Development of Admittance Control Considering Operability in Human-Robot Cooperative Motion*

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Abstract— **This paper is concerned with an advanced admittance control system for efficiently performing cooperative work between a human and a robot. An assembly work of heavy parts in factories is one of hard physical works. Therefore, it is required to utilize a collaborative robot to assist the worker. However, it is difficult to manipulate the robot directly at will. In this study, we propose the admittance control installing the virtual model with the bounded viscous resistance to improve the operability of direct manipulation to transport heavy objects by the cooperative work of humans and robots. Improving the operability of the proposed approach can be analyzed by frequency analysis. And, the efficacy of the proposed approach is verified by the experiments with the collaborative robot.**

I. INTRODUCTION

As production methods are shifting from mass production to high-mix low-volume production, factory automation is evolving from simple repetitive tasks to assembly tasks that require non-routine and skillful work and are becoming increasingly complex[1]. In addition to knowledge of mechatronics such as sensors, actuators, and control devices, the introduction of automation equipment in factories requires familiarity with the production site, such as the design of jigs and fixtures according to the manufacturing process. In addition, industrial robots, which are general-purpose machines, are being used to robotize production processes, but teaching robot movements requires specialized knowledge in coordinate input and motion programming. To solve these problems, cooperative robots that can teach robot motion easily, such as direct teaching, have been required in recent years[2][3].

One possible application of cooperative robots is the cooperative assembly of heavy parts by a worker and a robot. The worker can directly manipulate the heavy parts while the cooperative robot grasps the heavy parts to reduce the workload. To directly manipulate the robot, a force sensor is installed on the robot's hand, and the robot moves in response to the manipulation force detected by admittance control. This kind of human performance improvement using cooperative robots is becoming common[4]. However, it is difficult to say that the operability is good when a mass-damper system with virtual mass and virtual viscous resistance in general use is applied to the virtual model of admittance control.

Therefore, in this study, we propose an admittance control method that considers operability in the cooperative work between a human and a robot to transfer heavy objects. In the proposed method, a mass-damper system with bounded viscous resistance is applied in a virtual model of admittance control. Frequency analysis reveals that the mass-damper system with bounded viscous resistance improves the operability. The usefulness of the proposed method is demonstrated by experiments using a cooperative robot to transfer heavy objects by direct manipulation of the robot.

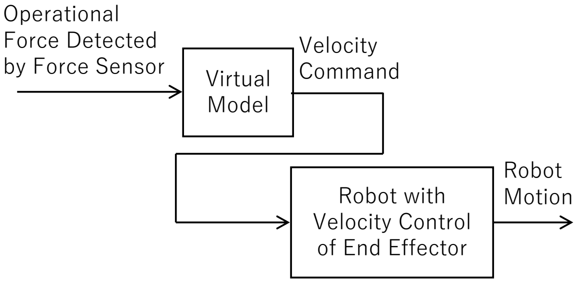

Fig. 1. Signal flow diagram of admittance control in robot motion control system

II. VIRTUAL MODEL IN ADMITTANCE CONTROL

A. Admittance Control

Admittance control is a control model that is widely known as a technique to enable compliant behavior of robots[5]. A signal flow diagram of admittance control that enables direct manipulation is shown in Fig. 1. In this study, a force sensor placed at the robot's hand end detects the manipulation force applied to the grasping tool or the grasping object attached to the robot's hand end. The detected manipulation force is given to the virtual model, and the robot motion is calculated based on the virtual model, and the velocity command of the robot tip is output. By giving the velocity commands to the robot controller, the robot moves according to the velocity commands. The virtual model in this study consists of a mass damper system and a dead zone against the manipulation force. The dead zone is set so that the robot does not move due to the sensor noise of the force sensor. The following equation shows the manipulative force F_d through the dead zone for the manipulative force F detected by the force sensor.

$$F_d(t) = \begin{cases} 0, (|F(t)| \leq d) \\ \mathrm{sgn}(F(t))(|F(t)| - d), (|F(t)| > d) \end{cases} \quad (1)$$

where d denotes the boundary value of the dead zone. t denotes time. This dead zone is considered to have similar characteristics to static friction. The operating force F_d is applied to the mass-damper system through the dead zone.

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*This work was not supported by any organization

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The general mass-damper system is represented as follows.

$$m\dot{v}(t)+cv(t)=F_d(t) \tag{2}$$

where m is the virtual mass, v is the velocity of the massive object, and c is the virtual viscosity coefficient.

B. Admittance control with bounded viscous resistance

In the cooperative behavior of human-robot interaction using admittance control, we believe good operability can be obtained by making the virtual model closer to the actual operating environment. Therefore, in this study, we consider that frictional resistance is more dominant than viscous resistance in damping motion, and propose to make viscous resistance similar to frictional resistance. By applying the bounded viscous resistance to the virtual model, we can realize the characteristics similar to kinetic friction and improve the operability of the model. The virtual model of the mass damper system with bounded viscous resistance is shown in the following equation.

$$\begin{cases} m\dot{v}(t)+cv(t)=F_d(t),(|v|\le v_s \land t<t_1) \\ m\dot{v}(t)+\mathrm{sgn}(v)cv_s=F_d(t),(|v|>v_s \lor t\ge t_1) \end{cases} \tag{3}$$

where v_s is the boundary velocity in bounded viscous resistance. The viscosity coefficient c_s when the boundary velocity is represented is given by

$$c_s(v)=\frac{\mathrm{sgn}(v)cv_s}{v}=\frac{cv_s}{|v|} \tag{4}$$

Substituting Equation (4) into Equation (3), we obtain the following equation.

$$\begin{cases} m\dot{v}(t)+cv(t)=F_d(t),(|v|\le v_s \land t<t_1) \\ m\dot{v}(t)+c_s(v)v=F_d(t),(|v|>v_s \lor t\ge t_1) \end{cases} \tag{5}$$

Equation (5), the control is switched depending on the velocity value. This allows us to consider that the viscosity coefficient of the mass-damper system varies depending on the velocity when the viscous resistance exceeds the boundary velocity. Furthermore, t and t_1 are given as follows.

$$\begin{aligned} &t: Time[s] \\ &t_1: Time\ when\ first\ |v|\ exceeds\ v_s \end{aligned}$$

By providing such a case separation, the term in the viscous resistance can be fixed at $c_s(v)v$ during the stopping motion. This makes it easier to stop the robot independent of the inertia value.

Assuming that the viscosity coefficient varies with respect to the steady-state velocity, the transfer function is given by

$$\frac{V(s)}{F_d(s)} = \left.\frac{\frac{1}{m}}{s+\frac{c_e}{m}}\right|_{c_e=\begin{cases} c,(|v|\le v_s) \\ c_s(v),(|v|>v_s)\end{cases}} \tag{6}$$

$$= \left.\frac{k\omega_c}{s+\omega_c}\right|_{c_e=\begin{cases} c,(|v|\le v_s) \\ c_s(v),(|v|>v_s)\end{cases}} \tag{7}$$

where $\omega_c=c_e/m$ is the cut off angular frequency and $k=1/c_e$ is the gain.

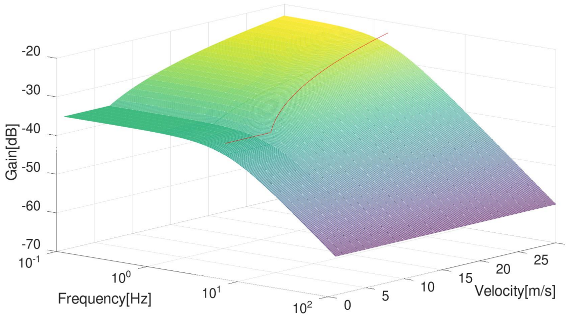

Fig. 2. Frequency response and cut-off frequency varying by velocity

The switching from low velocity to high velocity in the proposed mass damper system with bounded viscous resistance is analyzed from the frequency response. From the Equation (7), the gain characteristic is given by

$$\left|\frac{V(\omega)}{F_d(\omega)}\right| = k\left.\sqrt{\frac{(\frac{\omega_c}{\omega})^2}{1+(\frac{\omega_c}{\omega})^2}}\right|_{c_e=\begin{cases} c,(|v|\le v_s) \\ c_s(v),(|v|>v_s)\end{cases}} \tag{8}$$

Therefore, the gain and the cut off angular frequency are represented as follows

$$k=\frac{1}{c_e}=\begin{cases} \frac{1}{c},\ (|v|\le v_s) \\ \frac{|v|}{cv_s},\ (|v|>v_s) \end{cases} \tag{9}$$

$$\omega_c=\frac{c_e}{m}=\begin{cases} \frac{c}{m},\ (|v|\le v_s) \\ \frac{cv_s}{m|v|},\ (|v|>v_s) \end{cases} \tag{10}$$

Fig. 2 shows the gain characteristics of Equation (8) and the cut off frequency of Equation (10). In Fig. 2, the virtual mass is set to $m=$10[kg], the virtual viscosity coefficient is set to $c=$60[kg/s], and the boundary velocity is set to $v_s=$7[m/s]. The mesh surface plots show the frequency response varying with each steady-state velocity, and the red line indicates the cut off angular frequency. The results show that beyond the boundary velocity, the gain increases, and the cut off frequency decreases as the steady-state velocity increases.

Substituting Equations (9), (10) into Equation (8), we obtain the following equation

$$\left|\frac{V(\omega)}{F_d(\omega)}\right| = \left.\sqrt{\frac{1}{m^2\omega^2+c_e^2}}\right|_{c_e=\begin{cases} c,(|v|\le v_s) \\ c_s(v),(|v|>v_s)\end{cases}} \tag{11}$$

where $m^2\omega^2 \gg c_e^2$ can be approximated by

$$\left|\frac{V(\omega)}{F_d(\omega)}\right| \approx \left.\sqrt{\frac{1}{m^2\omega^2}}\right|_{c_e=\begin{cases} c,(|v|\le v_s) \\ c_s(v),(|v|>v_s)\end{cases}} \tag{12}$$

This means that the gain characteristics do not depend on the viscosity coefficient in the high band with respect to the cut off frequency. Therefore, it can be said that, beyond the boundary velocity, the gain in the low frequency band increases as the steady-state velocity increases, while the gain characteristics in the high frequency band remain unchanged.

The results of this analysis suggest that in the admittance control equipped with a virtual model of a mass-damper system with bounded viscous resistance, the velocity can be increased with a small force in the region beyond the boundary velocity, which improves the operability of the system.

III. VERIFICATION BY SUBJECT EXPERIMENT

A. Experiment Summary

To confirm the usefulness of the admittance control with bounded viscous resistance proposed in this study in an actual machine, we will conduct a subject experiment using a cooperative robot. Fig. 3 shows the environment in which a heavy object is transported by cooperative work with a robot. The admittance control parameters used in this experiment are virtual mass $m = 8$ [kg], virtual viscosity $c = 60$ [kg/s], boundary value of dead zone $d = 3$ [N], and boundary velocity $v_s = 0.07$ [m/s]. A total of four subjects are subjected to both conventional admittance control and the proposed method of admittance control with bounded viscous resistance in turn.

The first step of the experiment is to train the subject to become accustomed to the robot's operation. The training is continued for an unlimited time until the subject feels comfortable. The subject will also be advised on the best way to apply force to manipulate the robot arm. After the training is completed, a test of the robot's operation is conducted. In the test, the test run consists of a single lap around the path indicated by the yellow lines, as shown in Fig. 3. This is repeated 5 times for measurement. These training and testing processes are conducted using both the conventional and the proposed methods.

Finally, a questionnaire based on the Likert scale is administered, and a comparison is made between the conventional and the proposed methods based on subjective evaluations. For the questionnaire, we focus on lightness during operation, positioning, and operability, and evaluate the following eight items on a 5-point scale.

Q1. Whether the operation felt light or not
Q2. Whether you felt it was easy to position
Q3. Whether you felt it was easy to operate
Q4. Whether you felt you could operate for long periods
Q5. Whether the operation felt familiar or not
Q6. Whether you felt you could operate faster
Q7. Whether you felt the task was easy to accomplish
Q8. Whether you felt it was easy to operate as per the operating path

The items Q1, Q4, and Q6 are intended to evaluate the lightness of operation, Q2 and Q8 are intended to evaluate the positioning, and Q3, Q5, and Q7 are intended to evaluate the operability. For each question, 5 is " very applicable " and 1 is " not applicable" at all.

B. Experimental Results and Discussion

Figures 4, 5 show an example of a subject as a comparison between the conventional and the proposed methods in terms of operating force and velocity. In this figure, the conventional and proposed methods are compared in the force and velocity data of x- and y-axes. Fig. 6 shows a comparison of the motion trajectories of the conventional and proposed methods. Fig. 7 shows box-and-whisker diagrams of the results of the questionnaire. In Fig. 7, the blue color indicates the results of the questionnaire for the conventional method and the green color indicates the results for the proposed method. In the box-and-whisker diagram, the red line represents the median value, and the whisker ends represent the minimum and maximum values. The dots indicate outliers.

We compare the force and velocity data in Figs. 4 and 5. First, the conventional method uses a constant input force of 15[N]. The proposed method operates with a force of 10[N]. On the other hand, the velocity graphs show that the proposed method outputs the same level of velocity. These

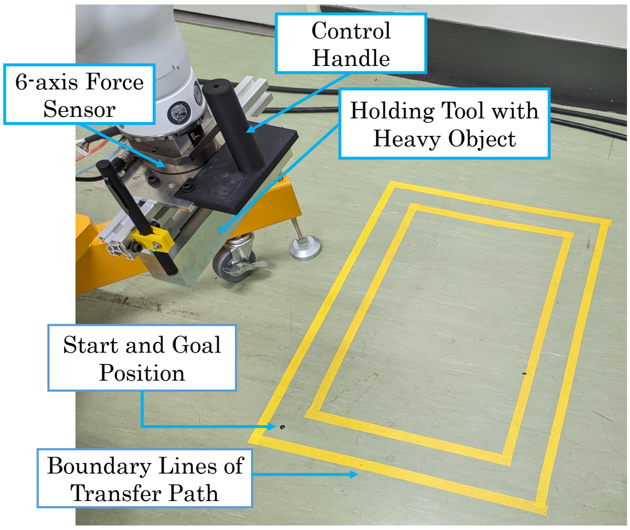

Fig. 3. Experimental apparatus with collaborative robot

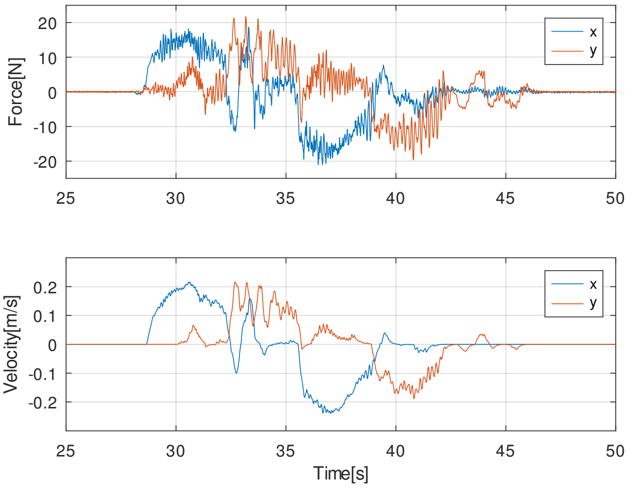

Fig. 4. Experimental results of operational forces and moving velocities by applying conventional admittance controls

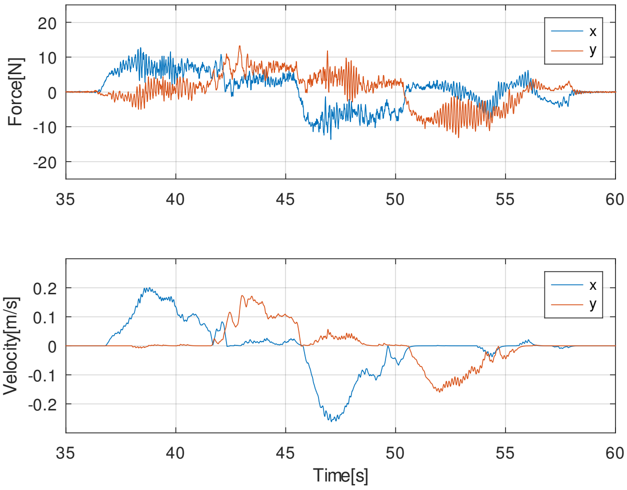

Fig. 5. Experimental results of operational forces and moving velocities by applying proposed admittance controls

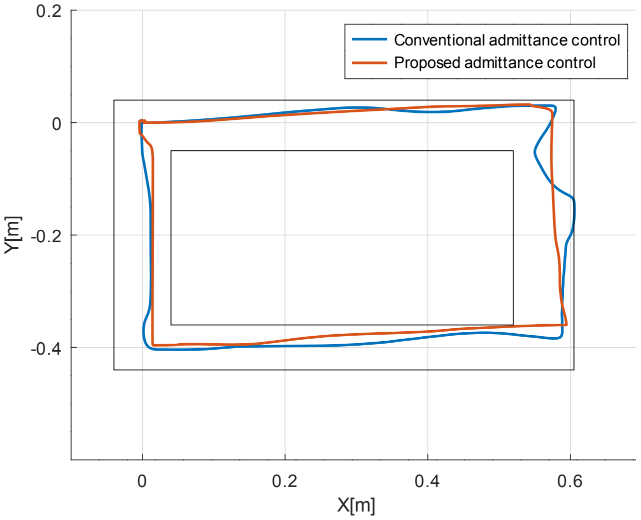

Fig. 6. Experimental results of transfer pahts by applying conventional and proposed admittance controls

results show that the proposed method can operate the robot arm lighter and faster than the conventional method.

In Fig. 6, the blue line shows the trajectory by applying the conventional model and the red line shows that by applying the proposed model. In the conventional method, the trajectory during motion correction in the high speed range swings significantly due to the difficulty of stopping. The proposed method can operate lightly in the high-speed range, resulting in a straight trajectory. In addition, the model makes a turn while making an angle by utilizing the model's ease of stopping. Finally, the model continues to operate in the low-speed range by small force input and corrects to the goal position.

Next, we compare the box-and-whisker plots of the questionnaire results shown in Fig. 7. The results of the questionnaire show that Q1, Q2, Q3, Q4, and Q6 are superior to the conventional method. The other items, Q5, Q7, and Q8, have the same level of evaluation.

Q1, Q4, and Q6, which are the items intended for lightness in operation, show clear superiority. The quantitative evaluation in the graphs of the force and velocity data and the qualitative evaluation in the subject's subjective evaluation agreed with each other in terms of lightness during operation. From these results, we believe that the model proposed in this study enables long-time operation of the robot arm when it is used for direct manipulation in factories and so on.

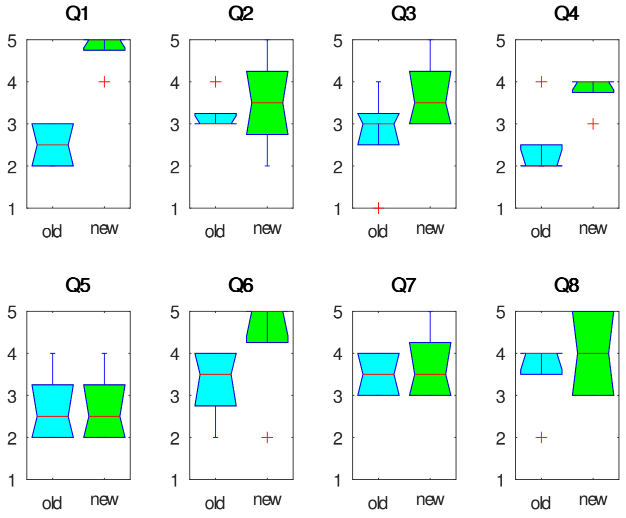

Fig. 7. Results of questionnaire by Likert scale

Q2 and Q3, which ask about ease of positioning and ease of operation, do not show as clear an advantage as the questions for the item intended to be light. In addition, Q5 and Q7, which evaluate the ease of operation, and Q8, which evaluate the ease of positioning, have the same level of evaluation. We believe that these results are due to the difficulty of operation of the proposed model. The new model in this study keeps the term of viscous resistance constant during stopping, which makes it easier to stop even when outputting a large velocity. However, since the behavior at the start and the top of the operation are different, the behavior is hysteresis. This results in an increase in the difficulty of operation of the model of the proposed method. We believe that this increase in the difficulty of operation is the reason why there is no clear superiority in the results of the positioning and operability questionnaires.

IV. CONCLUSIONS

In this study, we developed the admittance control by applying the virtual model of the mass-damper system with bounded viscous resistance. To confirm the effectiveness of the proposed method, we applied the virtual model to a co-operative robot and conducted experiments on test subjects.

From the results of the subject experiments, it was confirmed that the cooperative work using the proposed method is lighter than that using the conventional method, based on the agreement between objective and subjective evaluations. However, the model of the proposed method did not show clear superiority in operability and positioning due to the increased difficulty of operation. We believe that the model of the proposed method enables long-time operation when the robot arm is directly operated in a factory, etc., by getting the hang of the operation.

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