Designing robot eyes for communicating gaze

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Abstract—Human eyes not only serve the function of enabling us "to see" something, but also perform the vital role of allowing us "to show" our gaze for non-verbal communication, such as through establishing eye contact and joint attention. The eyes of service robots should therefore also perform both of these functions. Moreover, they should be friendly in appearance so that humans may feel comfortable with the robots. Therefore we maintain that it is important to consider gaze communication capability and friendliness in designing the appearance of robot eyes. In this paper, we propose a new robot face with rear-projected eyes for changing their appearance while simultaneously realizing the showing of gaze by incorporating stereo cameras. Additionally, we examine which shape of robot eyes is most suitable for gaze reading and gives the friendliest impression, through experiments where we altered the shape and iris size of robot eyes.

Keywords: Gaze reading; facial design; projector camera system

1. Introduction

As the organs of vision, eyes are a vital means of information acquisition. It is therefore not surprising that a vast amount of research has been carried out in the field of computer vision in relation to the information acquisition capacities of robots.

However, for human beings, eyes are not only a means of seeing. They also serve the purpose of communicating gaze, which plays an important social role. It is for this reason that there has been extensive research into robots' vision in the field of HRI. Furthermore, in order to create a more human appearance and impression, eyes are one of the most critical elements. For instance, one blackens the eyes if they want a face to be unidentifiable.

Appearance is important for robots that live symbiotically with humans, and consequently robot developers carefully consider face design. The well-publicized robots Asimo (Honda Motor Co., Ltd., world.honda.com/ASIMO/index.html)

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and HRP-4 (National Institute of Advanced Industrial Science and Technology, www.aist.go.jp/aist_j/press_release/pr2010/pr20100915/pr20100915.html) do not show distinct eyes, instead creating an effect similar to a person covering their eyes with sunglasses. It may be the case that the designers wanted to make the robot appear aesthetically appealing by avoiding a strong impact from the eyes. However, for the purpose of communicating with human beings it is better to show the robot's eyes. Robots such as Robovie (Vstone Co., Ltd., www.vstone.co.jp/english/products.html) and Papero (NEC Co., jpn.nec.com/robot/), which were specifically developed for communication research purposes, feature round eyes. They appear to give the robots a somewhat comical impression. This paper will examine the design of the shape of robot eyes from the perspectives of both gaze communication and impression fostered by appearance.

From the perspective of gaze communication, a gaze that is easily read is clearly the most desirable. As for appearance, what is most suitable depends on the purpose at hand as well as subjective feelings, making it difficult to clearly define what is best. However, if the robot is designed to assist with daily activities, then a good appearance would be one conducive to fostering an impression of a friendly helper of whom one could ask service without hesitation.

Many communication robots, such as Robovie and Papero, have already been developed. With these robots, the issues of gaze communication and impression conveyed by appearance have been taken into consideration in the process of designing their eyes. However, it is the developer who decides the eye design. There has been little research on designing eyes systematically (rather than intuitively) from the perspectives of both gaze communication and impression. There has been work on the readability of gaze using projection eyes; however, the co-relationship between readability and the shape of the eyes has not been discussed. Neither has prior work examined the impression afforded by appearance. This current paper examines the design of the shape of the eyes from both these perspectives.

There are many possible forms of eye shape, but here we focus on two parameters, (1) the flattening of the eye shape, and (2) the size of the iris. According to Kobayashi and Kohshima (2001), human eyes have a white sclera, which makes it easier to detect where the gaze is directed. Moreover, the open area of an eye is relatively flat, and the readability of the gaze from the side remains high. In this paper, we explore which eye shapes are most suited to service robots by testing nine different shapes, consisting of a combination of three levels of flatness and three different sizes of iris based on human eyes.

We began by examining the co-relationship between eye shapes and participants' impressions in terms of perceived level of friendliness. We employed the paired comparison method where the participants saw a pair of faces with different eye shapes. Next, we developed a "projection eye" for our gaze readability experiment. We made a spherical screen, resembling the shape of human eyes, upon which a computer generated (CG) image of eyes was projected. This enabled us to imitate the correct way of gazing in certain directions. We conducted a gaze reading experiment with a static robot gaze by using a robot head with projection eyes. We then evaluated errors in gaze reading, to check the easiness of gaze reading geometric relations. Since realistically one's gaze shifts from direction to direction, we conducted an experiment where the robot eyes would move dynamically in order to analyze gaze reading errors under such circumstances.

The robot head that was used in the experiments consisted of only the front half of a head (i.e. the face). Finally, we miniaturized the projection eye system, and situated it inside the robot head. Additionally, we put ultra-small cameras in the robot head for image recognition processing. This resulted in a new robot head suitable for our purposes. It is obvious that projected eyes possess a high degree of expressiveness. However, humans may find the combination of projected eyes and a mechanical body to be strange. Accordingly, we carried out an investigation of what impressions participants had, in order to compare mechanical eyes (the original ones supplied with the robot that are driven by internal motors and have cameras) and the projection eyes we developed. The results revealed that our eyes gave a favorable impression to the participants, making them acceptable for the intended purpose.

Through these experiments, we were able to establish guidelines for designing robot eyes by clarifying which type of eye shape provides the highest level of gaze readability and effectively conveys a sense of friendliness. Furthermore, we examined the possibility of projected eyes being applied in other research contexts where richly expressive eyes may be required.

2. Related work

The eyes and gaze have been examined in various fields. In biology, Kobayashi and Kohshima (2001) found that among primates only human eyes have no pigment in the sclera; moreover they also have the horizontally longest shape with the largest exposed area of sclera. Various explanations were offered as to why other primates have sclera colored in a similar fashion to their irises or the outside of their eyes. But all the explanations were based on the consensus that primates may avoid clearly showing their gaze. In contrast, human eyes have sclera with clearly different colors from those of the irises and the outside of the eyes. This enables the human gaze to be readily comprehended by others. Kobayashi and Kohshima proposed the hypothesis of "gaze grooming" as the reason for why human eyes have this feature. From this study, we decided to focus in our own study on whether the difference in the shape of the eyes changes the ease of gaze reading.

Aspects of gaze are studied to a considerable extent in sociology and psychology. A mechanism called reflexive visual orienting is identified as a social clue indicating a specific direction that causes the person who sensed it to shift attention reflexively (Langton & Bruce 1999). Reflexive visual orienting is difficult to induce with physical stress (e.g. arrows) (Jonides 1981), and the neural circuits which relate to reflexive visual orienting are different from those which relate to reflexive shifts of attention resulting from physical stress, sudden movement, and others (Kingstone, Friesen & Gazzaniga 2000). Human infants become able to discriminate between direct and averted gaze by the age of four months (Vecera & Johnson 1995). This raises the possibility that even infants use gaze for social interaction with others such as rearers. Moreover, gaze has been shown to play an important role in turn-taking in the field of conversational analysis (Kendon 1967).

Gaze has been studied in the field of human-robot interaction because of the importance of gaze for human beings. The importance of showing a robot's gaze to users has been discussed by Sidner, Lee, Kidd and Rich (2005), and Mutlu, Forlizzi and Hodgins (2006). Meanwhile, Chikaraishi, Nakamura, Matumoto and Ishiguro (2008) developed a natural idling motion system by enabling robot eyes to perform gaze movements indicating reactions to sight information. Kondo, Kawamura, Takemura, Takamatsu and Ogasawara (2011) created a robot gaze expression by linking the eyes and head, and Yamazaki et al. (2007) utilized an eye robot able to express intentions. However, the primary purpose of these studies was to assess issues related to the effective use of gaze, such as eye contact or gaze distribution, in conversations and so forth. The shape of eye most suitable for gaze communication, on the other hand, was not explicitly examined.

Concerning accuracy of gaze reading, differences related to the shape of the face have been examined by Delaunay, Greeff and Belpaeme (2010). They proposed a retro-projected robotic face and conducted experiments assessing a user's ability to read gaze direction for a selection of different robotic face designs. They compared an actual human face, a human face displayed on a screen, a character face projected on a dome, and a character face projected on a human-like 3D-shaped mask. Through these experiments, they concluded that except for an actual human face, gaze-reading by the user was performed most successfully for the 3D-shaped mask with a human appearance. Recently, several more research studies have been conducted. Ando (2004) reported that the perceived direction of the human gaze is affected by luminance distributions in the eye area. Studies focusing on reading gaze direction with human face models were reported by Muro and Sato (2005), and by Misawa, Ishiguro, and Rekimoto (2012).

In terms of robot appearance, not only engineers but specialists in fine-arts have examined related design issues. It is important for service/communication robots working with humans in daily life situations to provide not only functional value but also emotional value (Sonoyama 2007). The amount of information which people receive from robots increases rapidly in the process of shifting from sensory perception to the brain if the robot is dynamic and active. Accordingly, Nakagawa argued that robots require a design which can facilitate positive results from people processing information; he also stated that the design of the eyes is important for a humanoid robot (Nakagawa 2012).

On the topic of the impression conveyed by a robot's design, Blow, Dautenhahn, Appleby, Nehaniv and Lee (2006) explained that natural behavior gives a good impression to users, and that consistency of appearance and behavior is important. Moreover, they stated that an abstracted face made it easier for users to self-project onto the robot (Blow et al. 2006). This is important because self-projection facilitates comfort and ease of interaction.

Although there have been many robots developed, and designers have tried to implement effective designs, there has yet to be a study systematically examining the shape of robot eyes.

This is a serious shortcoming because if the robot's eyes are not suitable they may foster an uneasy impression in the user, making communication and service difficult. It is important to keep in mind Mori's theory of an "uncanny valley" relating to the appearance of robots (Mori 1970). This hypothesis holds that familiarity increases if a robot's appearance is closely modeled on a human, but small differences with humans become conversely conspicuous if a certain point is exceeded, whereupon the robot becomes uncanny and humans are repulsed. Mori proposed that robot design aim at the point just prior to the level of familiarity dropping into the uncanny valley. An abstracted face lies at this point. Accordingly, we conceptually aimed at a design of robot eyes which retain a robot-likeness while approaching those of a human.

3. Design of robot eyes

Based on the eye parameters of pigments focused on by Kobayashi and Kohshima (2001), we changed the lid distance of the eyes when preparing design candidates. We prepared three types of outline shape for the eyes, specifically "round," "ellipse," and "squint." These three shapes were generated by setting the lid distance at 1.0, 0.5, and 0.25 times as long as the eye width, respectively. In the same manner, we changed the iris diameter to 0.75, 0.5, and 0.25 times as long as the eye width, and labeled them "large," "medium," and "small," respectively. Consequently, we had 9 types (the combination of 3 outline shapes and 3 iris sizes) of eye design, as shown in Figure 1. A spherical shape and medium gray color were employed for the robot face in all instances to negate any effect of facial design. Notably, the eye employing the ellipse outline shape and the medium iris diameter (Figure 1-E) is the most similar to the human eye in terms of the ratio of these parameters.

In this paper, we first propose a novel robot head with eyes enabling the functions outlined above, and then we evaluate the accuracy of gaze reading and friendliness in impression for each design candidate.

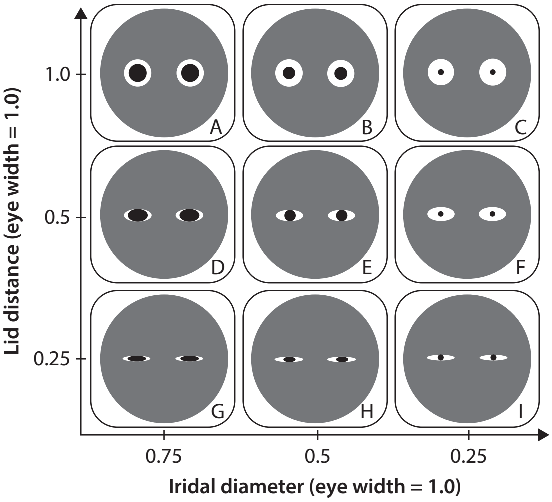


Figure 1. Candidate designs for robot eyes derived by varying lid distance and iridal diameter

4. Evaluation of impression of design candidates for robot eyes

We sought to examine the impression of friendliness by changing the outline shape of the eyes and the size of the iris, and seeing how participants responded. We conducted experiments to ascertain the apparent friendliness of the nine types of robot eyes shown in Figure 1. We evaluated the degree of apparent friendliness by using Thurstone's method of paired comparison. We developed a web-based system for collecting answers from participants. As shown in Figure 2, participants could choose one of the two images of a pair of robot eyes by tapping the iPad screen. We asked participants to answer the question, "These are robot faces. Which face do you think is friendlier?" for all 36 pairs of combinations of the nine types of robot eyes, which appeared in random order. Participants were not permitted to answer the next question until they had answered the previous

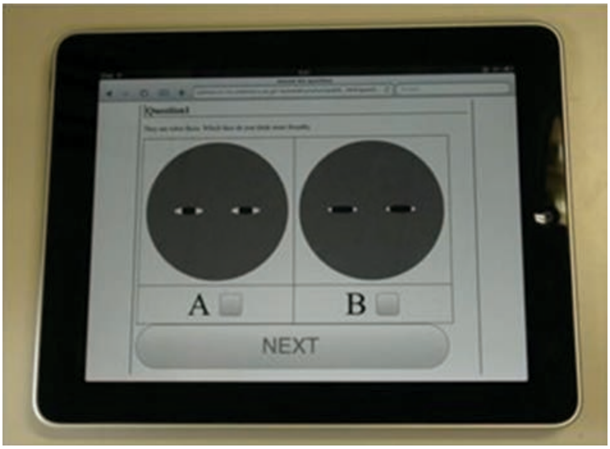


Figure 2. Evaluating the impression of robot eyes through the method of paired comparisons

Table 1. Aggregation results of paired comparison by Japanese students. There are sums of the number of times chosen in the "Sum" line

Participants: 105	A	B	C	D	E	F	G	H	I
A		24	17	18	23	10	7	7	4
B	81		10	30	35	11	10	9	7
C	88	95		44	57	23	28	25	17
D	87	75	61		59	30	5	10	18
E	82	70	48	46		9	13	5	8
F	95	94	82	75	96		43	51	26
G	95	94	82	100	92	62		48	51
H	98	96	80	95	99	54	57		34
I	101	98	88	87	97	79	54	71	
Sum	727	646	468	495	558	278	217	226	165

question. They were also prohibited from seeing their previous answers. Actually, the question was in Japanese. We used 105 participants: 60 males, 43 females, and 2 no-records. They were Japanese students of the school of liberal arts at our university. Participants were not able to see the answers of other participants during the experiment. There was no time restriction for answers.

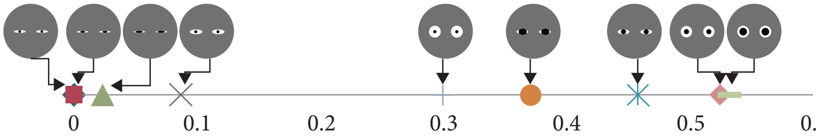
The aggregation results are shown in Table 1. Each figure indicates the number of participants who preferred the eyes in the row to that in the column. We then analyzed the data by using Thurstone's method of paired comparison for scaling the impression of the robot eyes. We adopted the Case III model instead of Case V, which is often used, because the x^2 goodness of fit test showed that the x^2 value of the Case III model became $p > .05$ (Table 2) (Thurstone 1927; Tsukida & Gupta 2011), whereas that for Case V did not (the Case V model assumes the same variation for all distributions, whereas Case III does not). The results are shown in Figure 3. In Figure 3, we performed a scaling so that Figure 1-I, where the scale value is the smallest, became 0. The more chosen the shape of eyes was by participants, the more scale value that shape gained. Clearly, the eyes with round and ellipse outline shapes received a higher score. By analyzing the ratio of the iris and sclera area, we found that the four types of robot eyes that received the highest scores were all characterized by having the iris region occupying more than half of the whole eye region.

This suggests that the apparent friendliness was induced by, first, an outline shape that is not too narrow. Second, it is induced by an iris that is comparatively large with respect to the whole eye region. Thus, from this experiment we can conclude that the friendliest robot face is one with eyes featuring a round outline shape and a large iris (Figure 1-A).

In the previous experiment, all of the participants were Japanese. We sought to investigate whether the result of the experiment with people from other

Table 2. Result of x^2 goodness of fit test in Thurstone's method of paired comparison

	Case V	**Case III**
Degree of freedom	28	20
x^2 value	118.044	3.769
x^2 distribution (5%)	41.34	31.41



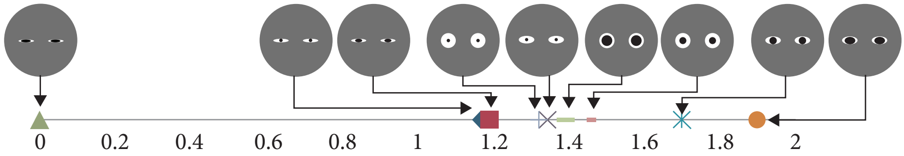
	A	B	C	D	E	F	G	H	I
Scale value	0.531	0.524	0.300	0.371	0.458	0.087	0.023	0.00017	0

Figure 3. Result of scaled experiment in impression of robot eyes by Thurstone's method of paired comparison, case III model by Japanese students. The graph is made by scaling so that Figure 1-I, where the scale value is the smallest, becomes 0. The more a shape of eyes is chosen by participants, the more the scale value that shape of eyes gains

countries would also demonstrate the same tendency. We then conducted the same experiment with Westerners studying in Japan. We gathered 29 participants. The aggregation results are shown in Table 3. The results that we analyzed the data by using Thurstone's method of paired comparison, Case III model are shown in Figure 4 (x^2 value = 29.69, $p > .05$). In Figure 4, we performed a scaling so that Figure 1-G, where the scale value is the smallest, became 0. The results are in general similar to those for the Japanese participants. The apparent friendliness was induced by a not too narrow outline shape and an iris that is comparatively large with respect to the whole eye region. However, the most preferred eyes were different. Westerners preferred the ellipse outline, which is similar to

Table 3. Aggregation results of paired comparison by Westerner students. There are sums of the number of times chosen in the "Sum" line

Participants: 29	A	B	C	D	E	F	G	H	I
A		11	10	23	28	18	18	26	18
B	18		1	22	25	22	20	21	25
C	19	28		23	27	29	24	24	26
D	6	7	6		22	17	12	17	13
E	1	4	2	7		2	6	7	7
F	11	7	0	12	27		13	19	13
G	11	9	5	17	23	16		22	17
H	3	8	5	12	22	10	7		16
I	11	4	3	16	22	16	12	13	
Sum	80	78	32	132	196	130	112	149	135



	A	B	C	D	E	F	G	H	I
Scale value	1.393	1.449	1.320	1.900	1.700	1.344	0	1.190	1.168

Figure 4. Result of scaled experiment in impression of robot eyes by Thurstone's method of paired comparison, case III model by Westerner students. The graph is made by scaling so that Figure 1-G, where the scale value is the smallest, becomes 0. The more a shape of eyes is chosen by participants, the more the scale value that shape of eyes gains

that of a human, whereas Japanese preferred the round outline. This difference is interesting considering the fact that characters often have round eyes in Japanese comics (Manga) and animation.

5. Development of robot head enabling a variety of gaze expressions

In this section, we propose a new robot head with eyes enabling the functions of both "seeing" and "showing" gaze. For the latter function we employ projectors to display various types of eye images generated by computer graphics. For the former function we attach cameras to the robot head to enable the robot "to see." Furthermore, to enable precise control of the eye gaze towards a certain object, we establish calibrations among CG coordinates, camera coordinates and real world coordinates.

An overview of our prototype robot head is shown in Figure 5 (left). As shown in Figure 5 (right), the robot mask can be removed. By replacing the mask, we can change the outline shape of the eyes. The diameter of the face mask is 25cm. The diameter of the eyeballs, which serve as the screens for the projected eyes, is 5cm. The distance between the centers of the eyes (i.e. what for humans would be called the Pupillary Distance) is 10 cm.

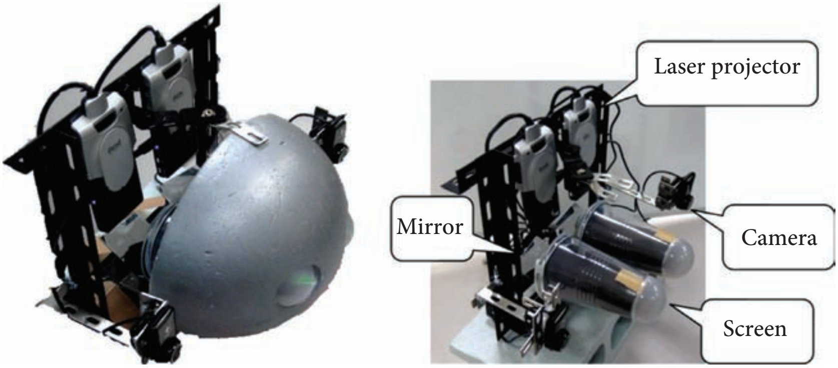


Figure 5. (left) Overview of our proposed robot head (right) The inside of the robot head consists of laser projectors, mirrors and screens

Each of the eyes consists of a projector, a mirror and a screen. The eye images, generated by CG, are projected onto the hemisphere screen via rear-projection. We use a laser projector (PicoP Software Development Kit by Micro Vision Inc.) to obtain the benefit of infinity focus that can project images onto a non-planar screen without focus blur. To avoid extension of the back length of the robot head, we employ a direct reflection mirror.

Additionally, we attach two web cameras (Logicool 2-MP Portable Webcam C905m by Logitech) on both sides of the robot head to acquire images in front of the robot face.

5.1 Projection of eyes

Projection of the eye image is realized through projectors, mirrors, and screens. We use semi-transparent hemisphere screens for the eyeballs of the robot. We then project the CG eyeball, which has the same 3D shape as the projector screen. Generally speaking, the direction of the human gaze is indicated by the normal vector at the center of the iris surface. When we develop robot eyes, then, it is important to consider whether or not we can physically realize this normal vector in a precise way at the center of the pupil of the robot eye. When such images are projected onto a non-planer surface without considering its 3D shape, the appearance of the images on the surface will be distorted. In the case of eye projection, this induces distortion of the iris shape on the eyeball screen. This is a concern as it may affect gaze reading and cause errors. In this paper, therefore, we propose a method utilizing a hemisphere screen that has the same physical shape as the eyeball model generated by CG. By doing so, we can produce a physical object in the real world that has the same shape and texture as the CG model in the virtual world, and thereby avoid errors in gaze reading of projected robot eyes. We employ the top cover of an LED light bulb as the screen of the actual eyeball projection.

In practice, as shown in Figure 6, we first draw the 3D eyeball models in the virtual CG world. Next, the models are captured and rendered by virtual cameras that have the same optical properties as the corresponding projectors in the real world. These rendered images are then projected from the rear onto the screens with the same shape as the 3D CG eyeball model.

As mentioned above, there have been several systems that display human/robot faces on a semi-transparent screen by projecting images from the rear (Delaunay et al. 2010; Misawa et al. 2012) However, in previous systems, the physical shape of the screens and the resulting distortion of the projected images were not considered carefully.

We consider the accuracy of both shape and texture of the projected eyes to be important, especially for gaze reading. In contrast to previous systems, our proposed system is able to produce accurate gaze direction by using the hemisphere screens and eyeball model and through considering correspondence among CG coordinates, camera coordinates and real world coordinates.

We proceeded to conduct preliminary experiments using an aspherical surface for the projection screen. Figure 7 shows the average degree of error calculated on the date of the experiment reading robot gaze by using the round eye outline and all

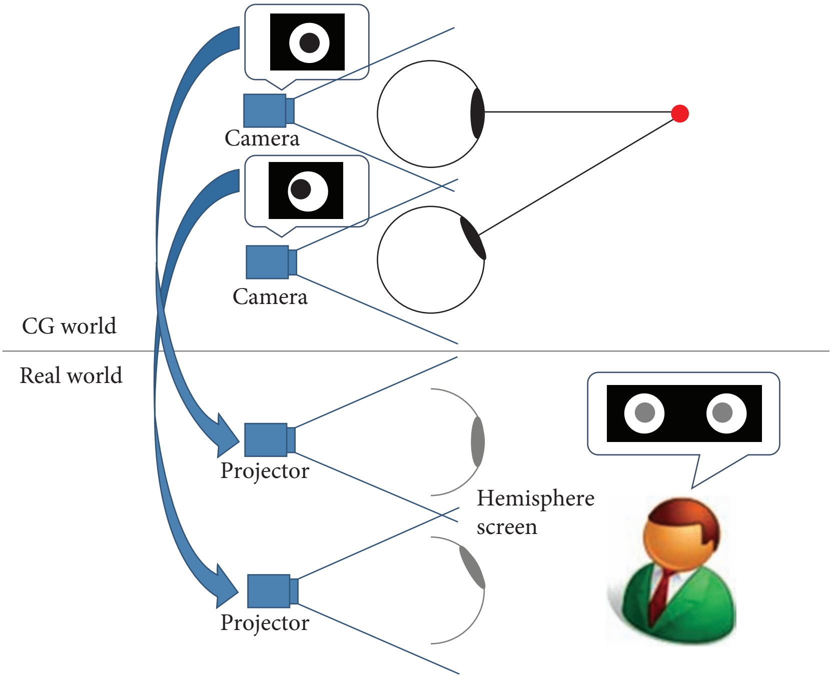


Figure 6. Projection of eyeball model in 3D computer graphics onto the hemisphere screen

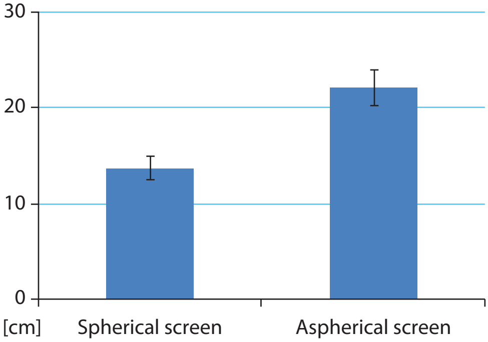


Figure 7. Comparison of average errors in gaze readingbetween spherical screen and aspherical screen. The vertical axis shows the average error (cm)

iris sizes. The left side of Figure 7 shows the result using spherical screens (Figure 8) with the mask shown in Figure 5, while the right side of Figure 7 shows the result using aspherical screens (Figure 9) with the mask. The methods employed in the robot gaze reading experiment are explained in detail in Section VI-A below. The screen shown in Figure 9 is not an accurate sphere, and the eye animations being

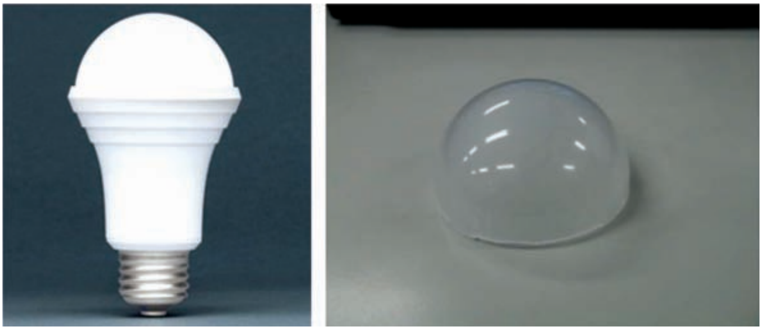


Figure 8. Spherical screens (LED light bulb by HITACHI). These were affixed to the mask shown in Figure 5

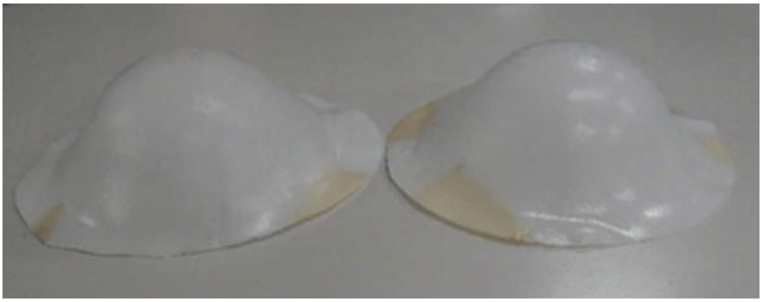


Figure 9. Aspherical screens. These were affixed to the mask shown in Figure 5

projected were not fitted to the screen shape. The screen shown in Figure 8 is an accurate sphere, and the eye animations were fitted to the screen shape.

As shown in Figure 7, the average degree of error when employing an aspherical surface is much larger than when employing a spherical screen. This may be caused by distortion of the iris shape and inaccurate representation of convergence. We noticed this issue when analyzing the gaze reading error distribution for our earlier prototype system which employed an aspherical surface. Neither was the distribution of errors on the left-hand side and the right-hand side symmetrical when an aspherical surface was employed.

In addition to resolving this issue, our proposed method is able to show various types of gaze representations since the projection images are drawn by computer graphics. For example, as shown in Figure 10, nine types of robot eyes could be represented by combining the three types of iris sizes drawn by CG and the three types of masks featuring eyes with different outline shapes.

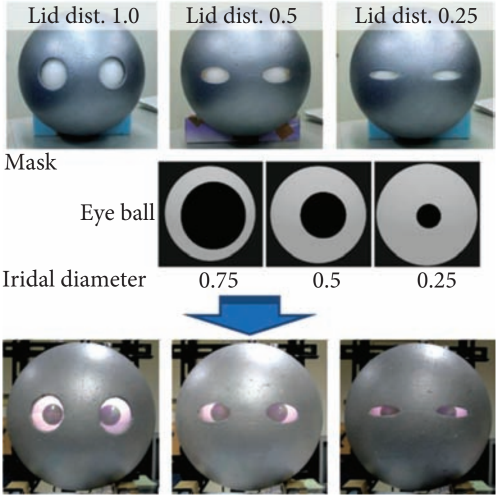


Figure 10. Design candidates for robot eyes are produced by combining the three types of robot masks and eye balls

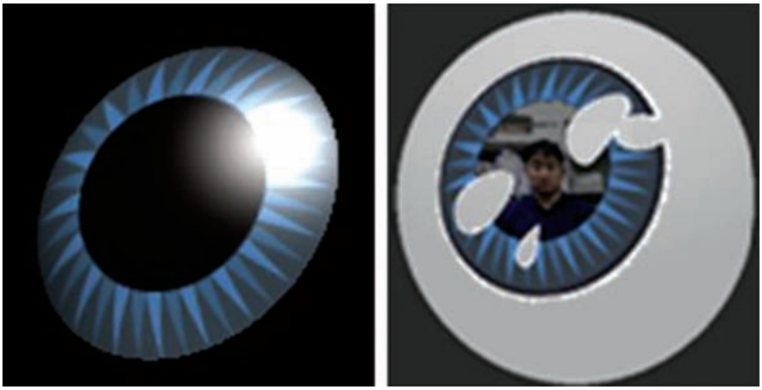


Figure 11. (left) Corneal model with pupil texture (right) Eye ball with video texture to express the surface refraction

Needless to say, it is easy to draw the eyelids so as to represent the eyes blinking. By changing the textures of the iris model, irises of various types of appearance can be displayed. For example, the cornea image in Figure 11 (left) represents the pupil via texture mapping. The image in Figure 11 (right) depicts a trial of the video texture which represents the visual focus of attention through the surface reflection on the cornea. Moreover we can easily apply findings of the studies on virtual agents such as expression of eye movement and emotion (Sate, Kodama & Azuma 2005) to our system. Finally, our method can also represent high-speed eye movement because it does not use any driving mechanism.

5.2 Observing the real world for controlling gaze direction

Human eye pupils are closer to each other when they are looking at a close point located just in front of the face. This convergence plays an important role when a person recognizes where another person is looking at in a 3D environment. In the case of robot eyes, it is necessary to control the left and right eye independently to represent this convergence and thereby show the visual focus of attention. Thus, we use two cameras attached to both sides of the robot head for estimating the 3D position of the target object, enabling us to direct its gaze toward the object as shown in Figure 12 (left).

We use the images captured by the two cameras to estimate the target position in 3D by using stereo triangulation. The target 3D position in world coordinates can then be transferred into a 3D position in CG coordinates, as shown in Figure 12 (right), by establishing the correspondence between the world coordinates and the CG coordinates in advance. The angles on the XY-plane θ_l and θ_r can then be computed. Finally, the CG models of the eyes are rotated toward the target object independently. Vertical control of the gaze direction can be performed in the same fashion.

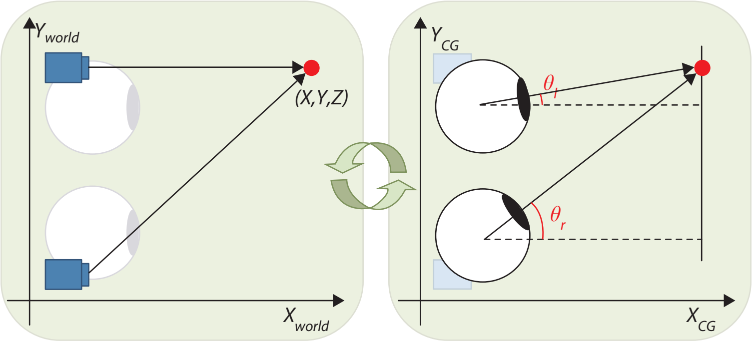


Figure 12. Controlling lines of sight in both eyes based on the 3D position acquired by stereo vision

6. Evaluation of accuracy in robot gaze reading

6.1 Evaluation of accuracy in gaze reading of static robot eyes

To examine how only robot eye design can show gaze direction precisely to humans, we next conducted experiments to analyze the relationship between the accuracy of gaze reading and the shape of the robot eyes. We evaluated errors in gaze reading using the nine types of design candidates for robot eyes shown in Figure 1. These experiments were conducted in the following format.

We lined up a series of markers between the participant and the robot head, as shown in Figure 13. We asked the participant to stand in front of the robot head, face-to-face, with his/her head fixed on the mount. We then asked the participant to state at which marker the robot looked. We used the robot head described in Section V. The distance between the participant and the markers was 100cm and the distance between the markers and the robot head was 50cm. We asked the participants to put their chin on the stand to keep their head position steady. We set the markers at intervals of every 10cm, and numbered these from no. 0 to no. 18. The center marker, which was no. 9, was placed directly in front of the participant. An example, taken from the view of a participant, is shown in Figure 14.

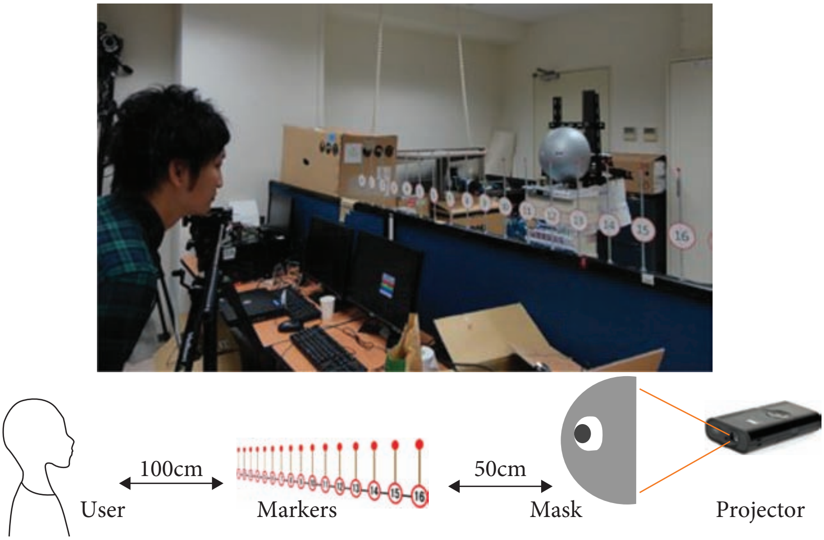


Figure 13. Experimental scene of robot gaze reading

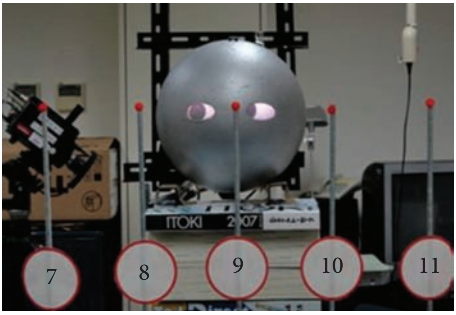


Figure 14. Example of robot's gaze as seen by the participant

In the experiment, the robot only looked at the middle markers, ranging from no. 4 to no. 14, so that the participant would perceive the robot as only looking within the range of space demarcated by the markers. If, for instance, we had the robot look at marker no. 0, the participant may have answered, "the robot looks at no. 0," even when the participant felt that the robot was in fact looking at a position further away beyond the markers. Thus, we used the markers near the end of both sides as dummies to avoid this problem.

We used 36 participants: 30 males and 6 females. They were students in the Faculty of Engineering at our university and were about 20 years old. We divided the 36 participants into 3 groups. The participants in different groups experienced different outline shapes of the eyes shown in Figure 5. All the participants in each group experienced different sizes of iris projected in a random order, with each iris projected for up to 5 seconds with a 5-second interval. Examining how only the robot eye design can show gaze direction precisely to humans, the projected eyes could already see each marker. In order to ensure that the participants answered intuitively, we turned off the CG eyes as soon as they answered. Each participant experienced the robot gazing at 5 predetermined markers, using three iris sizes. Consequently, each participant was required to identify a marker 15 times in total. The experiments needed about 5 minutes per participant.

We calculated the average errors for each design candidate for robot eyes shown in Figure 1. The experimental results are shown in Figure 15. The data were analyzed by a mixed 2-factor ANOVA, with the results shown in Table 4 and Table 5. We used the Holm test (Holm 1979) for multiple comparison, which is a modified method of the Bonferroni method. As shown in Table 4, there were differences among the sizes of iris. Moreover, as shown in Table 5, while there was no difference between the large iris and the medium iris, there were differences between the large and small irises and between the medium and small irises. As a result, it is clear that large and medium irises are more suitable for gaze reading than are small irises.

We then calculated average errors and standard deviations for each marker. The results are shown in Figure 15, Figure 16 and Figure 17. The table in Figure 17 shows the average errors and standard deviations for all shapes' data combined. In

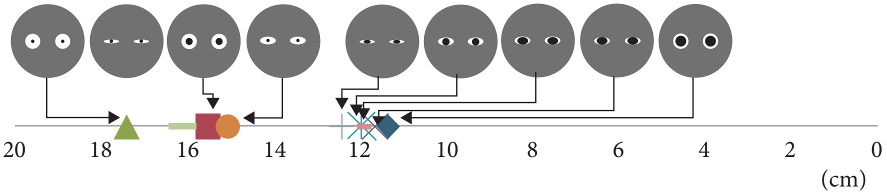


Figure 15. Errors of gaze reading for each design candidate for robot eyes. A smaller value is a smaller error and thus a more readable gaze

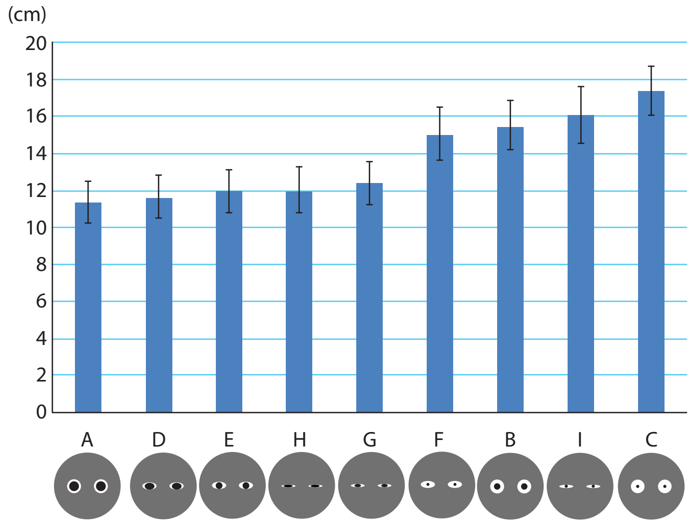
Table 4. Analysis of Variance for accuracy gaze reading (static)

S.V	df	F	η^2	p
A	2	0.76	.023	.26
B	2	12.78	.13	.001
A × B (interaction)	4	1.19	.023	.59
s × B	66			

A = outline shape of the eyes.
B = iris sizes.

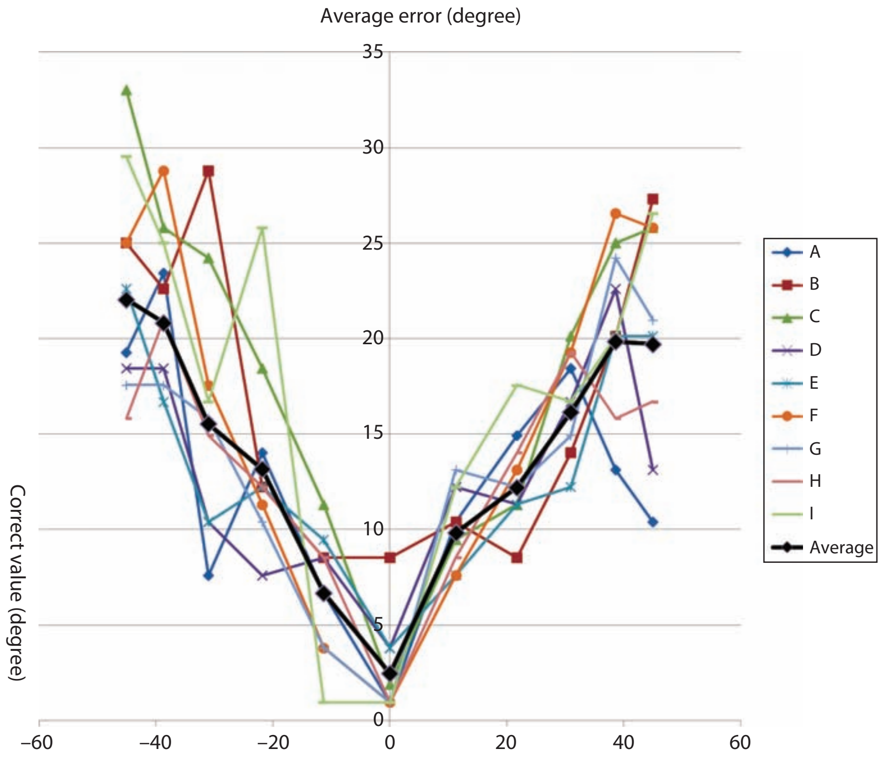
Table 5. Multiple comparisons by Holm

Iris size	Number of data	Mean
Large	36	11.83
Medium	36	13.25
Small	36	16.25
Large = Medium	n.s. (alpha' = .0500)	
Large < Small	$p < .05$ (alpha' = .0167)	
Medium < Small	$p < .05$ (alpha' = .0250)	



	A	D	E	H	G	F	B	I	C
Average error (cm)	11.36	11.67	11.97	12.05	12.42	15.08	15.53	16.14	17.42
Standard deviation	1.113	1.156	1.158	1.235	1.169	1.401	1.305	1.546	1.324

Figure 16. Error and standard deviation of gaze reading. The vertical axis shows the average error (cm). The mark in each bar is the standard deviation. The results are arranged in ascending order of the average error from left to right



(A-I: Eye shapes in Figure 1)

Marker number	4	5	6	7	8	9	10	11	12	13	14
Correct value (degree)	−45	−38.7	−31	−21.8	−11.3	0	11.3	21.8	31	38.7	45
Average (degree)	22.06	20.84	15.53	13.17	6.69	2.46	9.82	12.21	16.14	19.85	19.72
SD	12.66	14.04	12.28	10.98	7.63	5.84	8.45	9.39	11.59	12.84	13.92

Figure 17. Error and standard deviation for each marker. The horizontal bar at each data point in the average result shows the standard deviation

this figure, the horizontal axis indicates each marker's position by the robot's gaze direction (angle) to the marker measured by degree. In general, the error increases as the maker is diverted from the center.

6.2 Comparison of gaze reading between static gaze and dynamic gaze

In the experiment in the previous subsection, the robot eyes were displayed statically. We conducted a further experiment where the robot eyes would dynamically move toward the target marker. The results of this next experiment are shown in Table 6 and Figure 18. We compared the average errors between static gaze and dynamic gaze. Note that we omitted the data pertaining to when the robot looked at marker no. 9 because the dynamic gaze always looked at marker no. 9 first, and so could not perform a dynamic move to no. 9. Correspondingly, the average error of static gaze was calculated for all data except cases where the correct answer was no. 9. As shown in Table 6, there are statistically significant differences between static gaze and dynamic gaze. As shown in Figure 18 all of the average errors of the dynamic gazes are smaller than those of static gazes. Also, all of the standard deviations of dynamic gazes are smaller than those of static gazes. We can therefore conclude that motion can serve as a useful cue for gaze reading. On the other hand, the errors of dynamic gaze demonstrated almost the same trend as those of static gaze, suggesting that motion is not sufficient to compensate for a shape disadvantage in gaze reading.

We then calculated average errors and standard deviations for each marker. Figure 19 shows the result for all dynamic gaze data. The horizontal axis shows the same as in Figure 17. The error also increases as the marker is diverted from the center in the dynamic gaze case.

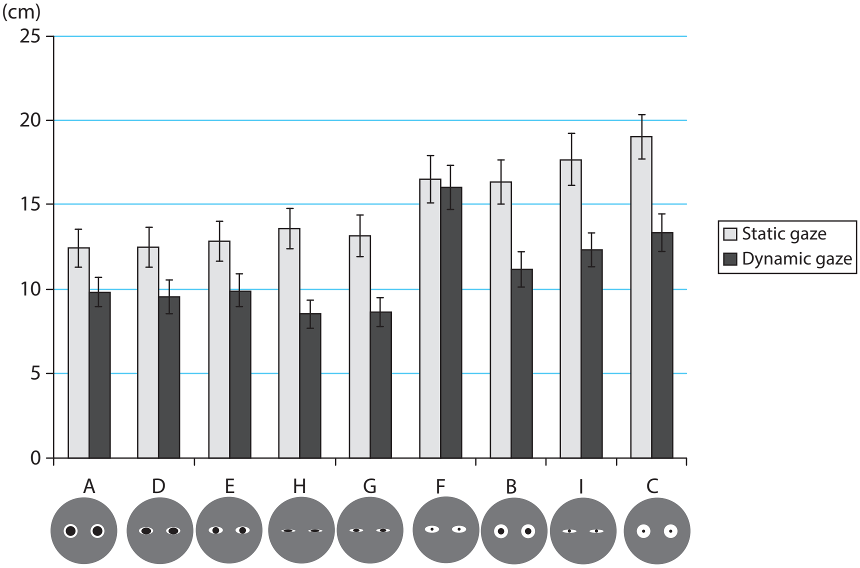
Table 6. Analysis of variance for accuracy gaze reading (dynamic)

S.V	df	F	η^2	p
A	2	0.63	.017	.18
B	2	20.85	.10	.00
A × B	4	1.87	.018	.45
s × B	52			
C	1	16.26	.099	.00
A × C	2	0.80	.0097	0.29
s × C	26			
B × C	2	0.56	.0022	.77
A × B × C	4	1.80	.014	0.29
s × B × C	52			

A = outline shape of the eyes.
B = iris sizes.
C = static gaze or dynamic gaze.

7. Embedding projected eyes into robot products

From the experimental results in the previous section, we can conclude that among the nine design candidates for robot eyes, the design with a round outline shape and a large iris (Figure 1-A) is most suitable for gaze reading and conveying an impression of friendliness.



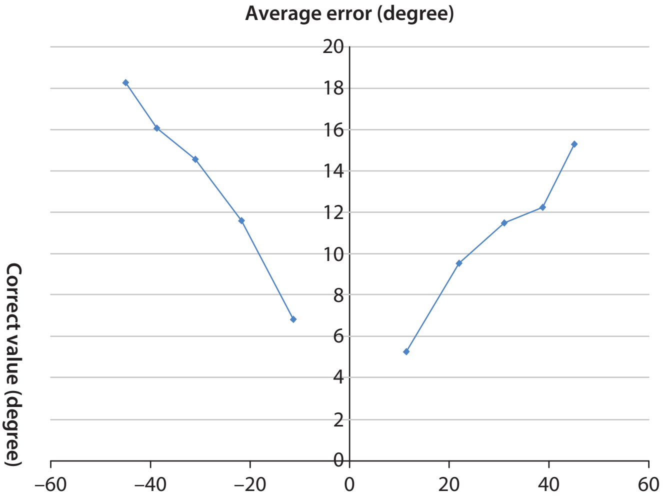
Average error (cm)	A	D	E	H	G	F	B	I	C
Static gaze	12.42	12.5	12.83	13.17	13.58	16.5	16.33	17.67	19
Dynamic gaze	9.83	9.55	9.91	8.5	8.67	16	11.17	12.33	13.33

SD	A	D	E	H	G	F	B	I	C
Static gaze	1.113	1.156	1.158	1.235	1.169	1.401	1.305	1.546	1.324
Dynamic gaze	0.8464	0.9852	0.9486	0.8332	0.8654	1.295	1.034	0.9894	1.135

Figure 18. Comparison of errors in gaze reading between static gaze and dynamic gaze. The vertical axis shows the average error (cm). The mark in each bar is the standard deviation. The order of faces corresponds to Figure 16

Based on this result we embedded our proposed system in a robot product. Figure 20 shows the head of the robot (Robovie-R ver.3 by Vstone) before and after the system was embedded. We employed an ultra-small camera (CMOS Camera module NCM03-V by Asahi Electronics Laboratory) to enable it "to see." Because this camera is very small, it can be installed in the robot face with just a small hole as shown in Figure 20. We drilled a small hole in the face of the Robovie just below the eyes. The cameras were installed in the eye sockets of the original Robovie.

We conducted an experiment to compare the impression given by the mechanical eyes (original) with that of the CG projection eyes (proposed) as shown in Figure 20. Participants saw each motion and were asked to give a rating from 1 to 7 for each question (1: preferred the CG projection eyes most; 7: preferred the



Marker number	4	5	6	7	8	10	11	12	13	14
Correct value (degree)	−45	−38.7	−31	−21.8	−11.3	11.3	21.8	31	38.7	45
Average (degree)	18.27	16.05	14.56	11.62	6.822	5.292	9.559	11.48	12.27	15.3
SD	10.31	11.07	11.26	9.945	8.298	6.546	8.103	10.66	10.99	11.39

Figure 19. Error and standard deviation for each marker for all dynamic gaze data

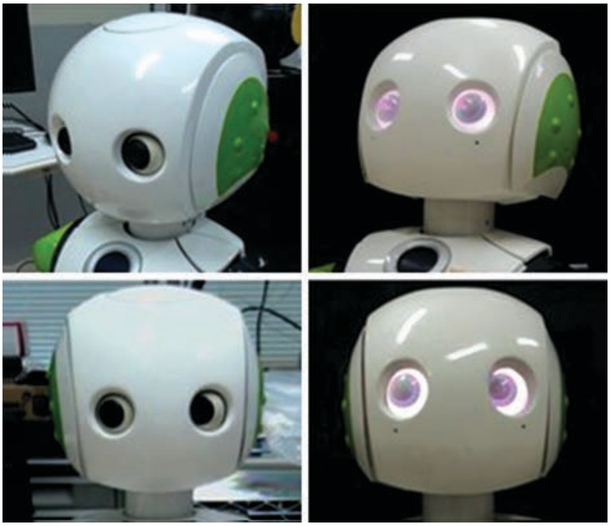
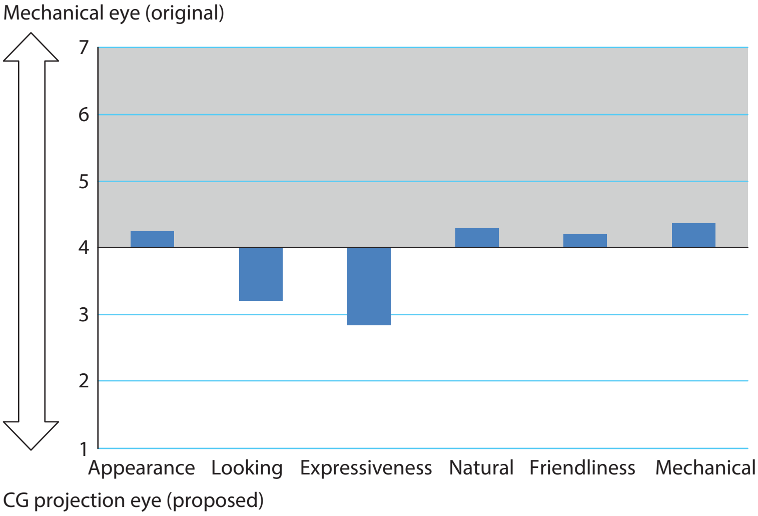


Figure 20. The best design of robot eyes embedded in Robovie-R ver.3

mechanical eyes most). Participants answered 6 questions: “Which appearance of eyes do you like?” (Appearance), “Which eyes do you think are more “looking at” something?” (Looking), “Which eyes do you think are more expressive?” (Expressiveness), “Which eyes do you think are less uncomfortable and more natural?” (Natural), “Which eyes do you think are friendlier?” (Friendliness), and “Which eyes do you think are more mechanical?” (Mechanical). We showed participants the mechanical eyes that moved from side to side by using a video recording. Participants were shown the actual CG projection eyes installed in a robot moving from side to side. We had originally intended to do this for both formats, but having only one robot at our disposal we used a recording to illustrate the mechanical eyes. The CG projection eyes utilized laser projectors. Accordingly, horizontal lines and a slight difference in brightness appear in the CG projection eyes if recorded by a camera. We used 25 participants. They were Japanese students of the Faculty of Engineering at our university. The results are shown in Figure 21. We then analyzed the data by using a sign test. The CG projection eyes were preferred to the mechanical eyes for the questions, “Which eyes do you think are more “looking at” something?” (Looking) and “Which eyes do you think are more expressive?” (Expressiveness). A significant difference was recognized for expressiveness ($p < 0.05$). The other questions did not produce large differences in answers between the CG projection eyes and the mechanical eyes. However the



	Appearance	Looking	Expressiveness	Natural	Friendliness	Mechanical
Average	4.25	3.21	2.83	4.29	4.21	4.38
p value	0.08307	0.08306	0.03469	0.1343	0.1783	0.08318

Figure 21. Result of comparing impressions of mechanical eye and 3D-modelled eye

original eyes moved with a mechanical sound and were slower than the human eyes. In contrast to the original Rovobie eyes, our projected eyes are able to move speedily, smoothly and silently.

Previously, cameras are often embedded inside robot eyes. However, from the gaze communication point of view, though the eyes should be placed at a suitable position, it is possible to situate the stereo cameras on a robot in whatever place is advantageous.

In our robot head design, the cameras can be placed anywhere as long as target objects can be observed. When the robot needs to capture an image from the position of its own eyes, the image can be synthesized from images taken from cameras at different places. We are planning to embed many ultra-small cameras into the robot head and synthesize the viewing image from the position of the robot eyes by applying Light Field Rendering (Levoy & Hanrahan 1996) to improve the sight function of our robot eyes.

8. Discussion

In Section IV, we conducted a scaling of perceived friendliness with 9 shapes of eyes. The shape of eyes that was similar to the human eye shape or rounder in shape seemed to participants to convey the highest degree of friendliness. While it cannot be stated conclusively because of the range of purposes to which a robot may be put, this can nevertheless serve as an indicator for the general design of robot eyes. We concluded the experiment by analyzing with the paired comparison method two faces shown on a tablet PC. It would be ideal in this situation to employ the 3D face which we developed and discussed in Section V, but we would need to create three robot faces equipped with projection eyes. We would change their positions and show them to participants in order to consider a counterbalance of the positions of two of the three faces for the paired comparison method, and it would be difficult to carry out these experiments. There is also a phenomenon known as the Mona Lisa effect (where the eyes always appear to follow the viewer) (Kendon 1967). We believe that it would not be difficult to compare and examine impressions of appearance by using 2D indications from this effect, even though it is necessary to check this in 3D as well.

In the experiment covered in Section VI-A, a state where no eyes were displayed (representing closed eyes) was followed by a depiction of eyes looking in a certain direction. This examined how accurately humans can detect static gaze direction. Recognizing horizontal gaze, we expected that an eye shape akin to that of humans would enable more accurate reading, in line with what Kobayashi and

Kohshima had explained. The results of the experiment, however, showed that eyes with a shape like those of a human did not necessarily enable better accuracy, but rather that there were two groups divided between five eyes which were better and four eyes which were worse. The eye shapes fostering better accuracy all had an iris size like that of a human eye or larger, and an outline shape like a human's or rounder, and all of these experienced a similar result in the degree of accuracy of gaze reading. Conversely, the eye shapes which measured lower in degree of accuracy had a smaller iris compared to the area of the sclera. It seemed that with this group of eyes, it was difficult to comprehend the position of the iris relative to the eye as a whole. Therefore, from the viewpoint of ease of gaze reading, we can conclude that robot eyes should have a large iris vis-à-vis the whole outline shape of the eyes.

In Section VI-A we examined the degree of ease in reading static gaze. However, a real human's gaze shifts from one direction to another, and so in Section VI-B, we examined the accuracy of gaze reading in the case of a dynamic gaze. As with the static gaze, it was possible to classify the results into two groups, namely those eyes conducive to better accuracy and those conducive to worse accuracy. Moreover, the absolute value of accuracy in all cases of dynamic gaze was better than in the case of static gaze. We had been concerned that a round outline shape of eye would prove ill-suited to accurate gaze reading despite conveying a friendly impression, but this turned out to be unwarranted because accurate gaze reading in this case was fine so long as the round outline shape contained a comparatively large iris.

We then proceeded to implement in an actual robot the shape of eyes in Figure 1-A which proved the best in both factors. It is obvious that projection eyes display a high degree of expressiveness simply because of their projected nature. However, the balance with other parts might not prove appealing to a human when the projection eyes are implemented in an actual robot. In Section VII, we conducted a supporting experiment to assess this issue, and concluded that it posed no particular problems. We were thus able to confirm that our method is valid for implementation in applications where expressiveness is desirable.

The mass-produced robot employed in the experiments originally had cameras situated in mechanical eyes. These eyes can turn towards an object if the cameras inside the eyes track an object. Using our proposed eyes, a stereo camera setup consisting of ultra-small cameras attached elsewhere than the projection eyes may recognize the 3D position of an object and control gaze direction appropriately. Therefore, a problem arises if accurate gaze is not indicated should stereo vision fail. However, motor-driven cameras are similarly unable to turn towards an object should tracking fail.

9. Conclusion and future work

In this paper we proposed robot eyes which have the functions of not only "seeing," but also "showing" gaze communication. We developed our proposed system by using projectors and cameras. Projecting various kinds of images onto the eyeball screen enabled various expressions of robot gaze. In particular, we produced physical eyeballs for the real world which have the same shape and texture as the models in the virtual world, by using hemisphere screens. This contributed to representing the precise gaze direction of the robot. Furthermore, we employed a stereo camera system to estimate the 3D position of the target object. Thus, our robot can look at 3D positions in the real world accurately.

We discussed which shape of robot eyes is most suitable for enabling reliable gaze reading and conveying a friendly impression. Because these capabilities are essential for robots working with humans in daily life, it is necessary to consider not only gaze communication capability but also friendliness in designing the appearance of robot eyes. Thorough experiments, we concluded that eyes with a round outline shape and a large iris were most suitable for meeting both requirements.

In future work, we plan to rethink the expression of the robot's visual focus of attention. Doshi and Trivedi (2009) reported that there is a difference in the coordination of eye and head movement between goal-oriented gaze shifts and stimulus-oriented gaze shifts. We are considering applying this human nature onto our robot's gaze behavior to realize more lively expression of the visual focus of attention. Given that we hold the interaction between the robot and its surrounding world to be vitally important, we are continuing to analyze human behavioral patterns for insight.

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