Impedance Characteristics of Robots Considering Human Emotions*

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It is expected that in the future, robots will play important roles in coexisting with humans. Whenever humans come into contact with these robots unexpectedly, the robots must not only be safe for the humans but also be able to adjust their physical softness parameters, which will help humans remain calm and which will be favorable for human emotions. Therefore, it is desirable for robots to control their impedance characteristics in such cases. From these points of view, desirable values of the impedance parameters of robots are investigated in this work by a rating scale method. In the experiment, 11 subjects come into physical contact with an impedance-controlled robot and evaluate this contact subjectively. The evaluations are performed on 48 combinations of virtual mass, viscosity coefficient, and stiffness. In terms of the results, the emotions felt by the subjects with regard to the robots being soft, pleasant, and human-like are explained by a linear regression model of the impedance values, and the emotions of being reassuring are classified into four groups.

Key Words: Robot, Human Engineering, Reliability Engineering, Human Interface

1. Introduction

Robots have made significant progress in the field of industry. It is expected that in the future robots will play important roles in areas such as social welfare and services in the home or office. These robots must coexist with humans in the same work space and may function near humans when required. One of the important tasks of robots could be to transport patients and move them to a certain position, or to manipulate an extremely heavy object. Since great power is essential for such tasks, the robots must have a certain amount of stiffness and be heavy. On the other hand, when humans come into contact with robots unexpectedly, the robots should calm and reassure them and be favorable to human emotions, as well as being safe. Therefore, it is expected that robots will have impedance characteristics and change their impedance values according to the relationship between robots and humans. These

impedance values must be changed in order for robots to generate a reassuring and favorable reaction in humans, especially when they come into contact.

Research on robots coexisting with humans has intensified recently. Research dealing with, for example, service or welfare robots⁽¹⁾⁻⁽³⁾, coexistence or cooperation between humans and robots⁽⁴⁾⁻⁽⁶⁾, and the safety of robots^{(7),(8)}, has been carried out. However, in this research human emotions when people work with robots were not considered. Tejima⁽⁹⁾ examined the influence on the human mind of the speed of a robot arm and the distance between the robot and a human. It was experimentally confirmed that psychological safety is related to distance rather than speed. Ootsuka et al.⁽¹⁰⁾ evaluated human fear, fright, and surprise in relation to robot motions under various maximum velocities and acceleration profiles using the reaction of a living body (galvanic skin reflex). It was reported that sudden changes of acceleration at the start of movement generate surprise and fear in humans. Shibata and Inooka⁽¹¹⁾ evaluated human emotions in response to robot motions under various velocity patterns using the rating scale method. It was confirmed that human emotions change in

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relation to velocity profile, velocity peak position in the duration, and maximum velocity. This research is significant because it involved evaluation of human emotions, but it did not take into account contact phenomena between robots and humans.

In this paper, we will first examine the concept that robots coexisting with humans should be able to adjust their impedance characteristics, and should change them according to stimulation from humans.

Second, the impedance parameters that robots should possess, especially when humans come into contact with them unexpectedly, are determined from the viewpoint that robots should calm and reassure, and that this contact should be favorable to humans.

In the experiments, human subjects added contact force to the impedance controlled robot by pushing or hitting it, and then evaluated the robot using the rating scale method. By analysis of the results obtained in the rating scale method, it is possible to confirm the relation between the impedance values and human emotions.

2. Experiment

2.1 Experimental design

Figure 1 shows the experimental setup. The subject adds force or impact to the end effector of the one-dimensional robot (THK Co. Ltd.) with his or her palm. The added impact is measured by the force sensor (NITTA Co. Ltd.) and recorded in the computer through an A/D converter. An NEC PC9821 AP2 is used for the impedance control. When the force F is given by the force sensor, the desired acceleration $\ddot{Z}$, velocity $\dot{Z}$, and position Z , which satisfy Eq. (1), are calculated in real time using the 4th-order Runge-Kutta method. The sampling time for the calculation and trajectory tracking control is 2 ms.

Fig. 1 Experimental system

$$F(s) = M_d \ddot{Z}(s) + C_d \dot{Z}(s) + K_d Z(s) \quad (1)$$

Here, M_d is the desired mass, C_d is the desired viscosity coefficient, and K_d is the desired stiffness.

2.2 Representative values of impedance parameters

In the experiment, the subjects evaluated their impressions of the robot's response, which has representative values of desired mass, desired viscosity coefficient, and desired stiffness, using the rating scale method. For determination of these values, preliminary experiments were conducted by healthy students aged from 20 to 24 years.

When we determine one of the impedance parameters among M_d , C_d , and K_d , the others are restricted to a constant value, and the representative values are determined in ascending order.

First, a paired comparison is conducted between two values which are the favorites for the representative value of M_d in the preliminary experiment. If a significant difference is observed, the smaller value is chosen as the representative value, and we then proceed to the next preliminary experiment between the larger value and a new value.

This procedure for determining the representative value of one impedance parameter is conducted on more than three combinations of the two remaining impedance parameters.

The representative impedance parameters that were decided upon are

$$M_d = 3, 8, 13, 20 \text{ (kg)}$$

$$C_d = 20, 50, 120, 200 \text{ (Nsec/m)}$$

$$K_d = 30, 80, 130 \text{ (N/m)}$$

We select a comparatively small value of K_d because if K_d is larger than 130 (N/m), the physical hardness of the robot is excessive and human subjects feel that it is "hard" in spite of the values of M_d and C_d , and give "negative" evaluations. When K_d is greater than or equal to 350 (N/m), human subjects give extremely "negative" evaluations. We do not adopt values resulting in excessive physical hardness of the robot because the main idea of our research is that robots coexisting with humans should be relatively "soft" and humans should show a favorable response to the unexpected contact.

• The representative values of desired mass

Representative values of desired mass are also determined in ascending order. The values of the desired viscosity coefficient and the desired stiffness are constant through the preliminary experiment. The procedures of the preliminary experiment are as follows. The robot is impedance-controlled with a certain value of desired mass which is the favorite choice for the representative desired mass. After that, the robot is impedance-controlled with the value of

the next step (for example, 6 kg). Seven subjects add force or impact to the robot in the above two cases, and evaluate whether their impressions are the same or different. When a significant difference is observed, the smaller value is selected as the representative value, and we then proceed to the next preliminary experiment. When no significant difference is observed, the values to be investigated are changed in proportion to the number of subjects sensing a difference. The preliminary experiments are conducted on two pairs of desired viscosity coefficient and stiffness values; that is, (50(N·sec/m), 50(N/m)) and (80(N·sec/m), 100(N/m)). From these two preliminary experiments, the representative values are determined as

$$M_d = 3, 8, 13, 20(\text{kg}).$$

- The representative values of desired viscosity coefficient

The representative values of viscosity coefficient are determined according to the same procedure as that used to determine the representative values of desired mass. The preliminary experiments are conducted on two pairs of desired mass and stiffness values; that is, (3(kg), 50(N/m)) and (8(kg), 100(N/m)). From these two preliminary experiments, the representative values of desired viscosity coefficient are determined as

$$C_d = 20, 50, 120, 200(\text{N} \cdot \text{sec}/\text{m}).$$

- The representative values of desired stiffness

The representative values of stiffness are determined in a similar way to that described above. The preliminary experiments are conducted on two pairs of desired mass and viscosity coefficient values; that is, (8(kg), 50(N·sec/m)) and (10(kg), 20(N·sec/m)). From the preliminary experiments, the representative values of desired stiffness are determined as

$$K_d = 30, 80, 130(\text{N}/\text{m}).$$

2.3 Selection of adjective measures in the rating scale method

As mentioned above, a subject adds force or impact to the end effector with his or her palm and evaluates its response subjectively. As a way of describing subjective human emotions, the SD method has been used for measuring how people feel about various stimuli such as music, color, smell and environment. This method has also been used in the field of ergonomics for evaluating task environments, the movement of machines, and amusement robots. The SD method is an evaluation tool based on several step-wise measures in which adjective pairs are located at opposite poles. 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 robots that have favorable characteristics for coexisting with humans. Therefore, a minimum number of adjective pairs was selected for this purpose. Hence, factor analysis has been omitted in this research.

Following this procedure, four adjective pairs were used to evaluate coexistence with robots. The subject chooses one of seven categories between opposite poles in each adjective pair in the test sheet, in accordance with his or her impression of the robot. These four adjective pairs are determined by both the purpose of the above-mentioned procedure, and a survey conducted on more than twenty persons who described their preferences, as follows.

1. “reassuring··anxious”·····This adjective pair is adopted from the viewpoint that robots coexisting with humans must not only be safe physically but also reassuring for the human mind.

2. “flexible··hard”·····This adjective pair is adopted from the viewpoint that robots should give humans the impression of being soft when they come into contact. Moreover, it is important to change the commonly held idea that robots are hard and dangerous due to their materials of which they are made.

3. “pleasant··unpleasant”·····This adjective pair is adopted from the viewpoint that robots should be pleasant for humans in order that they can co-exist amicably together.

4. “human-like··mechanical”·····This adjective pair is adopted from the viewpoint that humans should have a friendly feeling toward robots if the robots show human-like responses.

Another important adjective pair is “favorable··dislike” from the emotion of interest towards robots. We confirmed that the results for this adjective pair were almost the same as those for “pleasant··unpleasant.”

2.4 Methods

Eleven healthy students aged from 20 to 24 years conducted evaluations on all combinations of the representative values of the impedance parameters. A test sheet was handed to each subject and the method of completion was explained to him or her before the experiment. The subject was told to imagine that he or she came into contact with the robot unexpectedly while coexisting in the same work space, and evaluate the reaction of the robot when adding force and impact to the end-effector of the one-dimensional robot in the experiments. No other information about the robot was given to the subject. The order of the experiment was randomly changed. The height of the

robot was changed according to the tables below so that the subject's outstretched palm naturally came into contact with the end-effector of the robot.

3. Results

Numbers were assigned to all combinations of M_d , C_d , and K_d as in Table 1 for convenience. The units are omitted in the table. We refer to the assigned number as the parameter number in this paper.

As an example of the results, the evaluations for the combination of $M_d=8(\text{kg})$, $C_d=120(\text{N}\cdot\text{sec}/\text{m})$, and $K_d=130(\text{N}/\text{m})$ (i.e., the parameter number 21) are shown in Fig. 2. In the figure, the mean value and variance of the evaluations calculated based on assignment of one to seven points to each category between opposite poles are shown for each adjective. Here, "positive" is defined as the mean value located in a left position in the seven steps between opposite poles, and "negative" is defined as the mean value located in a right one. As shown in the figure, the

Table 1 Parameter numbers

Num.	M_d	C_d	K_d	Num.	M_d	C_d	K_d	Num.	M_d	C_d	K_d
1	3	20	30	17	8	50	80	33	13	120	130
2	3	20	80	18	8	50	130	34	13	200	30
3	3	20	130	19	8	120	30	35	13	200	80
4	3	50	30	20	8	120	80	36	13	200	130
5	3	50	80	21	8	120	130	37	20	20	30
6	3	50	130	22	8	200	30	38	20	20	80
7	3	120	30	23	8	200	80	39	20	20	130
8	3	120	80	24	8	200	130	40	20	50	30
9	3	120	130	25	13	20	30	41	20	50	80
10	3	200	30	26	13	20	80	42	20	50	130
11	3	200	80	27	13	20	130	43	20	120	30
12	3	200	130	28	13	50	30	44	20	120	80
13	8	20	30	29	13	50	80	45	20	120	130
14	8	20	80	30	13	50	130	46	20	200	30
15	8	20	130	31	13	120	30	47	20	200	80
16	8	50	30	32	13	120	80	48	20	200	130

Fig. 2 Results for parameter number 21

variances are not very large, which means that the characteristics for each emotion can be discussed according to the mean value. That is, the representative values of impedance parameters are appropriate for representing human impressions, and the four adjective pairs are valid parameters for evaluation. It is found that subjects show a "negative" reaction for the emotion of being flexible and pleasant, but show a "positive" reaction for the emotion of being reassuring. Neutral results are observed for the emotion of being human-like.

3.1 Explanation using a linear regression model

It is considered that the mean value of the evaluations is an important index of human emotions. The results can be explained using a regression model taking the mean value as the criterion variable, and the impedance parameters as explanatory variables, as in the formulation

$$Y = \beta_1 M_d + \beta_2 C_d + \beta_3 K_d + \beta_0. \quad (2)$$

Here, $\beta_1 - \beta_3$ indicate partial regression coefficients and β_0 indicates a constant.

From the magnitude of the F test statistic, it is confirmed that the models obtained for the emotion of being flexible, pleasant, and human-like are adequate under the significance level of 2.5%. In contrast, it is confirmed that the model for the emotion of being reassuring is not adequate under the significance level of 5.0%. The obtained partial regression coefficients and the constant are as follows.

For the emotion of being flexible :

$$\beta_1=0.126, \beta_2=0.019, \beta_3=0, \beta_0=0.778.$$

For the emotion of being pleasant :

$$\beta_1=0.094, \beta_2=0.011, \beta_3=0.001, \beta_0=1.94.$$

For the emotion of being human-like :

$$\beta_1=0.064, \beta_2=0.008, \beta_3=0, \beta_0=2.62.$$

From the test of partial regression coefficients, it is confirmed that M_d and C_d influence the mean values of the evaluations under the significance level of 5.0%. In contrast, it is found that K_d has little influence on the mean value of the evaluations. Figure 3 shows a comparison of the models with the experimental results for the emotions of being flexible, pleasant, and human-like respectively. As shown in the figure, the models explain the experimental results clearly. But the evaluation for the emotion of being human-like is "negative," while that for the emotion of being flexible is outstandingly "positive." This is because the movement in response to the applied force is so large that humans cannot feel the "human-likeness" of the robot.

As shown in the above, linear regression models well explain the relations between the impedance parameters and the emotions flexible, pleasant, and human-like. These results give us the important

Fig. 3 Comparison of the model with the experimental results

Num.	Mv	Cv	Kv	Num.	Mv	Cv	Kv	Num.	Mv	Cv	Kv
1	3	20	30	17	8	50	80	33	13	120	130
2	3	20	80	18	8	50	130	34	13	200	30
3	3	20	130	19	8	120	30	35	13	200	80
4	3	50	30	20	8	120	80	36	13	200	130
5	3	50	80	21	8	120	130	37	20	20	30
6	3	50	130	22	8	200	30	38	20	20	80
7	3	120	30	23	8	200	80	39	20	20	130
8	3	120	80	24	8	200	130	40	20	50	30
9	3	120	130	25	13	20	30	41	20	50	80
10	3	200	30	26	13	20	80	42	20	50	130
11	3	200	80	27	13	20	130	43	20	120	30
12	3	200	130	28	13	50	30	44	20	120	80
13	8	20	30	29	13	50	80	45	20	120	130
14	8	20	80	30	13	50	130	46	20	200	30
15	8	20	130	31	13	120	30	47	20	200	80
16	8	50	30	32	13	120	80	48	20	200	130

□ Group A □ Group B
 ■ Group C ■ Group D

Fig. 4 Four groups of the emotion of being reassuring

guide that the simple linear regression model obtained here is effective to estimate the impedance parameters of robots causing human essential emotions for co-existing with robots.

3.2 Consideration of the emotion of being reassuring

The evaluations for the emotion of being reassuring are divided into four groups (A, B, C, and D) according to the distribution of the mean values of the evaluation as shown in Fig. 4. In other words, it is confirmed that the difference in the average among the four groups is adequate under the significance level of 5.0% in the *t* test. Representative examples of the results in groups A, B, C, and D are shown in Figs. 5, 6, 2, and 7, respectively. The representative contact

Fig. 5 Results for parameter number 1

Fig. 6 Results for parameter number 16

Fig. 7 Results for parameter number 46

Fig. 8 Contact force, position and speed of the robot

force, position, and velocity of the end effector for a subject in the experiment for each group are shown in Fig. 8. The characteristics of the evaluations for each group are as follows.

- In group A, the response is very fast, but the contact force is very small. The emotions of being flexible and pleasant are “positive” and the emotion of being human-like is somewhat “positive,” but the emotion of being reassuring is “negative.” It is considered that subjects feel danger because the robot over-reacts to the applied force.
- In group B, all the emotions are “positive” because the contact force and response speed are appropriate for humans. The combination of impedance parameters in this group is reasonable for robots coexisting with humans.
- In group C (see Fig. 8), the contact force is much smaller and the response is slow. The emotions of being flexible and pleasant are “negative” and the emotion of being human-like is somewhat “negative,” but the emotion of being reassuring is “positive.” It is considered that subjects feel stiffness from the robot to some extent, but feel reassured because the response of the robot is slow.
- In group D, the response is very slow, but the contact force is very large. The emotion of being reassuring is “negative” and the other three adjective pairs are also “negative.” It is considered that the subjects feel too much stiffness and a sense of danger from the robot.

4. Conclusions

It is important that robots have impedance characteristics and can change their impedance values according to the relationship between robots and humans. These impedance values must be changed for robots to generate reassuring and favorable reactions from humans, especially when robots come into

contact with them unexpectedly. From these points of view, the relationships between human emotions and the impedance parameters of robots coexisting with humans, especially when humans come into contact with the robots unexpectedly, have been studied using the rating scale method in this work. The results obtained are as follows.

- The emotions of being flexible, pleasant, and human-like are explained by the linear regression model of impedance parameters. Both desired mass and desired viscosity coefficient values influence human emotions, but desired stiffness values have little influence on them.
- The results on the emotion of being reassuring are classified into four groups, which are explained by the magnitude of contact force and response speed of the robot.
- The results in one of the four groups of combinations of impedance parameters are “positive” for all the adjective pairs. It is considered that the combinations in this group are appropriate for robots when they come into contact with humans unexpectedly.

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