A Fundamental Approach of Avoidance Planning of Robots Considering Human Emotions*

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In the planning of robots, the avoidance of humans working in the same work space, considering human emotions, was examined experimentally. We adopt the control law that the robot's evasive motion should follow the motion of an approaching human hand at a constant interval (referred to as the following distance). First, the relationship between human emotions and the motion parameters of robots (that is, the following distance and velocity of motion in the task direction) were experimentally clarified first using the rating scale method. The results show that appropriate combinations of motion parameters exist, and that the emotion "*Pleasant*" was representative of the emotions. Second, the control law of the robot's avoidance motion, in which the following distance is adjusted based on fuzzy inference with respect to the emotion "*Pleasant*", was proposed. The effectiveness of the proposed method was experimentally confirmed using an existing two-degree-of-freedom robot.

Key Words: Human Engineering, Robot, Human Interface, Fuzzy Set Theory, Avoidance Planning, Human Emotions

1. Introduction

The active roles of robots in such environments as factories, nuclear reactors, outer space, have been isolated from humans. In the future, however, due to the recent remarkable improvements in robotic intelligence, it is expected that robots will coexist with humans to assist or cooperate with them in areas such as social welfare and services in the home and office. In such cases, robots must function in the same work space as human beings, and must also be safe so that human beings can interact with them comfortably. It goes without saying that such robots must be physically safe for human beings. Research on robots coexisting with humans has been discussed recently. Ben-lamine et al.⁽¹⁾ examined impedance characteristics of robots particularly when they come into contact with humans, and realized soft reaction of robots. Lim et al.⁽²⁾ examined impact-absorbing compliance

characteristics of mobile robots, in which the base of the robot moves softly to absorb impact forces from unexpected collision with humans. This research is very important for the safe coexistence of humans and robots. However, even if the impact force of a collision between robots and humans can be greatly diminished, the fact that collision occurs will affect human emotions such as fear, surprise, and disgust to no small extent. To realize the desirable coexistence, human should not hold such strong emotions against robots. Therefore, it is necessary to examine the robot's motion in avoiding contact with humans. When robots avoid contact with humans, the movements must not interfere with human voluntary motion, and must be acceptable to human sensitivities. In other words, the movements should be considered by most people as emotionally reasonable. Here, the word "emotion" is defined as the feeling that humans experience when robots avoid contact with humans, and do not include strong emotions such as fear, surprise, and disgust.

It is important for robots to accomplish smooth and favorable motion in avoiding unexpected collision with humans. There has been much research concern-

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ing the avoidance of obstacles by robots such as research on methods based on the potentials or configuration spaces⁽³⁾⁻⁽⁶⁾. That research was focused on dynamic analysis based on factors such as energy, and minimum movement time. Moreover, the obstacles to be avoided were not humans, and human emotions concerning the avoiding motion were not discussed. It is necessary for robots to consider human emotions in avoiding contact with humans so that humans can be physically and psychologically relaxed without pain or other unpleasant sensations, but there is little research on this topic.

Research clarifying the relationship between a robot's motion and human emotion has recently been conducted. Tejima⁽⁷⁾ examined the human emotion of fear of a scalar-type robot and verified that humans are more greatly affected by distance than speed. Ikeura et al.⁽⁸⁾ examined robot motion using the response of living body, and showed that maximum speed affects the emotion of fear, while the change of acceleration affects the emotion of surprise. Ogawa et al.⁽⁹⁾, attempted to analyze human emotions with regard to a variety of mechanical motions using the semantic differential method, and showed that formulated human arm movement (called cybernetic motion in their paper) might be a mechanical motion that is emotionally acceptable by humans. Shibata et al.⁽¹⁰⁾ conducted a psychological evaluation of two-joint extension and retraction motions of an industrial robot using the rating scale method, and showed that the velocity profile and velocity peak position in the duration of the motion greatly affected human emotions. However, these experiments did not clarify the robot's motion in avoiding collision with humans, and the results clarified in the research were not applicable to the synthesis of robot control systems.

In this research, we focus on the relationship between a human and a robot in which the robot coexists with the human in the same work space, e.g., a room. This relationship has not yet been realized in practice. As an initial step in the realization of this relation, it is desired that the robot does not take charge of complicated tasks, and that the construction of the robot, including degrees of freedom, be simple to enable the human to easily imagine the robot's appearance after movement and the work area. From these points of view, the relationships between human emotions and motion parameters of robots in avoiding humans are first experimentally clarified using an existing two-degree-of-freedom robot.

Recently, much research concerning the coexistence of humans and robots has been discussed. On the contrary, few examples of practical coexistence of robots with humans have been realized up to now.

This is because the safety of robots has not been definitively guaranteed especially when the robots generate various motions interacting with humans. If the human's face or body is within the working area of robots, it is not easy for the human to immediately avoid collision with the robot when the robot is out of control. This possibility will give humans negative and strong emotions, such as fear and disgust, which is not desirable for our purpose. Therefore, we consider the case that a human hand approaches the robot, that is, the hand is the part of the human body closest to the robot, and human's face and body are outside of the working area of robots. A simple control law that the robot follows the approaching motion of the human hand at a constant interval is adopted to avoid contact with the human. The reason why we adopt this simple control law is as follows. When an appropriate distance is chosen, humans will feel reassured. In addition, since human hand motion has a smooth velocity profile⁽¹⁰⁾, it is expected that the robot motion will also become smooth because the robot will follow the motion of the human hand.

A simple task in which the robot moves an object from an initial position to a target position is considered here. The constant interval and motion velocity in the task direction (the direction which connects the initial position and the target position) are chosen as the motion parameters, and the relationships between these parameters and human emotions are analyzed using the rating scale method. The rating scale method is one of the subjective evaluation methods used in psychology. Second, we propose a method for adjusting the length of the interval by constructing fuzzy inference based on the qualitative characteristics of the important emotion clarified by the rating scale method. The effectiveness of the proposed method is confirmed experimentally by comparing the results of the proposed method with those of the method in which the interval is constant.

2. Control Strategy of Robots in Avoiding Humans

When the robot must avoid an unexpected human approach, it is necessary to generate an acceptable trajectory in which the profiles of velocity and acceleration undergo smooth changes. Ikeura et al.⁽⁸⁾, showed that humans react sensitively to a robot approaching from the front, and also that unexpected changes of acceleration arouse unfavorable emotions in humans. Therefore, it is necessary for robots to move smoothly in front of the human. Tejima⁽⁷⁾ examined human emotion of fear with respect to the planar rotational movement of the scalar type robot arm. Two important issues were clarified in his research. (1) If the distance between the robot and the human is more

than a certain value, humans did not feel much fear even if the movement speed of the robot was high. (2) On the contrary, if the distance between the robot and the human was small, the human felt fear more strongly even if the movement speed of the robot was low. Judging from this, the robot should be controlled so as not to approach humans within a certain distance in avoidance performance.

The minimum jerk model, which minimizes Eq. (1) below, can accurately reproduce the point-to-point planar motion of human hands⁽¹¹⁾.

$$C = \frac{1}{2} \int_0^{t_f} \left\{ \left(\frac{d^3x}{dt^3} \right)^2 + \left(\frac{d^3y}{dt^3} \right)^2 \right\} dt \quad (1)$$

Here, (x, y) is the human hand position, and t_f is movement time. Profiles of position and velocity, which satisfy Eq. (1), are shown in Fig. 1. Vertical and horizontal axes in the figure are normalized by the maximum values. As shown in the figure, the change of position is very smooth, and the change of velocity shows a smooth, symmetrical bell-shaped profile. If robots coexisting with humans can display these characteristics, their motion will become more emotionally acceptable to humans. It is possible for robots to display these characteristics by following human hand motion.

Based on these points, we adopted the control law that robots follow the approach motion of a human hand at a constant interval (referred to as the following distance in this paper) in front of the human face. This control law can make the robot motion have a human-like smoothness expressed by the minimum jerk model. It is expected that this motion will be emotionally acceptable to humans. Therefore, what we should discuss here is how the robot should select the following distance.

We assigned a very simple task to the robot in the horizontal direction, that is, moving an object from one position to another. Here, it is also important to discuss the relationship between the movement trajectory of the given task and human emotions. In the

Fig. 1 Minimum jerk model

movement trajectory of the robot, the velocity is one of the important elements, that affect human emotions, as determined by Shibata et al.⁽¹⁾ For this reason, we consider the velocity in the horizontal direction as the second parameter to be evaluated in this work.

3. Methods

Psychological evaluations are conducted through experiments using an existing two-degrees-of-freedom robot to clarify the effectiveness of the adopted control law, and also to clarify how the parameters (that is, the following distance and the velocity in the task direction) affect human emotions. In the experiments, the adopted control law is realized for the two-degree-of-freedom robot under one of the representative values of following distances and one of the representative values of velocities in the task direction. A human subject holds his or her hand out in the reference path of the end effector, and the induced evasive motion is evaluated using the rating scale method. The evaluation is conducted for all the combinations of representative values of the following distances and velocities in the task direction, and the results are analyzed.

3.1 Experimental system

Figure 2 shows the experimental setup. A two-degree-of-freedom robot driven by a DC servomotor is used in the evasive motion experiment. The robot is made of aluminum. The output signal from the rotary encoder is input to the computer through a 24 bit counter board, and the signal is converted to the

Fig. 2 Experimental setup

position of the robot. A 32 bit personal computer is used for the experiment. A PSD sensor system is used for the measurement of the position of the subject's hand. In the system, the analogue output signal from the PSD camera, which corresponds to the position of the LED marker on the subject's hand, is input to the computer through a 12 bit A/D converter. The position of the human hand on the table is calculated by the computer in real time. The input signal calculated by the computer using the position of the human hand is fed to the DC servomotor through a 12 bit D/A converter and driver to realize position control of the robot. The accuracy of the robot motion in following the reference speed is better than 1.6 [mm/s] , which means that the robot can generate the desired trajectory very accurately. The sampling time for the calculation and trajectory tracking control is 5 ms. The background behind the robot is covered with white paper so that the human subject can concentrate on the robot's motion.

3.2 Experimental method

Figure 3 shows the top view of the experimental setup. Figure 4 shows the experimental situation. The experiments are performed under the assumption that robots play active roles working near humans. There are several possible relationships between humans and robots possible in such situations. Since this research adopts a fundamental approach, a simple relationship between humans and robots is considered as follows. The human subject sits in a chair and faces the robot on a table. The positions of the human and the robot are determined so that they can occupy a common work space. The height of the chair is adjusted so that the height of the subject's face is the same height as the end effector of the robot. The human subject wears earplugs to reduce the influence of noise from the robot on human emotions.

We assign the robot the task of moving an object from an initial position to a target position along a straight line on the X -axis, as shown in Fig. 3. The object is cylinder with the diameter of 55 mm and the height of 135 mm, and is made of aluminum. Each human subject evaluates all combinations of the representative values of the distances and velocity in the task direction (which is the direction connecting the initial position with the target position), as shown in table 1. An evaluation test sheet is given to each subject and the method of completion is explained to the subject before the experiment. The subject is instructed to imagine that he or she coexists with the robot in the same work space, and to evaluate the movement of the robot. No other information about the robot is given to the subject. The order of the experiment is changed randomly.

Fig. 3 Experimental method

Fig. 4 Photograph of the robot and human

After the robot starts its task, the subject begins to move his or her hand from point A to point B to interfere with the movement of the robot. Point B is located in the reference path of the robot motion. When the subject's hand approaches the robot, the robot begins evasive motion to maintain the following distance. The subject fills in his or her impressions for the robot's evasive motion on the evaluation sheet subjectively. After the subjects have filled in their impressions the test sheet, motion parameters are changed and the next evaluation begins. The interval between attempts is about two minutes.

Motion parameters of robots, that is, representative values of the velocity in the task direction and the distance between the subject's hand and the robot were predetermined in preparatory experiments such that psychological evaluations of the robot's evasive motion with each parameter show significant differences. Table 1 shows the parameters determined.

3.3 Selection of adjective measures in the rating scale method

As mentioned above, the human subject moves his or her hand in the reference path of the robot motion

Table 1 Following distance and velocity in the task direction

Following distance (mm)	100	150	200	250
Velocity in the task direction (mm/sec)	100	200	300	400

and evaluates the robot's evasive motion subjectively. As a way of describing subjective human emotions, the SD method is applicable for measuring how people feel about various stimuli such as music, color, smell and environment. This method has also been used in ergonomics to evaluate task environments, the movement of machines, and amusement robots. The SD method is an evaluation tool based on several stepwise measures in which pairs of opposing adjectives are given. As many adjective pairs as possible must be listed with respect to the given stimulus. In the procedure, subjects evaluate their emotions according to these adjective pairs, and the main factors are deduced from the results using factor analysis.

However, in this research, since the stimulus is a momentary phenomenon, it is not effective for subjects to evaluate their emotions according to an excessive number of adjective pairs. In addition, the purpose of this research is to identify the characteristics of robots favorable characteristics for coexisting with humans. Therefore, a minimum number of adjective pairs were selected for this purpose. Hence, factor analysis has been omitted in this research. Following this consideration, four adjective pairs were determined as follows.

<Quick-Slow>

This adjective pair was adopted because it is important for robots to react quickly to unexpected human approach.

<Calm-Restless>

This adjective pair was adopted because the robot's motion should be calm so that the human can remain psychologically stable in the same workspace.

<Human-like-Mechanical>

This adjective pair was adopted because humans would have a friendly feeling toward robots if robots show human like responses.

<Pleasant-Unpleasant>

This adjective pair was adopted because robots should be enjoyable or attractive in a way that makes human feel pleased and satisfied in order that they can co-exist amicably.

The subject chooses one of seven grades between opposite poles in each adjective pair on the test sheet, in accordance with his or her impression of the robot.

4. Experimental Results

Fifteen healthy male and female students ranging in age from 18 to 24 participated in the experiments. Here, all the students had an arts background (that is, they do not have a scholarly knowledge of robots).

Representative results of the evaluations, that is, the results for the following distance of 150 mm, are shown in Fig. 5. In the figure, the mean value and variance of the evaluations, when one to seven points are assigned to respective step between opposite poles, are shown for each adjective pair. The horizontal position between adjective pairs corresponds to the strength of the emotion. Here, we define "positive" as the mean value being on the right side, and "negative" as the mean value being on the left side in the figure. As shown in Fig. 4(a)-(d), the evaluation of the measure "Quick" became positive when the velocity became high (the differences were adequate under the significance level of 5 % in a two-sided *t*-test).

Concerning the measure "Pleasant", the best evaluation was given when the task velocity was 200 mm/s, and the evaluations become worse when the velocity in the task direction was more than 200 mm/s and less than 200 mm/s (the differences were adequate under the significance level of 5 % in a two-sided *t*-test).

Concerning the measure "Calm", the evaluations when the velocity in the task direction was less than or equal to 200 mm/s were more positive than when the velocity in the task direction was more than or equal to 300 mm/s. On the contrary, concerning the measure "Human-like", the evaluation when the velocity in the task direction was 100 mm/s was worse than when the velocity in the task direction was 200 mm/s (the differences were adequate under the significance level of 5 % in a two-sided *t*-test). Judging from these results, good evaluations cannot be expected when the velocity in the task direction is lower than an appropriate value.

As shown in the figures, when the evaluation of the measure "Pleasant" became highly positive, the evaluations of all the other adjective pairs were also positive.

Figure 6 shows mean values of the evaluation of the measure "Pleasant" with respect to velocity in the task direction and following distance. As shown in the figure, the evaluation was best under the condition that velocity in the task direction was 200 mm/s and following distance was 150 mm. That is, the avoiding motion had a favorable effect on human emotions when both the following distance and the velocity in the task direction were appropriate values. Robots coexisting with humans should take human emotions into account, and should generate a motion acceptable

Fig. 5 Evaluations when the following distance is 150 (mm)

Fig. 6 Mean values of the evaluations of the measure "Pleasant"

to human emotions positively. It is expected that robots can become good partners if they can maintain the appropriate following distance and velocity in the task direction, as clarified in this section, particularly when the robot approaches close to a human.

5. Avoidance Planning with Adjustable Following Distance

If the velocity in the task direction is held at a constant value, the adopted control law has limits in improving human emotions according to the values of the velocity in the task direction, as shown in Fig. 5

(a) or Fig. 5(d). Therefore, by adjusting the following distance using fuzzy inference based on the qualitative characteristics between the motion parameters and the psychological evaluations, the improvement of robot motion is expected. In fuzzy inference, since a state is expressed by fuzzy rules of if-then forms, it is easy to understand the structure of the model⁽¹²⁾, and becomes possible to express a non-linear input-output relationship.

Let us emphasize the fact that the evaluation of the measure "Pleasant" is representative of all the emotions, particularly when the evaluations become positive. It is considered that the control strategy of the robot's evasive motion should be constructed so as to maintain a positive evaluation of the measure "Pleasant". From this viewpoint, fuzzy rules used to adjust the following distance are constructed so that the evaluation of the measure "Pleasant" will become positive for various velocities in the task direction. First, the mean values of the evaluations of the measure "Pleasant" for each velocity in the task direction are normalized using

$$E_n = 1 - \frac{E - E_{\min}}{E_{\max} - E_{\min}} \quad (2)$$

Here, E_n is the normalized evaluation, E is the mean value of the evaluations of the measure "Pleasant", $E_{\max}$ is the maximum of the evaluations, and $E_{\min}$ is the minimum of the evaluations. The results are

Table 2 Normalized values of the evaluations for the measure "Pleasant"

$V \backslash d$	100	150	200	250
100	0.62	0.00	1.00	0.94
200	0.64	0.00	0.56	1.00
300	0.38	0.17	0.00	1.00
400	0.03	0.00	0.21	1.00

Table 3 Fuzzy rules to adjust the following distance

$V \backslash d$	100	150	200	250
100	0.62	0.00	-1.00	-0.94
200	0.64	0.00	-0.56	-1.00
300	0.38	0.17	0.00	-1.00
400	1.00	0.00	-0.80	-1.00

shown in Table 2. In the table, d indicates the following distance (mm) and v the velocity in the task direction (mm/s). Secondly, these values are regarded as absolute values of the consequent variables in the fuzzy rule for each distance and velocity in the task direction. The fuzzy rules obtained by this procedure are shown in Table 3. Here, both the values of the following distance 100 mm and 200 mm for the velocity of 400 mm/s in the task direction in the table are re-adjusted through trial and error because these values were not appropriate. The membership function of the antecedent clause is determined to be a triangular type, as shown in Fig. 7, to simplify the calculation.

The effectiveness of the adjustment of the following distance based on these fuzzy rules is discussed here. Paired comparison is conducted between the results of the control method in which the following distance is a constant value of 150 mm, and those of the control method in which the following distance is adjusted by fuzzy rules. In the experiments, 13 students decide which of the two evasive motions is better. The results are shown in Fig. 8. In the figure, the histogram shows the proportion of subjects that regarded the motion as being better.

As shown in the figure, almost all the subjects considered that the evasive motion with fuzzy inference was more acceptable than the evasive motion in

Fig. 7 Membership function for the antecedent clause

Fig. 8 Results of paired comparisons

which the following distance was constant, when the velocity in the task direction was 200 mm/s or 300 mm/s. The results when the velocity in the task direction was 100 mm/s or 400 mm/s also show that the greater number of subjects gave the same evaluation. It is confirmed from these results that evasive motion using fuzzy inference based on the evaluation of the emotion "Pleasant" will become more acceptable to humans.

6. Conclusion

In this research, the evasive motion by robots of humans in the same work space considering human emotions was examined experimentally. We adopted the control law of the robot's evasive action to be that the robot follows the approaching motion of a human hand at a constant interval (we call this interval the following distance). First, the relationships between human emotions and the motion parameters of robots (that is, following distance and velocity in the task direction) were experimentally clarified using an existing two-degree-of-freedom robot, by the rating scale method. The results showed that there are appropriate combinations of the parameters, which make humans perceive the motion to be acceptable, and that the emotion "Pleasant" was the representative of all the emotions to be evaluated in this research. It is inferred that progressing toward the achievement of this emotion "Pleasant" will enhance

the other emotions.

Secondly, a control law of the robot's evasive motion in which the following distance is adjusted based on fuzzy inference with respect to the subjective evaluation results of the emotion "*Pleasant*" is proposed. The effectiveness of the proposed method is discussed based on the paired comparison evaluation between the results of the proposed method and those of the method in which the following distance is constant. It was clarified that the evasive motion became more acceptable to humans than the first method, which indicated the effectiveness of the proposed control law.

It is expected that the results presented in this paper will provide effective guidelines in planning the trajectory of robot motion to avoid a human, under a simple relationship of coexistence of the human and the robot such that the given task of the robots, as well as the construction of the robot, including degrees of freedom, will be simple.

The method in which the following distance is adjusted using fuzzy inference can be constructed with regard to the motion parameters if the distribution of the evaluation of the representative emotion of the motion has a peak. However, the values of parameters in the fuzzy rule (which corresponds to motion parameters) will change with the size of the robot, and the values should be determined experimentally.

If the condition that the part of the human body nearest to the robot is the hand cannot be satisfied, the control law of robot's avoiding motion should be synthesized based on the distance between the human's eyes and the robot.

Since characteristics such as the size of the robot, the construction (appearance) of the robot, including degrees of freedom, material of the robot, and noise from the robot, can strongly affect human emotions, we aim to clarify their effects on human emotions in the future.

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