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Influence of the Size Factor of a Mobile Robot Moving Toward a Human on Subjective Acceptable Distance

Yutaka Hiroi[1] and Akinori Ito[2]
[1]Osaka Institute of Technology,
[2]Tohoku University
Japan

1. Introduction

Service robots working around humans are expected to become widespread in the next decade. There have been numerous works for developing autonomous mobile robots, starting as early as the 1980s. For example, Crowley developed the Intelligent Mobile Platform (IMP) which moved around a known domain according to given commands (Crowley, 1985). The issue in the earlier works was how to navigate a robot in a room. HelpMate (Evans et al., 1989) was a mobile platform intended to be used in hospitals for carrying medical records, meal trays, medications, etc. In the 1990s, robots were developed which were equipped with manipulators and executed tasks such as moving objects. Bishoff (1997) developed a mobile robot called HERMES, which is an upper-body humanoid equipped with two arms with hands and an omni-directional vehicle. HERMES recognizes objects around it using stereo vision, and executes tasks such as moving an object from one place to another. Recently, service robots that can execute more complicated tasks using three-dimensional distance sensors and more powerful actuators have been actively developed (Borst et al., 2009; Graf et al., 2009; Droeschel et al., 2011). Along with the development of such service robots, service robot contests have been held such as RoboCup@Home League (RoboCup Federation, 2011), in which mobile service robots compete for accuracy, robustness and safety of task execution in home-like environments. We have also developed an experimental care service robot called IRIS (Hiroi et al., 2003). This robot understood a patient's commands through spoken dialogue and face recognition, and performed several care tasks such as carrying bottles or opening/closing curtains in a real environment. The other feature of IRIS was its safety; IRIS was equipped with various devices for physical safety, such as arms with torque limiters (Jeong et al., 2004).

Safety is the most important issue for this kind of robot, and there have been many studies on keeping a robot safe for humans. Here, we consider two kinds of "safety." The first one is the physical safety of avoiding collisions between a robot and humans; physical safety is the most important requirement for a mobile robot working around humans. The other is mental safety, which means ensuring that the robot does not frighten people around it. Mental safety is as important as physical safety; if a robot's appearance or behavior is frightening, it will not be accepted by people even if it is physically harmless.

There have been many researches for improving the physical safety of robots. For example, sensors are commonly used for avoiding collisions with humans (Prassler et al., 2002; Burgard, 1998), and shock absorbers are deployed around a robot to reduce the risk of injury in case of a collision with a human (Jeong et al., 2005). Heinzman and Zelinsky (2003) proposed a scheme that restricts the torque of a manipulator to a pre-defined limit for safety against collision. As mentioned above, IRIS had a similar kind of torque limiter (Jeong, 2004). Furthermore, a method for evaluating the physical safety of a robot has been proposed (Ikuta et al., 2003).

Compared with physical safety, there have been few studies on improving mental safety. The purpose of the present work was to investigate the relationship between a robot's physical properties—especially the size of the robot—and the psychological threat that humans feel from the robot.

2. Mental safety of mobile robots

In this section, we briefly review previous works that investigated issues related to the mental safety of robots, and describe the objective of our work.

2.1 Previous works

Ikeura et al. (1995) investigated the human response to an approaching mobile robot through subjective tests as well as objective analysis using skin resistance. They used a small robot (250×180×170 mm) moving on a desk. The robot was set at a distance of 700 mm from the subject, and moved along rails toward the seated subject at various velocities and accelerations. The robot approached to a distance of 400 mm from the subject. A subjective evaluation suggested that humans fear the robot's velocity, while they are surprised by its acceleration. Ikeura et al.'s work is interesting, but their robot was too small to generalize their conclusion to real service robots.

Nakashima and Sato (1999) investigated the relationship between a mobile robot's velocity and anxiety. They used HelpMate (Evans et al., 1989) as a mobile robot, and measured the distance between the robot and subject at which the subject did not feel anxiety or threat when the robot moved toward the subject. They changed the velocity with which the robot moved toward the subject, and investigated the relationship between the velocity and the distance. They used 21 university students aged from 22 to 28 as subjects, and five velocities of 0.2, 0.4, 0.6, 0.8 and 1.0 m/s. They examined two postures of the subject: standing and seated. The experimental results showed that the distance was proportional to the velocity, and that the distance was longer when the subject was seated.

Walters et al. (2005) carried out an experiment similar to that of Nakashima and Sato, using a mobile robot called PeopleBot. They discussed personal factors such as gender on the impression on the robot. As these studies used commercially available robots, they could not change the size of the robot.

2.2 Size does matter

Factors of a robot other than velocity also affect the psychological threat to humans around it. The size of a robot seems to have a great psychological effect. The size of a robot is determined by its width, depth and height. When a robot is approaching a subject from in front of the subject, the width and height are the factors that ought to be considered. In this chapter, we consider only the height of a robot because we cannot vary the width greatly

due to stability (a thin shape makes the robot unstable) and environmental (a very wide robot cannot pass through a door) restrictions. Thus, we define the height of a robot as the "robot size." The heights of robots used in conventional experiments have been around 1200 mm.

In this study, we investigated the psychological effects by varying the size of a robot. Although other factors such as the robot's color or materials also affect the impression of the robot, we assume that the effects of those factors are independent of the effects of the robot's size. Next, we define "subjective acceptable distance" as the minimum distance at which a subject does not feel any anxiety or threat. The concept of subjective acceptable distance is identical to that measured by Nakashima and Sato (1999). They defined this distance as "personal space" (Sommer, 1959). However, we decided to avoid the word "personal space" and used "subjective acceptable distance" instead because personal space seems to be a much broader concept compared with the distance we are trying to measure.

We measured subjective acceptable distances using robots of various sizes in order to investigate the relationship between robot size and subjective acceptable distance. Next, we determined whether or not changing the size of a robot affects the anxiety or threat perceived by a subject. We also asked the subjects to answer questionnaires to investigate differences in impression on the robots of different sizes.

3. Experimental conditions

3.1 Robot size

To decide the sizes of robots to be examined in the experiment, we considered the sizes of existing robots. Robots around 1200 mm tall are used in many works such as the general-purpose mobile humanoid Robovie (Ishiguro et al., 2001), a mobile robot for hospital work HOSPI (Sakai et al., 2005) and a mobile robot for health care (Kouno & Kanda, 1998). As a small robot, the assistive mobile robot AMOS was 700 mm tall (Takahashi et al., 2004). AMOS is not a humanoid but a cubic-shaped vehicle with a manipulator and camera. As a large robot, HERMES was 1850 mm tall (Bischoff, 1997). A robot smaller than AMOS could not easily carry objects in an office, for example, while a robot larger than HERMES would have difficulty in moving through a door. We therefore decided to examine three sizes around 1200 mm: 600, 1200 and 1800 mm.

3.2 Velocity of the robot

Next, we decided the velocity of the robots in the experiment. Nakashima and Sato (1999) examined five velocities in their experiment: 200, 400, 600, 800 and 1000 mm/s. They concluded that 800 and 1000 mm/s were too fast and caused great anxiety to the subjects. On the other hand, a velocity as slow as 200 mm/s caused no anxiety at all for some subjects. Considering their results, we set the velocity of our robot to 400 mm/s, which was an intermediate level in Nakashima's experiment.

3.3 Posture of the subjects

During experiments, subjects can either stand or sit on a chair. Nakashima et al. (1999) reported that the subjective acceptable distance became larger when the subject was seated. To investigate the relationship between this effect and the robot size, we conducted our experiment for both conditions of the subject standing or seated.

4. Experimental setup

Figure 1 shows the base of the robots used in the experiments. The base included two driving wheels and two castors, and was 450 mm wide, 390 mm deep and 250 mm high, and weighed 15.0 kg. The body of the robot could be changed by replacing the aluminum frame on its base. A sheet of white paper was glued to the front of the frame so that the robot looked like a white parallelepiped. We prepared three frames, 600 mm, 1200 mm and 1800 mm in height, as shown in Fig. 2.

Nineteen male subjects aged from 19 to 22 years old participated in the experiment. The mobile robot was first positioned at 3 m from the nearest part of the subject, as shown in Fig. 3. The subject started and stopped the robot using a push switch. After starting the robot to move toward himself, he stopped the robot when he did not want the robot to move any nearer toward him.
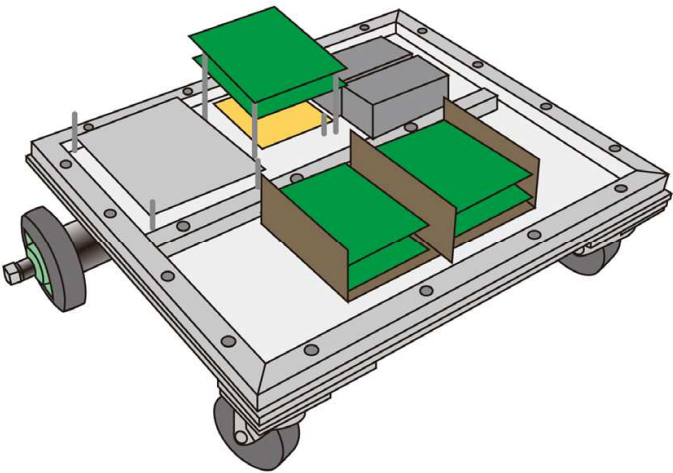

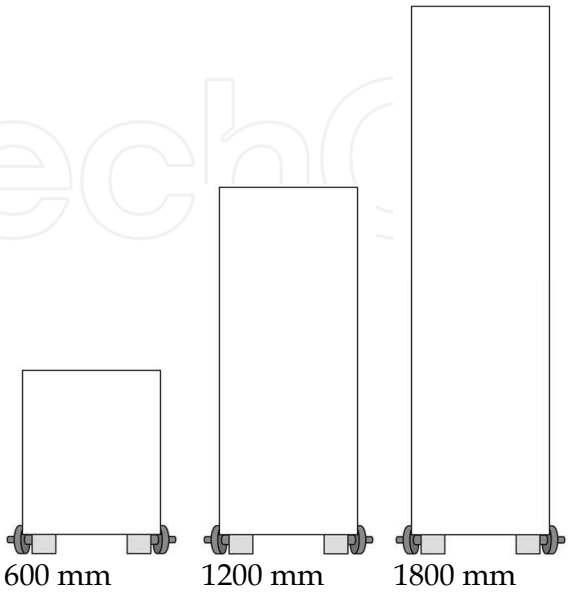Fig. 1. Overview of the base of the mobile robot

Fig. 2. External view of the robots

Influence of the Size Factor of a Mobile Robot
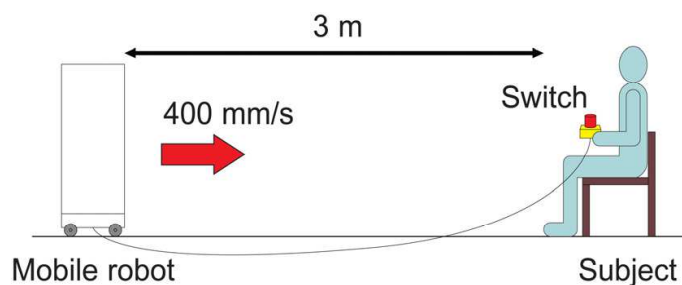Moving Toward a Human on Subjective Acceptable Distance
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Fig. 3. Arrangement of the robot and subject

We allowed the subjects to practice using the switch to ensure the safety of the experiment. Before the experiment, we gave all the subjects the following instructions:

Just after pushing the switch, the robot will immediately start to move toward you from a distance of 3 m at a speed of 400 mm/s. If you feel any anxiety or fear and do not want the robot to come any nearer, please push the switch again to stop the robot immediately. If you feel the distance between you and the halted robot is nearer or further than the distance you intended, please let us know. In case of emergency such as if the robot does not stop, please avoid the robot by yourself. This experiment will be conducted in two postures, seated and standing, using three robots. Please keep looking at the robot throughout the experiment. After the experiment, we will ask you to fill in a questionnaire.

We randomized the order of the experiment (robot size and posture) to cancel out the order effect. If a subject reported that the distance was different from his intention, the experiment was repeated. The measurement was conducted only once for each condition, except failure of measurement. Nakashima and Sato (1999) measured the subjective acceptable distances many times for the same condition, and reported that the variance of distances obtained by multiple measurements was sufficiently smaller than the change caused by other factors. In view of their result, we decided that we did not need to conduct multiple measurements for one condition.

As a result, no subject asked to measure the distance again. There was no operation accident involving the switch, and no collision between the robot and the subject either. The robot remained in good order throughout the experiment. Therefore, the measurement was done just once for one subject and one condition.
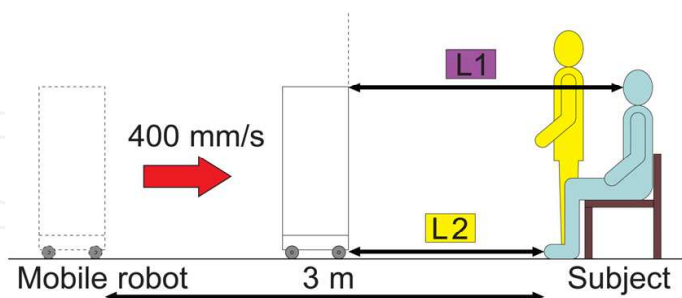

Fig. 4. Definition of distances between robot and subject

After stopping the robot, we measured two distances between the robot and the subject, as shown in Fig. 4. L1 is the distance between the front of the robot and the seated subject's eyes, and L2 is that between the front of the robot and the toes of the subject.

After the experiment, we asked the subjects to answer the following questions:

- Sort the six conditions (three robot sizes by two postures) in order of anxiety.
- Did you feel any differences between the two postures (standing and seated)? If you did, please describe them.

• Other suggestions (if any)

After a subject answered the questionnaire, we assigned scores to the conditions according to the order the subject gave. For example, if a subject answered that he felt the greatest anxiety for the (1800 mm, standing) condition, we gave a score of "6" to that condition (the larger the score, the more frightening the condition). Then we summed up the scores for a condition given by all subjects to calculate the final score for that condition.

5. Experimental results and discussion

5.1 Subjective acceptable distance and subjects' posture

Figure 5 shows the average subjective acceptable distances (L1 and L2) with respect to the three robot sizes. From the figure, L2 seems to change according to robot size. However, L1 for 1200 mm and 1800 mm does not look different. To validate these data, we conducted ANOVA using a randomized block design for both L1 and L2 to determine whether the subjective acceptable distance was affected by robot size. The results showed significant differences in both L1 and L2 ($p < 0.001$). Next, we conducted Dunnett's test to find out whether the subjective acceptable distances at 600 mm or 1800 mm were different from that at 1200 mm. The results showed significant differences for L2s of 600 mm and 1800 mm ($p < 0.05$), and an L1 of 600 mm ($p < 0.01$). However, there was no significant difference between L1s of 1200 mm and 1800 mm. These results suggest that the subjective acceptable distance is greater for larger robots when the subject is standing. However, the subjective acceptable distance does not increase when the robot is larger than 1200 mm and the subject is seated.
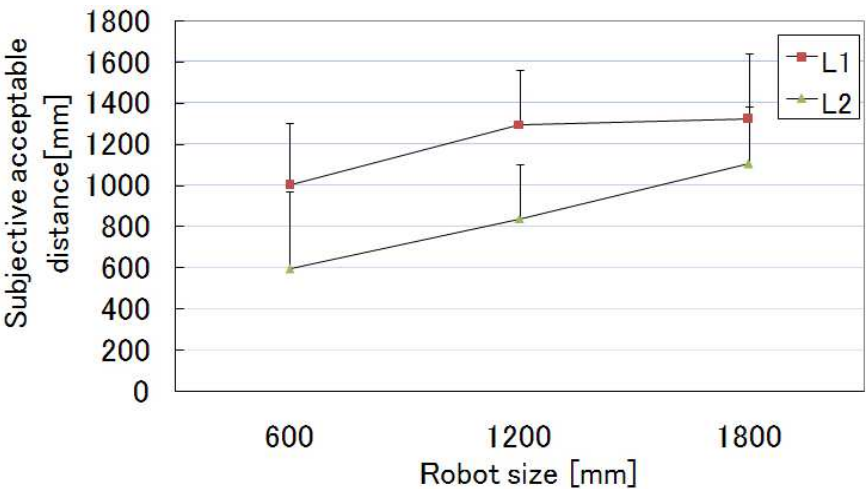

Fig. 5. Relationship between robot size and subjective acceptable distance
(error bars show standard deviation)

The average height of a seated subject's eyes from the floor was 1186 mm, which was comparable with the medium robot size of 1200 mm. When watching an object higher than the observer's eyes, the object's height within the observer's view does not change with the distance between the observer and the object, which means that one of the important cues for distance perception is lost (Gary, 2002). As the effect of cues for perceiving distance is additive (Cutting & Vishton, 1995), losing one of the cues may affect the observer's perception of distance.

When a subject was standing, the average height of the eyes was 1601 mm, which was larger than the small and medium robot sizes (600 and 1200 mm). This fact might have caused the significant differences of acceptable distances when a subject was standing.

If this conjecture is correct, the subjective acceptable distance does not increase for robots larger than 1800 mm even when the subject is standing. However, a robot taller than 1800 mm is not suitable for working in a typical environment such as a home, office or hospital, because it cannot go through a door. Therefore, we did not consider robots taller than 1800 mm.

5.2 Effect of posture on subjective acceptable distance

Nakashima et al. (1999) reported that the subjective acceptable distance was larger when subjects were seated than when standing. To confirm this relationship, we conducted a paired t-test to compare L1 and L2 for each robot size. As a result, we observed significant differences between L1 and L2 for all robot sizes ($p<0.001$ for 600 and 1200 mm, $p<0.01$ for 1800 mm). This result supports Nakashima's conclusion that the distance was larger when a subject was seated.

5.3 Questionnaire results

The results of the questionnaires are summarized in Fig. 6. The x-axis is the robot size, and the y-axis denotes the score of the condition. Each condition is denoted as a symbol from A to E, as shown in Table 1.
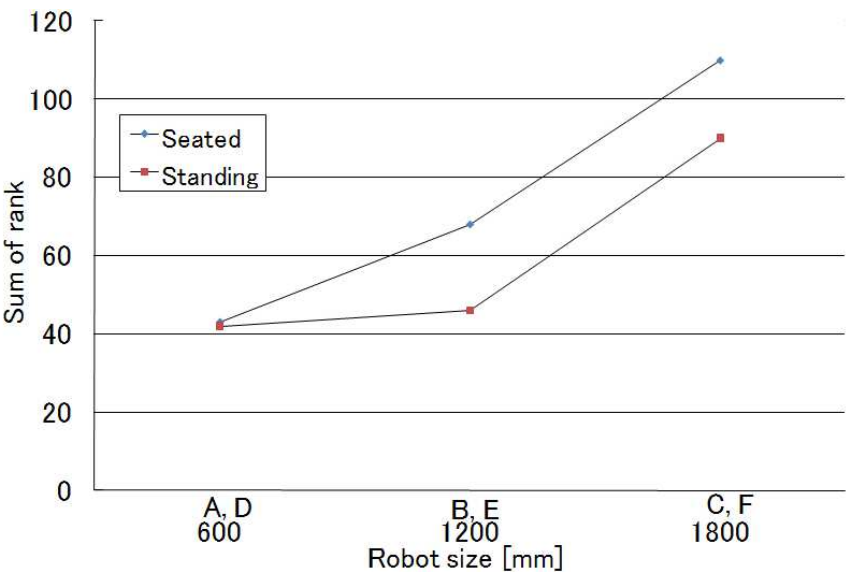

Fig. 6. Comparison of perceived psychological threat between seated posture and standing posture

We conducted Friedman's test upon the result, and obtained a significant difference between conditions ($p<0.001$). Therefore, the anxiety felt by the subjects differed from condition to condition. Next, we conducted a Steel-Dwass multiple comparison test to investigate if there were differences in anxiety between two specific conditions. Table 2 shows the results.
These results can be analyzed as follows.
1. Subjects felt the maximum anxiety for the 1800 mm robot regardless of their posture.
2. Different postures did not affect anxiety for the 600 mm robot. When the robot was larger than 600 mm, seated subjects felt more anxiety than when they were standing.
3. When subjects were seated, subjects felt more anxiety for the larger robot.

Compared with the results shown in Fig. 5, result 1 is consistent with the subjective acceptable distance. However, when the subject was seated, the subjective acceptable distances for the 1200 mm and 1800 mm robots were not different, whereas the anxiety was

larger for the 1800 mm robot. This result suggests that the subjective acceptable distance does not simply reflect the subject's anxiety about the robot.

Condition	Robot size (mm)	Subject's posture
A	600	
B	1200	Seated
C	1800	
D	600	
E	1200	Standing
F	1800	

Table 1. Symbols for the conditions

Cond.	Cond. B	Cond. C	Cond. D	Cond. E	Cond. F
Cond. A	p<0.05	p<0.001	NS	NS	p<0.001
Cond. B		p<0.001	p<0.05	p<0.05	p<0.01
Cond. C			p<0.001	p<0.001	p<0.05
Cond. D				NS	p<0.001
Cond. E					p<0.001

Table 2. Results of Steel-Dwass test

Next, let us consider result 2. In section 4.1, we observed that the subjective acceptable distance of a seated subject became longer than that of a standing subject regardless of the subject's posture. This result could be interpreted to mean that a subject feels more anxiety when standing; however, result 2 from the questionnaire suggests that there was no difference in anxiety between the two postures for the 600 mm robot. To investigate the reason for this inconsistency, we focus on the second question of the questionnaire that asks the subject to describe the difference in feeling between the two postures.

Nine out of the 19 subjects felt anxiety for the 600 mm robot. The comments given by those nine subjects are shown in Table 3; many of them pointed out the relationship between the robot and the subject's sight.

> - I was anxious when the robot went out of my sight
> - When standing, I felt anxious because I couldn't see the robot (anxious)
> - It went out of sight when it got nearer
> - The lower robot almost vanished from my sight and I felt anxious
> - I felt anxious when it went out of sight
> - I felt somewhat uncomfortable because it was below my sight
> - I felt it approached toward my feet
> - I was more scared than when standing because I had to look down
> - I didn't feel any threat, but it was uncomfortable to look down

Table 3. Descriptions of the reasons why the subjects felt more anxiety for the 600 mm robot when standing

Influence of the Size Factor of a Mobile Robot
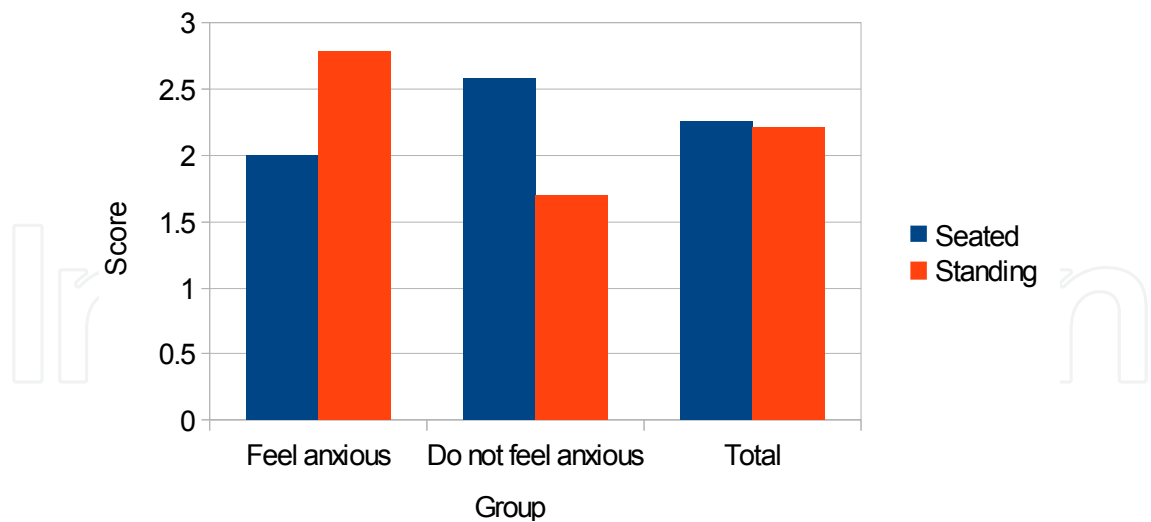Moving Toward a Human on Subjective Acceptable Distance
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Fig. 7. Effect of anxiety about small robot (600 mm) on the difference in perceived threat for different postures

Figure 7 shows the average score (order of anxiety, larger score for more anxiety) for the 600 mm robot for the two postures. "Feel anxious" is the average score for the subjects who felt anxiety for the 600 mm robot (9 subjects), and "Do not feel anxious" is that for the others (10 subjects). From this result, the anxiety score for the "feel anxious" group and the other group showed a different tendency for the two postures, and therefore the total average score for these two groups is similar (2.26 and 2.21). The existence of these two groups of subjects (subjects who were concerned when the robot went below their sight and those who did not care) seems to be the reason why there was no difference in score for the 600 mm robot.

Next, we investigate result 3. In section 4.1, we observed no difference between the subjective acceptable distances for the 1200 mm and 1800 mm robots when the subjects were seated. Result 3 looks inconsistent with this result. In fact, 13 out of the 19 subjects described anxiety for robots taller than their eye height. Therefore, we can conclude that the subjective acceptable distance does not become larger when the robot is taller than the subject's eye height, but it does not mean that the anxieties for larger robots are the same. The invariance of the subjective acceptable distance for larger robots is not because the larger robots cause the same impression of anxiety but is caused by the difficulty of estimating the distance to the robot.

In summary, the robot with 1800 mm height caused the most anxiety to the subjects and the subjective acceptable distance for that robot was the longest. In this case, note that a shorter subjective acceptable distance does not mean less anxiety. Thus, robots of 1800 mm height or more are not suitable for service robots working around humans. Humans will allow a smaller robot to get nearer, but some people feel anxiety for the robot's behavior when they are standing.

6. A method of reducing the threat and anxiety by using preliminary announcement

6.1 Preliminary announcement of a robot's behavior

The experimental results supported the conjecture that the subjective acceptable distance becomes smaller for a robot shorter than 1200 mm and vice versa. Therefore, we can design the size of a robot considering the assumed distance between the robot and users. However,

in reality, it is not usually possible to change the size of a robot, particularly when using a commercial robot. In this section, we discuss ways of reducing a person's psychological threat and anxiety about the robot without changing the robot's size.

In the above experiment, a subject could stop the robot at will when he did not want the robot to come any nearer. However, in real situations where a robot is working around humans, a person by the robot cannot stop it even if he/she does not want the robot to move any closer. Therefore, the distance kept between the human and the robot can be larger than that measured in the experiment.

One reason for keeping at a distance from a robot is that it is difficult to predict the robot's motion. As a robot is an artificial being, it is not possible for a human to infer a robot's behavior from common sense among humans; we cannot predict when a robot will begin to move and stop.

One possible method for reducing the threat or anxiety about robots derived from this uncertainty of behavior is to explicitly announce what the robot will do next. If humans around the robot know the direction in which it will move, they will not be so anxious even when in close proximity.

Existing works on this concept include announcing the robot's velocity and moving direction using a laser beam (Matsumaru et al., 2006) or LCD projector (Matsumaru, 2006). In the former method, the robot draws the trajectory along which it is going to move using a laser beam pointer. The direction of the laser beam is controlled by a mirror, and the beam is projected on and swept over the floor. They evaluated the effect of such an announcement by questionnaires conducted in an exhibition hall. As a result, they reported that half of the respondents answered that they could easily understand the direction and velocity of the robot, and received the following comments:

- The shape drawn by the laser beam should be an arrow, rather than a line
- The method of showing the velocity could be improved
- This method can be applied to industrial robots
- The method should be combined with another type of method, such as a speech-based method
- Children might have difficulty understanding the meaning of the beam

As shown, Matsumaru et al. received many opinions on ways of improving the display method, even though they explained to the respondents the background and purpose of their research, proposed announcement method, and overview of the robot. A preliminary announcement must be easy to understand for someone looking at the robot for the first time. These opinions reveal that the laser-beam-based announcement method needs further improvement.

The method based on video projector (Matsumaru, 2006) projects icons such as an arrow, turning signs, "STOP" sign and "BACK" sign onto the floor. A video projector can present more information than a laser beam. The direction of the robot is presented by the direction of the arrow, and the velocity is expressed as the thickness and color of the arrow. When the robot is going to rotate, the color of the turning sign changes. When the robot is going to stop or go backward, the color of "STOP" or "BACK" is changed. Matsumaru evaluated the announcement method using the same criteria as used for evaluating the laser-beam method. The subjective evaluation showed that the projector method was easier to understand than the laser-beam method for both direction and velocity. The problems of the projector method are summarized as follows:

- As the projected image depends on both the lighting condition and the floor, it cannot be used in a bright environment or on ground that is not sufficiently flat; for example, the method is difficult to use outdoors.
- As the information is projected in front of the robot, humans behind the robot cannot see the projected information.
- Humans around the robot need to pay attention to the floor rather than the robot itself.

Therefore, we need to develop a method that is not affected by the environmental conditions such as lighting or floor condition, is able to present the robot's behavior in all directions, and attracts human attention to the robot's body.
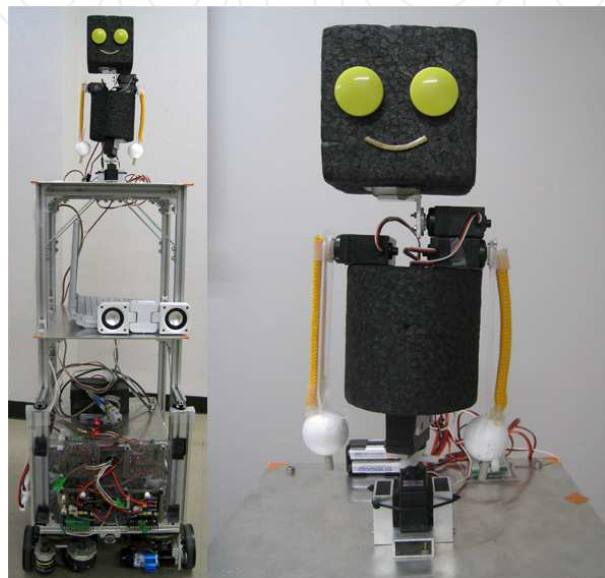
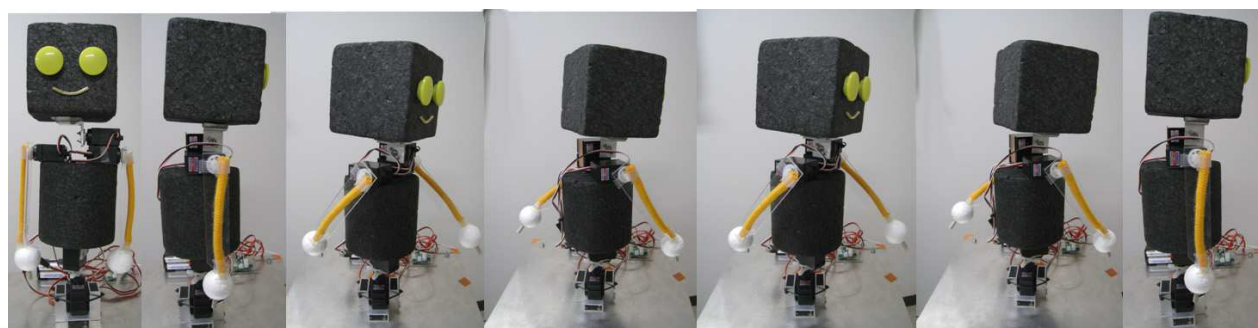Fig. 8. Overview of the experimental robot avatar

Fig. 9. Motion of the robot avatar

6.2 Preliminary announcement using a robot avatar

We propose a preliminary announcement method using a robot avatar. A robot avatar is a small robot mounted on a large robot for communication (Hiroi et al., 2005). An example of a robot avatar is shown in Fig. 8. The proposed method announces the (bigger) robot's behavior through the robot avatar's motion. There are many advantages of using a robot avatar for preliminary announcement of robot motion:

- The preliminary announcement can be intuitive.
- The motion of the robot avatar can be prominent if the avatar is mounted at around a human's eye height.

- Its visibility is more robust to environmental changes than the projection-based announcement method.
- If the large robot were to make announcements, the motion could be dangerous because the robot's arm could collide with a human. A robot avatar is safer because it is smaller and lighter.
- It is easy to make a robot avatar look friendly.

Figure 8 shows the robot avatar we are developing. This robot avatar can swing its arms and change direction in order to make the announcement motion. As an announcement motion, the robot avatar swings its arms and changes direction towards which the larger robot is about to move (Fig. 9). We are verifying the effectiveness of this method through subjective evaluations.

7. Conclusions

We investigated the effect of robot size on subjective acceptable distance using three robots of different sizes. The results showed that the acceptable distance becomes smaller when the robot is smaller than 1200 mm, and vice versa. However, the relationship between robot size and distance was nonlinear, and the acceptable distance saturated when a subject was seated. One possible reason for this saturation could be a relationship between a robot's height and the eye height of the subject. This experiment showed a mutual effect between robot size and posture of a subject. Therefore, the size of a robot should be designed considering the likely posture of robot users.

We also conducted a survey on the impression of the robots, and found that robots taller than 1800 mm caused too much anxiety to be used safely in practice.

This work is the first investigation of the relationship between robot size and its effect on human impression, considering the real use of service robots. The results of this work will be useful for designing actual robots working around humans.

The experimental results obtained for square-shaped robots can be directly applied to mobile carriers (Kouno & Kanda, 1998; Sakai et al., 2005). A smaller robot is desired if we wish to minimize the acceptable distance between a robot and a human; however, the robot should be larger for carrying larger payloads. Considering these conditions, a robot size of 1200 mm could be the best among the examined three robot sizes.

In future, we plan to evaluate various factors affecting the impression of a robot, including the age and gender of subjects (Walters et al., 2005; Mutlu et al., 2006), human factors such as knowledge and rapport with the robot (Nomura et al., 2007), as well as the robot's color (Goetz et al., 2003) and velocity patterns (Ikeura et al., 1995; Nakashima & Sato, 1999). The effectiveness of using a robot avatar for preliminary announcement should also be tested.

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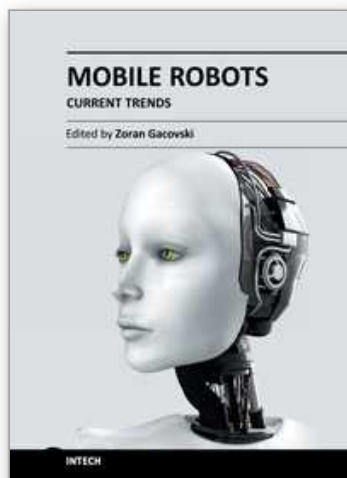
Mobile Robots - Current Trends

Edited by Dr. Zoran Gacovski

This book consists of 18 chapters divided in four sections: Robots for Educational Purposes, Health-Care and Medical Robots, Hardware - State of the Art, and Localization and Navigation. In the first section, there are four chapters covering autonomous mobile robot Emmy III, KCLBOT - mobile nonholonomic robot, and general overview of educational mobile robots. In the second section, the following themes are covered: walking support robots, control system for wheelchairs, leg-wheel mechanism as a mobile platform, micro mobile robot for abdominal use, and the influence of the robot size in the psychological treatment. In the third section, there are chapters about I2C bus system, vertical displacement service robots, quadruped robots - kinematics and dynamics model and Epi.q (hybrid) robots. Finally, in the last section, the following topics are covered: skid-steered vehicles, robotic exploration (new place recognition), omnidirectional mobile robots, ball-wheel mobile robots, and planetary wheeled mobile robots.

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