research projects ranging from basic research to application-oriented research.
- A discussion of the advantages and disadvantages of the socially interactive robot.

To conclude, designing socially interactive robots remains a challenging task. Depending on its envisaged purpose(s) different designs will be of different utility. Building a robot for a particular niche application is difficult, building a multi-purpose robot primarily for social interaction, as we did, is a huge challenge. The solution we found in KASPAR (and its offspring that already exists and new versions that are in the making) cannot be ideal, but it has served not only its original purpose but also exceeded our expectations to an unforeseen degree. The project to build KASPAR started in 2005 and was envisaged as a two-month, short-term project for a small study on humanoid expressiveness, and it was also the first attempt of our interdisciplinary research group to build a humanoid robot. We succeeded, as evidenced by a large number of peer-reviewed publications emerging from work with the robot. And KASPAR has been travelling the world to various conferences, exhibitions and therapy centres. But how to develop believable, socially interactive robots, in particular robots that can positively contribute to society as companions and assistants, remains a challenging (research) issue. We are still learning, and by writing this paper we would like to share our experiences with our peers.

## Acknowledgements

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## Appendix A

### *Head design and construction*

The head was designed to mount and support the face mask and provide actuation for the facial expressions. The neck has three main DoFs: pan, tilt and roll[8] (see Figures A1 and A2). This did not provide the same flexibility or range of movements possible by a real human (multi-jointed) neck, but allows the robot to express simple head gestures, such as shaking (side to side), nodding (up and down) and tilting (head to one side).

The head also provided another three DoFs for the eyes: eyes up/down, left/right, and eyelids open/close (Figure A1, A3). Miniature video cameras were also mounted in the eyes (Figure A4). Another two DoFs actuated the mouth; mouth open/close, and mouth smile/sad.

The video cameras incorporated into Kapar's eyes are miniature-type cameras, both with a 1/4 inch B & W CMOS Image sensor producing a PAL output of 288 (H) $\times$ 352 (V) with an effective resolution of 240 TV lines, 1/50 to 1/6000 shutter speed, sensitivity of 0.5 lux/f 1.4. The physical dimensions are approximately 20 $\times$ 14 mm (excluding lugs) with a depth of 25 mm and a weight of approximately 25 g. Three wire connections are available: red = +ve (DC 9 to 12 V, 20 mA max), black = common Gnd and yellow = video out.

The head frame was constructed mainly from sheet aluminium, with custom-machined components produced for the universal joint at the neck. The individual parts are bolted together with machine screws and nuts. The RC servos used were mounted on the head frames by means of screws, and transmission of actuation to the neck, face and eyes achieved by means of push-rods (Figure A5).

All the wiring to the servos used the standard three-wire RC connectors and extensions. The video camera wiring was made using fine twin (+Vs and signal) core screened (0 V) flexible cables. Strain relief for the wires was made at the neck joint by means of cable ties (Figures A2 and A5).

### *Arms design and construction*

The arms were constructed from standard kit parts, which are now available to hobbyists at a reasonable cost for making directly driven joint and link chains from standard size RC servos. The forearms from the original shop dummy were mounted on 6 mm machine screws, and attached to form the hand end of the arms (Figure A6). The shoulder ends of the arms were mounted on plates bolted into the shoulders of the shop dummy (Figure A7). The arm wiring consisted of standard RC three-wire connections from each servo back to the controller board, with strain relief provided by cable ties at appropriate points.

### *Controller*

The controller interface board used is a LynxMotion SSC32 Servo controller board (cf. LynxMotion (2007), Figure A8, right), with the ability to control up to 32 servos simultaneously. Only 16 servos are used for KASPAR's movements, so there is the possibility to use additional servos in future enhancements. The board interfaces the host computer via an RS232 serial port, which is mostly not provided as standard on most modern PCs or laptops. Therefore, a small RS232 to USB adaptor board is also included inside

[8]In fact, the neck joints would normally be described as pan, tilt and yaw. However, because of the unusual configuration of KASPAR's neck linkage, the configuration could be more correctly described as one pan, and left and right compound tilt/yaw movements.

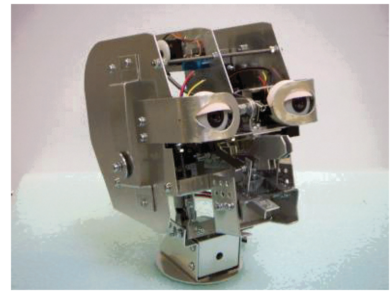

Figure A1. KASPAR's head with silicon rubber face mask removed.

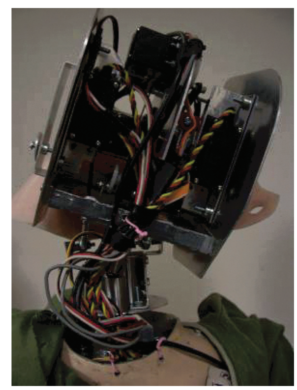

Figure A2. Rear view of head showing wiring and neck joints.

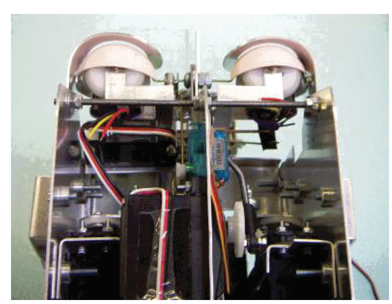

Figure A3. Detailed view of eye actuator linkages.

Figure A4. Miniature video cameras are fitted in each eye.

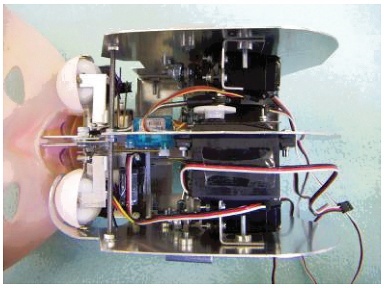

Figure A5. Top view of head showing actuator transmission linkages and wiring.

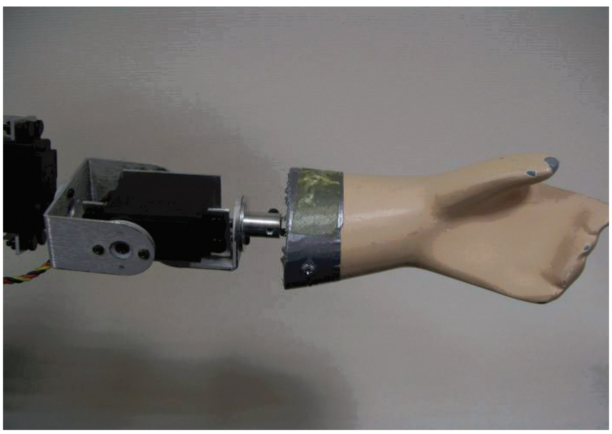

Figure A6. View of arm showing original shop dummy hand attachment.

KASPAR to provide a standard USB interface. Both controller and adaptor board are mounted on an aluminium backplate, which also provides mechanical protection and access to KASPAR's internal systems (Figure A8, left).

### *Power*

For safety, KASPAR is run from two low-voltage lead acid gel batteries. The servo actuators are powered from 6 V, 4 AH battery, and the controller, logic and cameras are supplied by a smaller 12 V, 1 AH battery. Both batteries are protected from short circuits and overload by in-line slow-blow fuses. The main 6 V power fuse value has been set deliberately low (15A) to avoid overloading and subsequent burnout of the expensive high torque shoulder RC servos when manhandling by clients occurs. The batteries are re-charged by two separate chargers, which are connected to KASPAR's batteries by different styles of plug to ensure correct connection. The 6 V charger does not have the capacity to keep the main motor power battery fully topped up while the robot is being used intensively, but if left connected while in use does increase the working time of the robot from about one hour to one and a half hours.

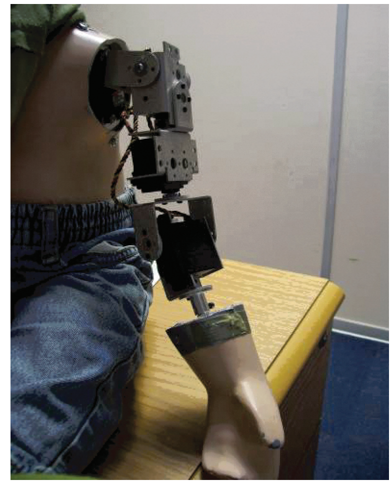

Figure A7. Arm is attached at shoulder end by plates fixed in the dummy body.

## Appendix B

### *KASPAR II*

KASPAR II uses colour video cameras, otherwise the specification of the cameras is identical to those used for KASPAR I, except they are slightly larger with dimensions of 25 × 15 mm and a depth of 20 mm.

KASPAR II's arms use five (one extra over KASPAR I) RC servos apiece, as each incorporates an extra wrist (twist) DoF. The arm links and fittings are custom-made from 1.5 mm thick aluminium sheet, which produces a cleaner, standardised design, avoids the sharp edges which are a feature of the kit linkage parts for KASPAR I and also incorporates extra brackets to mount additional joint position sensors.

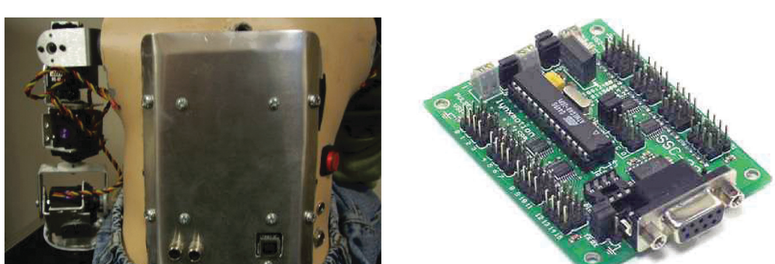

Figure A8. Rear view of KASPAR showing the back plate cover (left); controller board (right).

KASPAR II has arm joint position sensors that provide real-time feedback of the arm positions to the control computer/programme. This is achieved by mounting standard 10 K Ω rotary potentiometers on each arm joint, providing a 0–5 V DC analogue signal proportional to the respective arm joint positions. The analogue signals are then converted by two 8-channel Phidgit USB analogue to digital converters (ADC) which incorporate USB ‘pass through’ connectors allowing them to be ‘daisy-chained’ directly onto the standard USB bus to the host control computer.

Since the original dummy body used for KASPAR I was temporarily no longer available for purchase, the dummy body used for KASPAR II is one modelled after a larger approximately six-year-old child, which provides more physical space to accommodate the extra sensors and interface electronics. There is a hole in the chest, with suitable brackets where a Swiss Ranger 3000 (SR3000) general purpose range imaging camera may be mounted enabling straightforward measurement of real-time depth maps. It uses the on-board power supply (12 VDC, 1A max) and interfaces to a host computer via a mini USB 2.00 connection. The specifications are as follows: 176 × 144 pixels, field of view 47.5° × 39.6°, range up to 7.5 m (for 20 MHz modulation), lens f/1.4, illumination power (optical) = 1 W (average power) at 850 nm and physical dimensions 50 × 67 × 42.3 mm (aluminium).

The head mechanism is identical to that used for KASPAR I, although the wiring is made through connectors to allow easy removal and servicing.

### *Upgrades, changes and planned future improvements*

The limited time for which KASPAR can be operational between re-charges has been a problem, and it is desirable to increase the main 6 V battery life. This could be achieved in a number of ways, either by reducing the power requirements of the robot, or by using a larger capacity 6 V battery or charger. Currently, the fuses are mounted internally and require removal of the back plate for access. A relatively simple change would be to use panel-mounted fuses with external access, which would allow operators to change the fuse easily. A more long-term solution would be the incorporation of a flexible current limiting circuit.

While speech interaction is not the main focus of our research, other future applications would like to incorporate speech synthesis, which could be achieved using a dedicated speech synthesis module via the on-board USB adaptor. An on-board microphone for recording interaction partners’ speech and sound would be convenient, but the noise generated by the robot may make usage difficult. Both these functions may also be achieved very simply by the incorporation of a loudspeaker and a microphone on the robot which could then be connected to the host computer soundcard input and output connections.

The seven different types of servos originally used have now been standardised to just three types. The four shoulder servos and the base neck servo are high torque types ( HiTec 645 MG) and typically cost three times as much as the same sized servos (HiTec HS-422) used for other joints. A single small micro-sized servo (a Supertec NARO HPBB) is used for the pan movement of the eyes. The main limitations with regard to using these RC servos are the relatively poor accuracy obtained and the lack of control feedback. These deficiencies have now been remedied to some extent in new generation servos aimed specifically at the hobby robotics market, but these were not available when KASPAR was designed and built. A review of these new servo types would probably allow the replacement of the original servos with more capable ones, though it is likely that they would be more expensive and require some redesign of the head and arm parts.

The SSC-32 controller has the capacity to potentially control another 16 RC servo actuators. This might be used to add additional facial expressions, or leg movements (for gestures only rather than locomotion in order to maintain the simplicity of the design).