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A motion rule for human-friendly robots based on electrodermal activity investigations and its application to mobile robot*

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***Abstract*— This paper investigates impressions on the robot motion based on EDA experiments, deduces a motion rule for human-friendly robots from the investigations, and applies it to a mobile robot experimental apparatus. In our previous work, it was suggested that actuation noise come from the robots tended to raise the sympathetic nerve system (SNS) response of the heart rate variability. In another experiment it is observed that blocking out either the sound or the sight attenuated the electrodermal activity (EDA), which reflects the SNS, to the robot motion. In the present work, the experiment was designed not so as to avoid the influence of the habituation differently from the previous experiments, which was the significant factor contributing to reducing the EDA responses. As a result of statistical analysis, it was concluded that the present work supported the result of the previous work. Based on these investigations, we deduced the motion rule for human-friendly robots from this investigation, that robots must reduce their motion speed in the immediate vicinity of humans.**

We constructed the experimental setup that a mobile robot approached human with its speed decreased in conformity with the rule. To estimate the distance from the human, the skin color detection and depth-from-focus techniques were applied to a monocular color video camera system with pan/tilt/zoom operation. The experimental result showed that a proper choice of commands could perform the robot motion to reduce its speed in the immediate vicinity of the human.

***Index Terms*— motion generation, Human-friendly robot, Skin conductance response, EDA, Depth-from-focus**

I. Introduction

These days there are a lot of developments of human-friendly robots such as home robots, pet robots or service robots. The improvement in technologies of mechatronics and computer turns such developments into reality. The diffusion of such robotic device will make the space between robots and human narrower. In industrial applications, the robots are isolated from human to ensure the human safety [5], [6]. However in the living space environment where the overlap of the work space between the robots and human may happen, it is important to consider the safety of the users physically and mentally.

From the point of the view of safety, there has been done many researches. For physical safety of human the collision with robots must be avoided. Some researches devoted the detection of the collision. One approach to detect the collision is model-based analysis. It builds the model of objects and human in the computer and simulates their movements to check the collision[7]. Another approach is sensor-based detection. Usually robots have sensors to measure environment around the robot. By combining the sensor data it is also possible to introduce enhanced redundancy in the safety system[8], [9]. Once the collision happens, it is required to minimize damage of the human. Or the human may possibly come in contact with robots driven by necessity. One approach to avoid human's damage or pain is to give elasticity to the robots, such as with viscoelastic cover [10] or mechanical springs and dampers[11]. Simultaneously control of the robot is necessary. To concerning the safety issue into the control, the human pain tolerance limit[10] or the danger index [12] have been introduced. The cost functions for the safety should be optimized [13].

On the issue of the mental safety or stress of human facing to a moving robot, there are some analytical researches which evaluate human responses using subjective evaluation method or physiological data. Shibata et al. [14] showed several kinds of motions of a robot manipulator to subjects and investigated essential factor of the motions for human-likeness. They used a rating scale method for the subjects to evaluate the motions. Ikeura et al. [15] measured galvanic skin reflex (GSR) of subjects who saw a robot approaching to them, and evaluated the speed pattern of the robot using GSRs and subjective evaluations. Yamada et al. [16] used pupillary dilation of subjects for evaluation of feeling of fear when the subjects grasped a moving robotic gripper in several speeds.

Motions of robotic devices give stimulus to humans mainly through auditory and visual modalities. Our previous work indicated that actuation noise come from the robots tended to raise the sympathetic nerve system (SNS) response of the heart rate variability (HRV) [4]. In another experiment we used electrodermal activity (EDA) to evaluate the SNS response [1] for the reason that HRV analysis which processed data in frequency domain claimed data acquisition for more than 25 seconds. Alternatively, the signals related to EDA respond to the stimulus instantaneously. The experiment was

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performed with three conditions to control the influence of auditory and visual modalities; which were presented with blocking out the sound, with blocking out the sight, and without blocking. From the experimental results it is observed that blocking out either the sound or the sight attenuated the EDA responses to the robot motion. However for every experiment the order of three modal conditions has been fixed. It is known that the influence of the habituation was the significant factor contributing to reducing the EDA responses. Therefore the observation mentioned earlier could have a chance of being affected by the habituation.

This paper could be divided into two parts. First part described additional EDA experimentation. In this experiment a subject requested to test all combinations of the order of three modal conditions. Taking average of the data categorized by same condition, we could avoid the influence of the habituation caused by the order of the measurement. The analysis of variance leaded to the similar result as our previous EDA experimentation. Second part described a simple rule for the motion of human-friendly robots derived from the EDA investigation in the first part. If the robot would move rapidly and dynamically, the noise and the visual stimuli from the robot motion tended to be louder and large respectively. This could lead us to a simple consequence. Namely to prevent enhancement of the SNS responses of users around a human-friendly robot, the robot should move slowly in the immediate vicinity of the user. We constructed the experimental setup that the robot could detect human approaching and reduce speed. The robot was composed of a color video camera with pan/tilt/zoom operation and two-wheeled differential drive platform. To estimate the distance between the robot and the human, the skin color detection and depth-from-focus techniques was implemented [20][21][22][23]. Finally we showed the result of this experiment.

II. EDA EXPERIMENTATION FOR AUDITORY AND VISUAL MODALITIES

A. Method

1) Subjects: Subjects were two male volunteers age 21–22 years old. They were students with experience in mechanical engineering and familiar with the robotic device. They gave informed consents to take part in an experiment. They were notified of robot motion, procedure of the experiment, instruction to fill in questionnaire in advance of the experiment.

During the experiment, the subjects were asked to sit on a swivel armchair in front of a robot manipulator within the distance of one meter. The subject and the robot manipulator were surrounded by white curtain partitions and wall. Directions to the subjects were notified orally or by an LCD screen.

2) Presented motion of the robot: The robot manipulator (RM-501, Mitsubishi electric corp., Fig.1) with 5 D.O.F., whose DC motors equipped in each joint were driven by a robot driver in speed command mode (Titech robot driver, PC-0121-1, Okazaki Sangyo) , and controlled by a personal computer (IBM PC-AT compatible). The experimental setup is shown in Fig.2.

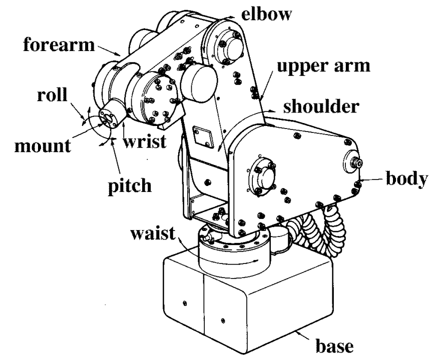

Fig. 1. Robot manipulator with 5 D.O.F involved in experiment. (quotation from the operating manual)

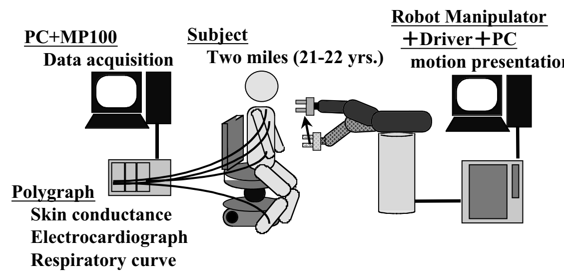

Fig. 2. Experimental setup and robot motion presented to subjects.

The prepared motion to be presented to the subject was that the robot stretched its arm toward the subject within two seconds, kept it in two seconds, and then instantly put it back to the original posture within two seconds. The displacement of the end-effector was ten centimeters forward and twenty centimeters upward on the first half way.

3) Conditions for modality: The measurements were carried out under three conditions for the modality; VA, V, and A, respectively.

In the VA condition, the subjects were able to hear the robot sound and see the robot motion, that is, they had both of visual and auditory modalities.

In the V condition, the subjects were not able to hear the robot sound but could see the robot motion, that is, they only had visual modality. To block out the robot sound, the subjects wore earplugs and a full-sized sealed headphone sounding white noise. Also the subjects adjusted the magnitude of the white noise appropriately by themselves in advance.

In the A condition, the subjects were not able to see the robot motion but hear the robot sound, that is, they only had auditory modality. To avoid seeing the robot, the subjects had blinders on.

4) Measurement: The skin conductance response (SCR) was measured by a physiological measuring equipments (MP100A-CE/UMI100C/GSR100C,BIOPAC), filtered through low-pass filter with cut-off frequency of 1.0 Hz and high-pass filter with cut-off frequency of 0.05 Hz, and recorded onto a personal computer (IBM PC-AT compatible) via USB interface. Two electrodes were placed on the index finger and the middle finger respectively. The data acquisition software on the PC managed, transformed and displayed the measured data. Simultaneously electrocardiogram and respiratory curve were measured and displayed to confirm whether the subject was at rest. During the experiment the room temperature was kept around 22 degree Celsius.

When we continue to give the same stimuli to a subject the SCR is intend to decrease. This phenomenon is well known as habituation. By changing the orders of the condition and averaging the data categorized by the same condition we would get rid of the influence of the habituation statistically. The orders of the experimental conditions are shown in Table I. One subject engaged in the experiments twelve times at intervals of three or four days. On each day one of the six combinations on the Table I was picked up by rotation and repeated twice. For example on the first day the experiment was proceeded in the order of the conditions; VA, V, A, VA, V, and A.

5) Questionnaires: In each condition, the subjects were requested to evaluate their impression on the robot motions. To do this the semantic differential technique was used and the questionnaires were prepared which included three pair of adjectives shown in Table II. The subjects rated their impression from the aspect of pairs of adjective according to the seven-grade system. That is, both of negative and positive adjectives in one pair were graded by three steps, and the neutral was assigned to zero. In the statical analysis, the rated values related to negative adjectives were regard as negative value.

6) Procedures: The experimental procedure was as follows. First of all, general instructions, such as procedures of the experiment and a way to fill the questionnaires, were given to the subjects. The subjects were asked to fill a interview sheet to check their physical condition, and also the Japanese version of the STAI-JYZ (State Trait Anxiety Inventory) sheet [19] to quantify their anxiety level. The subjects were seated in the chair in front of the robot manipulator. Electrodes to measure the SCR and ECG were attached to appropriate regions of the subjects and physiological measurement devices were calibrated. While the robot motion was demonstrated to the subjects, sound volume of white noise from the headphone was adjusted so that sound of the robot motion could not be heard. These were followed by around 3-minutes relaxation period and a physiological measurement of initial mood. After the proper measurement was confirmed, the data acquisition was started. The room was kept quiet until the signals became steady. Then the operator triggered the robot motion. The subjects were asked to keep their eyes front during the measurement. When instantaneous response of the SCR settled, the subjects asked to evaluate their feeling on the scales of three adjectives and fill the questionnaires. This procedure was repeated for all conditions of the modality. Finally all of equipments were removed from the subjects and they were asked to fill the STAI-JYZ sheet again.

TABLE I

THE ORDERS OF EXPERIMENTAL CONDITIONS. THE MEASUREMENT WAS CARRIED OUT AT INTERVALS OF THREE OR FOUR DAYS.

Date	First	Second	Third
1	VA	V	A
2	VA	A	V
3	V	VA	A
4	V	A	VA
5	A	VA	V
6	A	V	VA

TABLE II

ADJETIVE PAIRS FOR QUESTIONNAIRES

No.	negative		positive
1	tensional	↔	relaxed
2	unpleasant	↔	pleasant
3	anxious	↔	secure

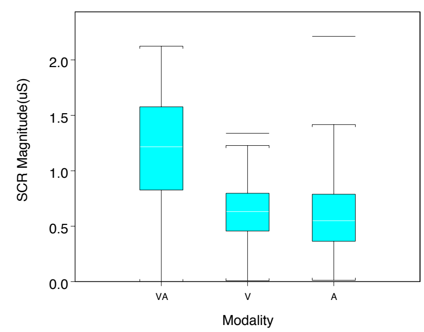

Fig. 3. Box-and-whisker plots of the magnitudes of the SCR with respect to each modality.

We could measure six sets of physiological and psychological data for one experimental procedure. One subject engaged in twelve experiments. Totally we could have 72 data from one subject.

7) Data analysis: Magnitude of SCR was measured as the amplitude from base line to peak of positive wave. Latency of SCR was measured as a period of time from the beginning of the robot motion to the beginning of the fluctuation.

To compare averages of the SCR magnitude, the SCR latency, and the subjective evaluations for each factor, the analysis of variance was performed with respect to the category of the modality (VA, V, and A) and the order of measurements [18].

B. Results

To investigate which factors effected the variance of the physiological and psychological data, we applied the ANOVA (analysis of variance) technique to the data for every subject individually. In the following we omitted the investigations of the data from the subjects whose SCR level was quite low.

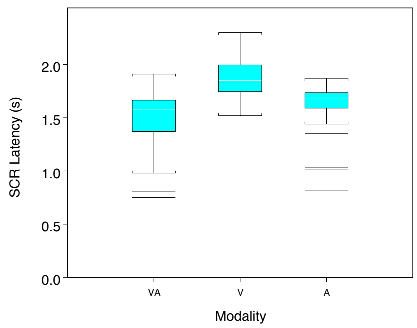

Fig. 4. Box-and-whisker plots of the latencies of the SCR with respect to each modality.

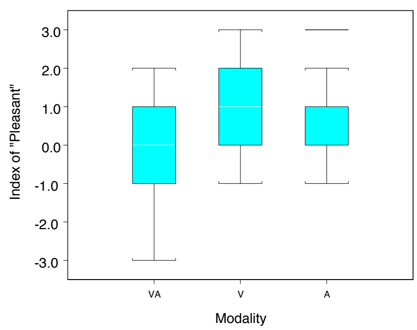

Fig. 5. Box-and-whisker plots of the indices of “Pleasant” with respect to each modality.

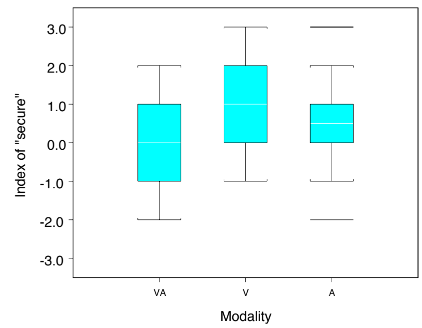

Fig. 6. Box-and-whisker plots of the indices of “secure” with respect to each modality.

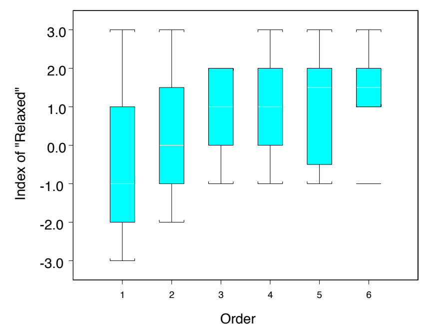

Fig. 7. Box-and-whisker plots of the indices of “Relaxed” with respect to time-series order of measurements.

1) Modalities: Fig.3, 4, 5 and 6 shows that the box-and-whisker plots of the magnitudes of the SCR, the latencies of the SCR, the index of “pleasant”, and the index of “secure” with respect to each modality respectively.

In Fig.3 the VA modality tended to be larger than both of the V modality and the A modality. There was significant difference between them ($F(2, 66) = 8.478$, $P < 0.01$). From the multiple comparison test, the significant differences ($P < 0.05$) was observed between the VA modality and the V modality, and also between the VA modality and the A modality.

In Fig.4 the VA modality tended to be shorter than both of the V modality and the A modality. There was significant difference between them ($F(2, 66) = 13.79928$, $P < 0.01$). From the multiple comparison test, the significant differences were observed between the VA modality and the V modality ($P < 0.05$), and also between the V modality and the A modality ($P < 0.05$).

In Fig.5 the VA modality tended to be lower than both of the V modality and the A modality. There was significant difference between them ($F(2, 66) = 4.91$, $P < 0.05$). From the multiple comparison test, the significant differences were observed between the VA modality and the V modality($P < 0.05$). In Fig.6 the same tendency was observed as well.

2) Habituation: To investigate the effect of habituation, the data were categorized with respect to time-series order of measurements. From the analysis of variance the significant differences were observed in the magnitudes of the SCR, the index of “relaxed”, the index of “pleasant”, and the index of “secure”. However from the multiple comparison test, there was no significant difference ($P < 0.05$) among them except for the index of “Relaxed”. In the index of “Relaxed”, there was significant difference between the first and the sixth as shown in Fig.7.

III. Discussion and a Derived Rule for Robot Motion

As mentioned earlier in order to get rid of the influence of the habituation, one subject engaged in the experiments several times with the different order of the condition every three or four days. This procedure led the total experimental period into about two months, and prevented us from investigating a large number of subjects. The limited number of subjects means that the results may not be generally applicable. However some subjects hardly responded to the stimuli in electrodermal measurements, the others responded well. Such individual differences in response tended to enlarge variance of the overall data meaninglessly. This time we chose the methodology to obtain a large number of data from the limited number of the subjects.

There was another concern about choice of the subjects. In our present experiment, since the subjects were experienced in mechanical technology, it was likely that the results might be biased. If the data is used in practice, we should sample subjects from a population of assumed users of the human-friendly robots. However in our experimental stage we will skip such involved procedure for a while, and proceed to a discussion on the result obtained in the present experiment.

In our previous work the order of the modal conditions, i.e. VA, V and A, was fixed throughout the experiments. There was some possibility that the habituation influenced the EDA responses. To avoid this effect, the subject engaged in the present experiment tested every different order of the modal conditions. From the statistical analysis of the data categorized by time-series order of measurements in the previous chapter, the significant differences between successive robot motions were observed. However there were few significant differences ($P < 0.05$) between pairwise comparisons among the time-series order of measurements. We could say that there were some effects due to habituation but they were not so much because we took slightly longer time interval between the successive robot motions and it might attenuate the habituation.

The result of SCR magnitude showed the VA modality tended to be larger than the V and A modalities. Namely blocking out either the sound or the sight might attenuate the SCR magnitude to the robot motion. The result of SCR latency showed the VA modality tended to be shorter than the V modalities. Namely blocking out the sound might lengthen the SCR latency to the robot motion. Since increasing the SCR magnitude or decreasing the SCR latency implies a rise in activities of the SNS, we could conclude that the lack of modality caused reduction of the SNS activities to the robot motion.

The result of the subjective evaluations supported this conclusion. The VA modality tended to be rated at lower scores than the V modality in the "Pleasant" index and the "Secure" index. It seems that this conclusion corresponds with our ordinary sense such that loud noise or quick movement close to us must be stressful for us. We should apply this result to robot motion generation with user's relief. One candidate of a rule for robot motion generation is as follows: robots must reduce their motion speed in the immediate vicinity of humans. Reducing the motion speed of the robots would result in making their noise smaller and their movement slower. This rule is not only concise but also convenient for practical use. In the next section we apply this rule to a mobile robot.

Alternatively another rule concerning with the feature of the habituation might be proposed. From the psychophysiological point of view, the habituation must be one of artifacts. However the aspect of the habituation so as to reduce the EDA responses under the successive same stimuli is regarded as a preferred feature for the robot motion generation with user's relief. For example, the following rule could be proposed: robots should repeat the same movement until the user gets familiar with the robot. Or robots should not change their attitude toward the same user whenever they provide services. These rules derived from the habituation aspect have not been applied to the mobile robot in this paper. We will leave it for the future work.

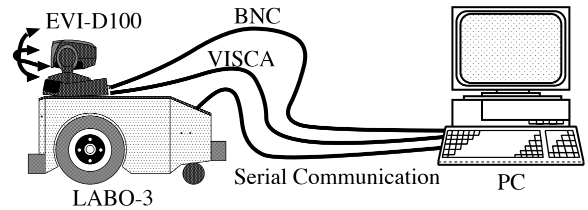

Fig. 8. Equipments employed in the experiment.

IV. Application of the rule to a mobile robot

We constructed the experimental setup that a mobile robot approached human with its speed decreased to keep the rule that robots must reduce their motion speed in the immediate vicinity of humans. The mobile robot was composed of visual equipments and two-wheeled differential drive platform (Fig.8). The robot searched a object with skin color of the human using a pan/tilt/zoom camera, measured distance to the object by technique of depth-from-focus, and orientated to the object. Then the robot approached the object till a designated distance between them. In the present experiment the color recognized as skin was calibrated to average Japanese people.

A. Experimental setup

The visual equipment was composed of a color video camera with remote pan/tilt/zoom operation (EVI-D100, Sony), a image processing board (IP-5005, Hitachi) and a personal computer (Pentium 266MHz, Windows NT). IP-5005 was installed on the PCI-BUS of the PC. EVI-D100 was connected to IP-5005 via a video cable for image processing. Further EVI-D100 was also connected to a serial connector of the PC via VISCA cable for remote operation with VISCA commands.

A two-wheeled differential drive platform (LABO-3, AAI) was connected to the PC with serial communication and equipped with EVI-D100. The commands for robot motion were generated by the PC and transmitted to LABO-3.

B. Estimation of the distance to the human

To estimate the distance to a human, the robot should search a human and measure the distance to the human. Although there are several ways to carry out such function, we would suggest that the use of one image processing device is convenient and effective because we do not need any calibration between devices to detect the human and to measure the distance.

In this experiment we needed simple algorithm to detect the human by the image processing. Therefore the skin color detection method was used. An image obtained by EVI-D100 was stored on IP-5005 and binarized at a certain threshold

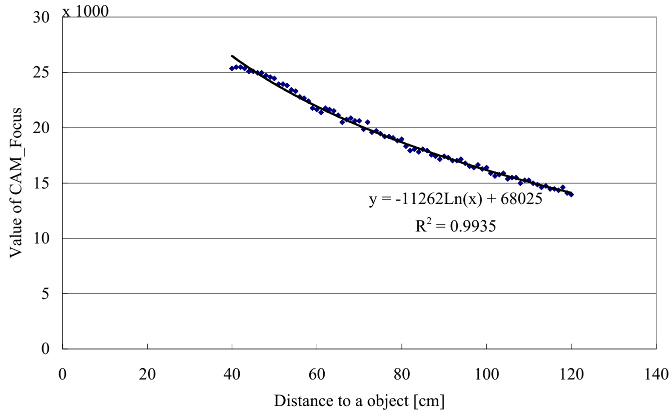

Fig. 9. Relationship between the CAM_Focus values and the distance to the object.

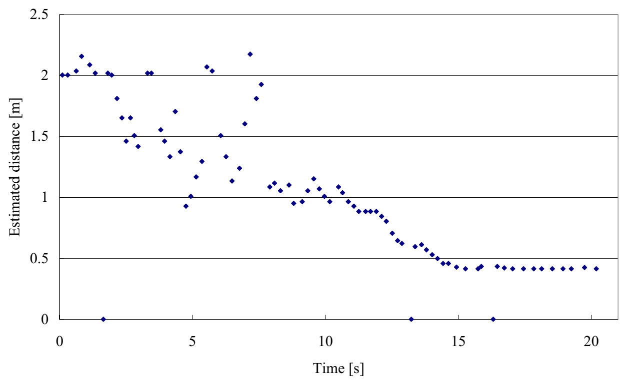

Fig. 10. Estimated distance when the speed command kept a constant value.

with skin color feature ($140 \leq U \leq 160$ and $100 \leq V \leq 120$ in UVY color space with 256 gradations). The skin color region whose area was largest among them was chosen and the coordinate of its center was regarded as the human position on the obtained image. Furthermore the angles of camera were adjusted by pan/tilt operations so that the human position was aligned onto the center of the camera image.

Using the autofocus approach so as to search for the lens position giving the best focus image, the distance can be estimated by the focused lens position uniquely. This method is known as depth-from-focus [20], [21]. We utilized this method to measure distance from the robot to the human. Also there are similar approaches to recover the three-dimensional shape from the focused lens position, so-called shape-from-focus [22]. Some researchers have applied the depth-from-focus approach to the mobile robot navigation such as obstacles avoidance [23].

In our application we could not know the lens parameters of EVI-D100. However EVI-D100 could report the focal value named as "CAM_Focus" to the PC via a VISCA command. We plotted the graph of the relationship between the autofocused CAM_Focus values and the distance to the object (Fig.9) and the approximation formula of the curve line on the graph was obtained.

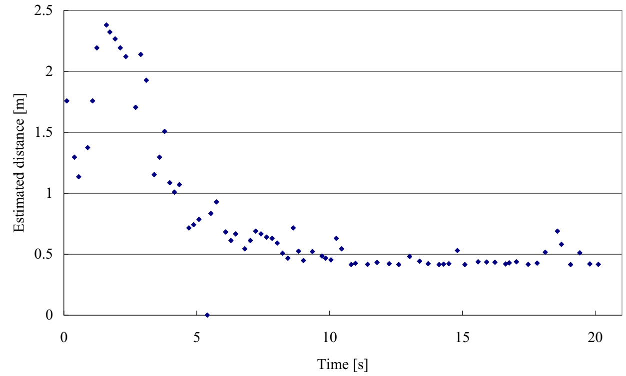

Fig. 11. Estimated distance when the speed command decreased with step-wise pattern depending on the distance.

C. Approach motion to the human

After finding a human the robot would orientate to and approach the human. The speed command given to the mobile robot was decided according to the distance to the human. The procedure of the robot motion was as follows.

1) The robot was located at a distance of 2m from the human.
2) The zoom value of the camera was set at 0x0 in VISCA command.
3) The detection of the skin color was performed within two seconds.
4) The camera began to track the detected region.
5) The zoom value of the camera was set at 0x3000 in VISCA command
6) The mobile robot began to move to the detected object.
7) The mobile robot stopped if the estimated distance became 0.45m.

Two types of robot motion were prepared. One motion was of constant speed. That is, the speed command to the robot kept a constant value independently of the distance. The estimated distances were shown in Fig.10. Another motion slowed down the robot step-wise. That is, the speed commands to the robot were reduced in three steps dependently of the distance. The estimated distances were shown in Fig.11.

In the both cases the robot approached the human successfully. At the beginning the estimated distances varied widely. When the robot began to move its body tended to shake unexpectedly. We were afraid that this phenomenon disturbed captured images and the measurement of the distance was affected.

In the second half of the graphs, in Fig.10 the estimated distance decreased linearly due to constant speed command, but in Fig.11 exponentially. Inclination of the trend line between 1 m and 0.5 m in Fig.11 was smaller than that in Fig.10. As a result the designated motion, that the robot reduce its speed in the immediate vicinity of human, was realized in Fig.11. We could conclude that the constructed system was capable enough of keeping the rule.

V. Conclusion and Future Work

From the psychophysiological experiments, the influence of auditory and visual modalities to the impression on the robot motion was investigated. Our previous and present works supported the hypothesis that blocking out either the sound or the sight attenuated the EDA responses to the robot motion. We deduced the motion rule for human-friendly robots from this investigation, that robots must reduce their motion speed in the immediate vicinity of humans.

We constructed the experimental setup that a mobile robot approached human with its speed decreased in conformity with the rule. The skin color detection and depth-from-focus techniques were utilized to realize the distance estimation system via a monocular color video camera with pan/tilt/zoom operation. By choosing proper commands we could realize the robot motion that the robot reduce its speed in the immediate vicinity of human.

It was observed that the unexpected robot motion disturbed captured images and the measurement of the distance was affected. To avoid this problem deep cooperation between vision system and wheel drive control would be needed.

In future work we plan to investigate user's impressions on approach motion using the constructed mobile robot system. We would like to confirm whether the motion rule deduced in this paper is applicable to the mobile robot system. Further we would like to give concrete shape to motion generation to make use of the motion rule concerning with the feature of the habituation.

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