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Force Control Law Selection for Elastic Part Assembly from Human Data and Parameter Optimization

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***Abstract*— This paper proposes a novel force control design method used to assemble a ring-shaped elastic part to a cylinder's outer groove. To assemble a ring-shaped elastic part, forces acting on an elastic part should be made as small as possible. To cope with this problem, we propose a novel method in which the force control strategy itself is automatically determined based on the human characteristics while the parameters of the controller are determined by using a numerical optimization.**

First, the position data and the force data while a human demonstrates the assembly are measured. From the measured data, two control methods are derived by using the normalized cross-correlation (NCC). Then, we optimize the parameters included in the obtained controller by using the downhill simplex method. The objective function of optimization is the peak force during the assembly. We confirmed that the applied force is considerably reduced compared with conventional methods.

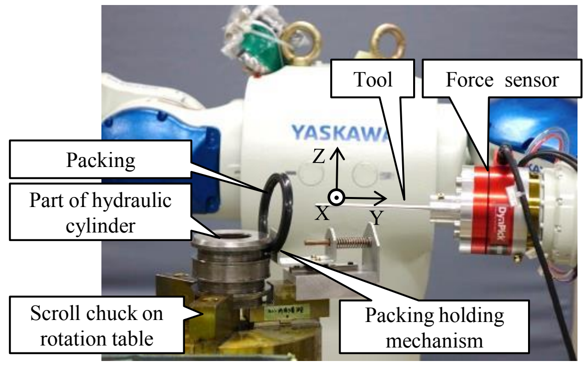

Figure 1. Experimental robot system to assemble a ring-shaped elastic part (packing) to a hydraulic cylinder part where a rod-shaped tool and a force sensor are attached at the tip of the robotic arm, and the scroll chuck is mounted on a rotation table.

I. Introduction

To assemble a hydraulic cylinder, a ring-shaped rubber packing should be attached to a cylindrical-shaped piston. This assembly is not easy since the rigidity of this rubber packing is relatively high. If this rigid rubber packing is damaged, permanent distortion or oil leakage may occur. Hence, it is desirable to avoid excessive force applied to a packing during its assembly. To cope with this problem, this paper proposes a new method for force-controlled assembly of a ring-shaped elastic part to a cylinder's outer groove where the force acting on an elastic part is made as small as possible where our experimental setup is shown in Fig. 1.

When humans perform the same assembly task, they work carefully so as not to add extra load to the objects. On the other hand, robots may exert an excessive force unless such human-like control strategy is used. Therefore, in this study, we analyze the force and motion of a human assembly task and then implement the force control method obtained based on the human force/motion analysis on the robot.

Many studies on robot manipulators performing force control based on human characteristics have been proposed [1]–[8]. However, although the parameters in the impedance control were determined based on human characteristics, the following two problems are unsolved. First, even if the impedance characteristics of a human were obtained, they are not necessarily the optimum impedance characteristics for a robot to perform that task. Secondly, correctly obtaining the impedance characteristics of a human is not easy [9], [10]. Taking these problems into consideration, this research does not completely transfer human impedance characteristics to a robot. Rather, we consider obtaining the force control law of a robot from qualitative analysis of human characteristics and obtaining the parameters of force control suitable for the robot by solving an optimization problem. By using the proposed method, an optimized control strategy with the characteristics of a human can be obtained. In our previous report [11], we have performed an elementary analysis on obtaining optimal parameters for force control. On the other hand, this research first proposes a framework on the force-controlled assembly where the force control law is obtained based on human characteristics and parameters of force control is numerically optimized.

Now, consider the problem of packing assembly as a problem of flexible-object manipulation. There are mainly two approaches to manipulate flexible objects: one is the model-based approach and the other is the data-driven approach. Since the former approach is difficult due to the complicated physical phenomenon of elastic deformation, this research considers adopting the latter approach where its control policy is derived from the qualitative analysis of human demonstration data. While there have been studies on manipulation of flexible objects such as cloth, thin plate and string, there have been few studies dealing with ring-shaped flexible objects. Different from a linear object, a ring-shaped object has a closed loop. Although some researches such as [12], [13] have already been conducted on assembling ring-shaped flexible parts, they assumed the ring-shaped objects to be of relatively low stiffness and deform the object largely. Applying these approaches to the stiff packings seems difficult due to the large deformation may causing scratches and permanent deformations. Some mechanical devices such

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as [14]–[18] have investigated for a flexible ring-shaped part to be assembled to a cylindrical part, these methods also assume rings to be of low stiffness and are different from our research.

In this paper, we introduce the related works in Section II, describe the target packing assembly task by human in Section III, present an outline of robotic assembly in Section IV, propose the force control based on human characteristics and an optimization technique in Section V and present the results of implementing the proposed force control strategy in Section VI. Section VII concludes this paper.

II. Related Works

As for the research on force control based on human characteristics, Asada et al. [1] and Itabashi et al. [2] obtained parameters of a force control law by analyzing the force and position data during a human performs a grinding task and a peg-in-hole task. Ajoudani et al. [3] proposed an impedance control law based on a human's impedance estimated from the muscular potential, and a ball catching task was realized. Tanaka et al. [4] obtained a sensor feedback law by using the target position trajectory of a manipulator obtained from the human demonstration data of a paper folding (*origami*) task. Lee et al. [5] proposed an impedance control law where the impedance parameters are extracted from the force and position trajectory of a human demonstration. Yoon et al. [6] used a master-slave robot with an impedance control strategy implemented on the slave arm and extracted a manipulation skill of a human operator. Gribovskaya et al. [7] made a robot follow both human position and force data in a well-balanced way by dynamically changing the stiffness parameter of impedance control. Racca et al. [8] also proposed a stiffness parameter changing method and conducted experiments of pulling a door handle and pushing a button. However, there has been no research on the force-controlled assembly where the force control strategy itself is automatically determined based on the human characteristics while the parameters of the controller are determined by using a numerical optimization.

As for the mechanical devices for an elastic ring to be inserted to a cylindrical part, Denso [14] and Mitsubishi Electric [15] proposed a mechanism that spreads the ring from the inside with multiple fingers and pushes it out at the position of the attachment groove. SCHUNK sells an O-ring gripper ORG [16] that has six fingers to make the ring spread out hexagonally from the inside and successfully fits it into the mounting groove. Nissan Motor [17] and Gastar [18] proposed a mechanism using a tubular jig with a taper. However, these devices can only be applied for a ring-shaped elastic object with relatively low stiffness.

III. Packing Assembly Task Overview

In this section, we explain some different human assembly methods of a ring-shaped elastic part as outlined in Figs. 2, 3, 4 and 5.

Fig. 2 shows the most intuitive method in which the packing is extended uniformly in the radial direction and then assembled on a cylinder part [14]–[18]. However, this method usually requires the use of a special tool to extend the packing uniformly. Moreover, although relatively large elastic deformation must be generated during the packing assembly, elastic deformations should be as small as possible due to the reason explained in the introduction.

Rather than the method shown in Fig. 2 which expands the whole packing, the method shown in Fig. 3 which can make the elastic deformation as small as possible is common in the case of packing assembly. In this method, first, a part of the packing is hooked to the edge of the cylinder. Then, the packing is extended by using the human hands, thereby gradually increasing the area where the packing is installed. When the packing hangs over the entire circumference of the cylinder, the packing is shifted down and fitted in the groove.

In this study, to make the force applied by the hand as small as possible during the packing assembly, a thin rod-shaped tool can be used (Fig. 4). In this method, the tool is hooked to the packing and the assembly operation is carried out by making a circle around the hydraulic cylinder along with the mounting groove. To realize this assembly state, two operations are required: to push the packing radially outward and take it outside the wide part of the groove's upper part, and to push down in the vertical direction and bring it to the groove. In the method using a thin rod-shaped tool, two constraints are used for them; one is a position constraint for the radial direction, and the other is a position constraint in the vertical direction. As the tool is moved in the circumferential direction, the packing is gradually expanded in the radial direction and pushed down to the height of the groove by the two constraints, and it enters the groove.

We modified the assembly method of Fig. 4 to Fig. 5. In this method, a scroll chuck mounted on a rotation table grasps and rotates the hydraulic cylinder part. This method is the easiest to port to a robot. It is observed that the position of the

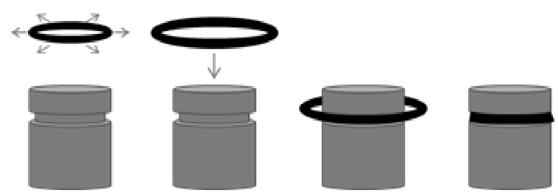
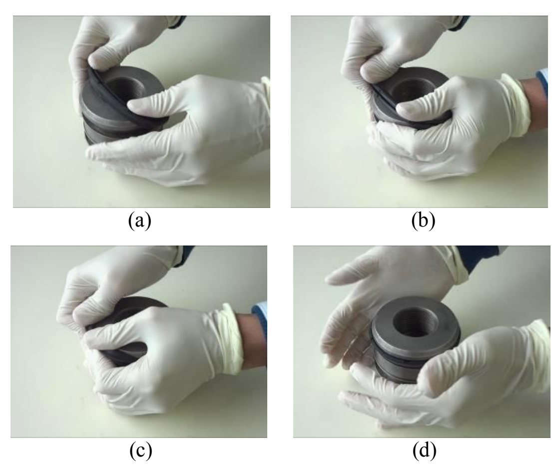


Figure 2. A simple assembly method used in [14]–[18]. Since this method requires a large elongation this is not suitable for stiff packings.



(a) (b) (c) (d)

Figure 3. An assembly method by human hands. This method is difficult to port to a robot since a mechanism of human hands are too complex.

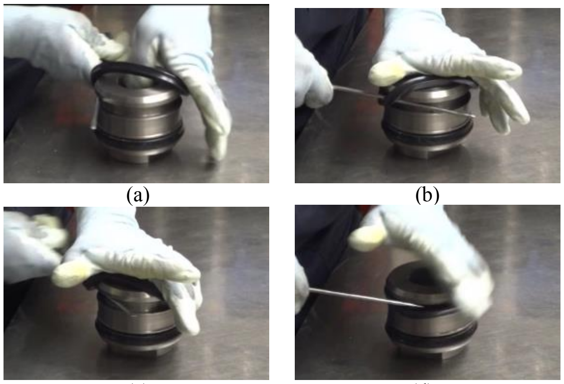


Figure 4. An assembly method by a human using a rod-shaped tool.

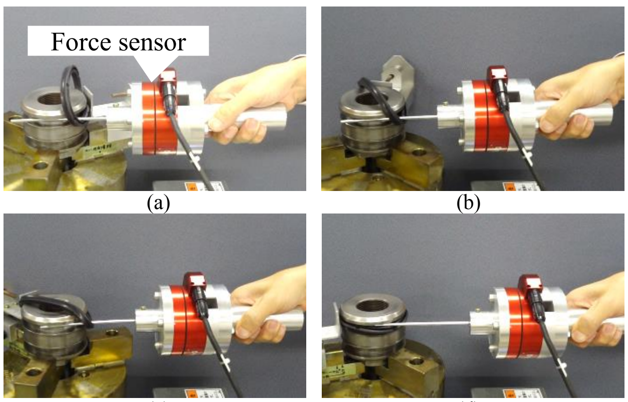


Figure 5. The human assembly using a rod-shaped tool and a scroll chuck on a rotation table where a human holds a force sensor with a rod mounted on the tip

tool is fluctuating in the horizontal plane during assembly. It seems that the human is relieving the load by moving the tool properly according to the received force. The force control based on this technique is required when robots conduct the packing assembly.

IV. Force Control Design Method

The assembly task shown in Fig. 5 was ported to a robot as Fig. 1. In this experimental system, we used MOTOMAN-SDA10F (YASKAWA Electric Co.). A six-axis force/moment sensor is mounted at the wrist, and the rod-shaped tool made of chromium vanadium steel is mounted on the force/moment sensor where the rod's diameter, the total length, and the weight are 4[mm], 160[mm], and 169 [g], respectively. The tool and the force/moment sensor are the same instruments used in the human demonstration. We used the packing and the metal part for a hydraulic cylinder with a diameter of 85 [mm], and they are shown in Figs. 3, 4 and 5.

Fig. 6 shows how the robot system assembles the packing. As shown in Fig. 6 (a), the packing is initially held between the packing holding mechanism and the cylinder part, and the rod tool is let to pass horizontally through the ring of the packing. From this state, as shown in Fig. 6 (b), the rod-shaped tool is lowered until the packing brought into contact with the groove. Then, the robot is controlled by using the proposed force control law while the rotating table is rotated, as shown in Fig. 6 (c). As a result, the packing is pushed down along the tool and the assembly is finished as shown in Fig. 6 (d).

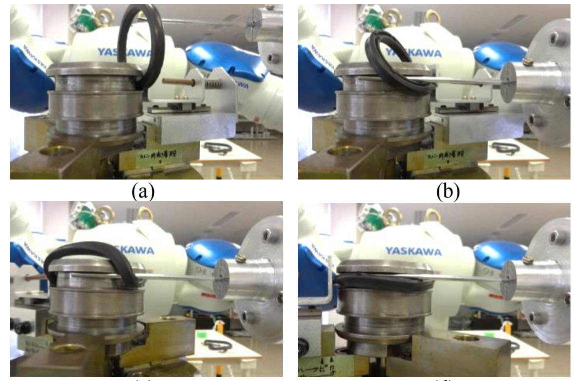


Figure 6. Assembly by a robot. (a) The packing is set to groove. (b) The tool is set to groove. (c) The chuck is rotated, and the packing is inserted. (d) The packing assembly is finished.

Now, how to design the force control for the packing assembly is explained. As described in Section III, the human moves the tool according to the received force. We consider constructing a force control law which replicates the human characteristics by analyzing the human demonstration data. The values of force control parameters are determined by a numerical optimization.

First, we explain how to determine the force control law. For each axis, we consider selecting a force control law which is closest to the human characteristics among the following three control laws:

$$p_i(t) = k_i f_i(t)\ , \qquad (1)$$

$$\dot{p}_i(t) = d_i f_i(t)\ , \qquad (2)$$

$$\ddot{p}_i(t) = m_i f_i(t)\ , \qquad (3)$$

where $i \in \{X, Y\}$ represents the axis of the coordinate system. Since we observed the horizontal movement of the human, only the X and Y axes are considered. $p_i(t)$ denotes a displacement from the initial position of the tool. $\dot{p}_i(t)$ and $\ddot{p}_i(t)$ denote the first and second derivatives of $p_i(t)$, respectively. $f_i(t)$ denotes an external force. Equations (1) and (2) are called "compliance control" and "damping control," respectively.

Here, the impedance control satisfying the following equation is also often used:

$$\hat{m}_i \ddot{p}_i(t) + \hat{d}_i \dot{p}_i(t) + \hat{k}_i p_i(t) = f_i(t)\ , \qquad (4)$$

with three parameters $\hat{m}_i$, $\hat{d}_i$, and $\hat{k}_i$. The impedance control is equivalent to (1), (2), and (3) when some of the parameters are set to zero. However, as the number of parameters increases, it becomes more and more difficult to set appropriate parameter values. Thus, we decided to selectively apply either (1), (2) or (3) for reducing parameters to determine.

We select the force control law by measuring the position and the force during human assembly demonstration. For each direction of human demonstration data, if the force is in proportion to the position, the velocity, and the acceleration, we consider applying the robotic force control law of (1), (2) and (3), respectively. We consider checking a proportional relation by using the normalized cross-correlation (NCC). Let $s_{pi}, s_{vi}, s_{ai}, s_{fi}$ be given by

$$s_{pi} = [p_i(0), \dots, p_i(nT)] \quad (5)$$

$$s_{vi} = [\dot{p}_i(0), \dots, \dot{p}_i(nT)], \quad (6)$$

$$s_{ai} = [\ddot{p}_i(0), \dots, \ddot{p}_i(nT)], \quad (7)$$

$$s_{fi} = [f_i(0), \dots, f_i(nT)]. \quad (8)$$

$\mathrm{NCC}(s_{pi}, s_{fi})$, $\mathrm{NCC}(s_{vi}, s_{fi})$ and $\mathrm{NCC}(s_{ai}, s_{fi})$ denote the NCCs between s_{pi} and s_{fi}, s_{vi} and s_{fi}, and s_{ai} and s_{fi}, respectively. If the largest one among the three is $\mathrm{NCC}(s_{pi}, s_{fi})$, $\mathrm{NCC}(s_{vi}, s_{fi})$ and $\mathrm{NCC}(s_{ai}, s_{fi})$, (1), (2) and (3) are selected as force control laws of i direction, respectively. $\mathrm{NCC}(s_{pi}, s_{fi})$,, $\mathrm{NCC}(s_{vi}, s_{fi})$ and $\mathrm{NCC}(s_{ai}, s_{fi})$ are obtained by the inner product of two signals divided by the norms of the two signals as follows:

$$\mathrm{NCC}(s_{pi}, s_{fi}) = \frac{\langle s_{pi}, s_{fi}\rangle}{\|s_{pi}\|\|s_{fi}\|}, \quad (9)$$

$$\mathrm{NCC}(s_{vi}, s_{fi}) = \frac{\langle s_{vi}, s_{fi}\rangle}{\|s_{vi}\|\|s_{fi}\|}, \quad (10)$$

$$\mathrm{NCC}(s_{ai}, s_{fi}) = \frac{\langle s_{ai}, s_{fi}\rangle}{\|s_{ai}\|\|s_{fi}\|}, \quad (11)$$

where $\langle \cdot, \cdot \rangle$ and $\|\cdot\|$ denote the inner product and the norm, respectively. NCC can measure the similarity of two signals since the inner product indicates the similarity between the two signals. As the NCC value approaches one, it can be said that the two signals have a strong proportional relation.

After a control law is selected, it is necessary to determine the values of parameters k_i, d_i or m_i included in the selected control law. We searched for values that maximize the performance by using the downhill simplex method (Nelder-Mead method, amoeba method) [19]. We assumed the maximum force during the assembly as an objective function of the optimization.

In the downhill simplex method, a simplex consisting of multiple points are considered. Due to the deformation of the simplex, the optimum solution can be searched. The downhill simplex method is applicable to multivariate nonlinear optimization and does not require the differentiation of the objective function. The downhill simplex is effective due to the following two reasons: first, the performance of the force-controlled task cannot be analytically solved in many cases. Second, the calculation of the numerical differentiation of force is difficult due to the effect of noise.

With our proposed framework, it becomes possible to select the optimum force control parameters for each robot having different hardware configuration, referring the human demonstration data qualitatively. In general, optimizing the force control parameters by experiments is not easy, because it requires a lot of experiments. Although Hirai et al. [20] and Yamanobe et al. [21] also performed optimization of force control parameters by using the downhill simplex method, they conducted physics simulations to reduce the number of trials before using an actual robot. If the task is too complex to construct a simulator, their methods are difficult to apply. On the other hand, since the qualitative analysis of a human demonstration suppressed the parameters in the proposed method, an optimization by experiments could be realized.

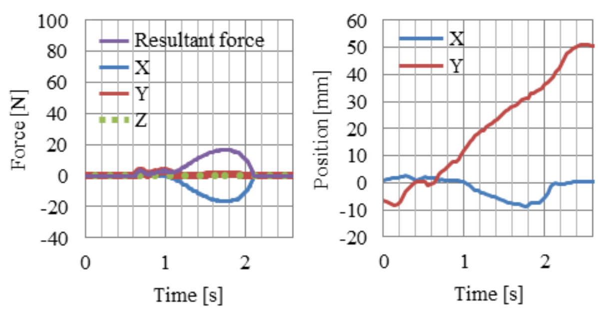
V. Force Control Experiments

We implemented the proposed force control and conducted packing assembly experiments. First, we show the experimental result of the proposed method. The force control law selected by the NCC analysis is adopted, the force control parameters are optimized by the downhill simplex method, and the performances of the force control using the optimum parameters are evaluated. Then, we show the experimental results of the other force control laws which are not selected by the NCC analysis. This reveals the control law selection by the NCC analysis is appropriate.

A. Experiment of Proposed Method

In this subsection, we test three types of control methods. Control method 0: the force control is not implemented, and the position of the rod is fixed. Control method 1: the proposed method is applied in the only Y direction. Control method 2: the proposed method is applied to both the X and Y directions.

To analyze the human characteristics, the force and position data during a human packing assembly were measured. Since we applied the force control only in the X and Y directions, we measured the 2D position of the rod by using a USB camera. A force/moment sensor, as shown in Fig. 5, was used to measure the force where Fig. 7 shows the measured data.



(a) Force (b) Position

Figure 7. Force position data of a human assembly by the method of Fig. 5.

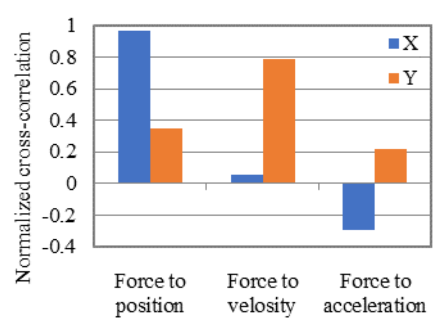


Figure 8. Normalized cross-correlation values from force to position, velocity, and acceleration of the human demonstration data

Fig. 8 shows the calculated NCC between the human force data shown in Fig. 7 (a) and the human motion data shown in Fig. 7 (b) where the velocity and acceleration data were obtained by numerical differentiation. Since the sampling rates of the force and position data were different, we adjusted them to 30 [Hz] by using the linear interpolation. For the NCC in the X direction, an extremely high correlation (0.967) is observed between the force and the position. Hence, the force control of (1) was used in the X direction. In the Y direction, the NCC between the force and the velocity is the highest (0.788). Hence, we adopted a force control law of (2). Therefore, different force control laws are used between X and Y directions. We set Control methods 0, 1 and 2 as follows:

Control method 0

$$\begin{bmatrix} \dot p_X(t) \\ \dot p_Y(t) \\ \dot p_Z(t) \\ \dot p_{RX}(t) \\ \dot p_{RY}(t) \\ \dot p_{RZ}(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{12}$$

Control method 1

$$\begin{bmatrix} \dot p_X(t) \\ \dot p_Y(t) \\ \dot p_Z(t) \\ \dot p_{RX}(t) \\ \dot p_{RY}(t) \\ \dot p_{RZ}(t) \end{bmatrix} = \begin{bmatrix} 0 \\ d_Y f_Y(t) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{13}$$

Control method 2

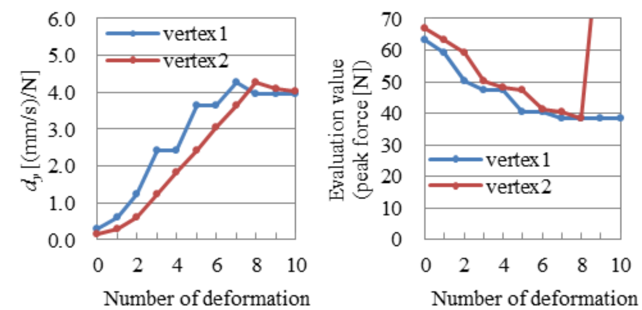
$$\begin{bmatrix} \dot p_X(t) \\ \dot p_Y(t) \\ \dot p_Z(t) \\ \dot p_{RX}(t) \\ \dot p_{RY}(t) \\ \dot p_{RZ}(t) \end{bmatrix} = \begin{bmatrix} k_X \dot f_X(t) \\ d_Y f_Y(t) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{14}$$

where X component of (14) is equivalent to (1).

To determine the force control parameters, the downhill simplex method was applied. In this case, the parameters are proportional gains d_Y and k_X in (2) and (1), respectively. The peak value of the force during packing assembly was used as the evaluation value of optimization. This value is obtained by carrying out an actual robotic assembly experiment. Since the force data will fluctuate for each trial even with the same parameter, the average of the evaluation value obtained by conducting the same assembly experiment for three times was used. To avoid selecting the parameters causing oscillations of the robot as an optimal parameter, the evaluation value is set to be 1000 if oscillation occurred. Since a single variable (d_Y) is optimized in Control method 1, the search was performed by the simplex consisting of two vertices. Similarly, two variables (d_Y and k_X) are optimized in Control method 2, the simplex consisting of three vertices was adopted. The termination condition of the search was set as the best vertex was not updated even when the simplex was deformed for three times. In addition, when multidimensional optimization is performed by the downhill simplex method, it can stop at a point that is not optimal for some reasons [19]. Therefore, the points close to where the search stopped were used as new initial values, and the search was performed again in Control method 2.

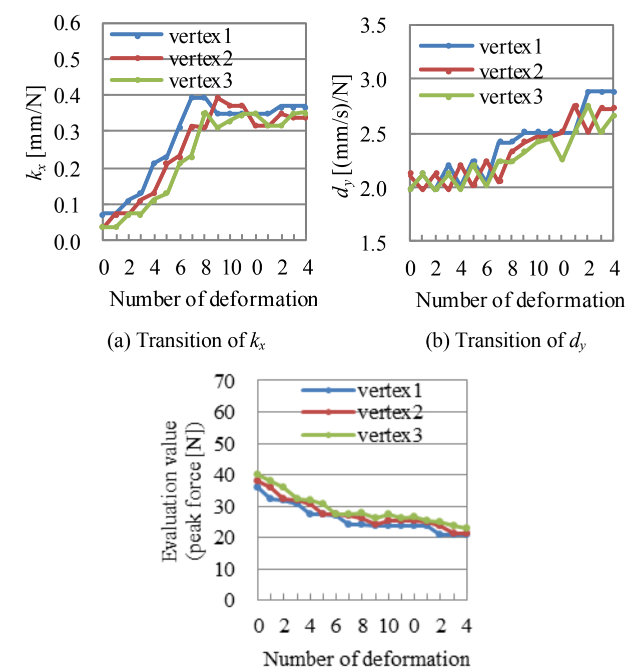
First, we show the optimization process of Control method 1 in Fig. 9. Fig. 9 (a) shows how simplex shifts in the parameter space. The initial values of d_Y were selected to be sufficiently low values for safety reason, and they gradually increase and are finally settled. Fig. 9 (b) shows the transition of the evaluation values. We confirmed that the load decreases to 38.3 [N]. The evaluation value exceeds 70 in the ninth deformation, because a penalty for oscillations was imposed. In this optimization, simplex was deformed for 10 times before it stopped. These experiments were conducted for totally 18 parameters.

Fig. 10 (a) and (b) show how the simplex deformed in the optimization of Control method 2. In this case, after the first optimization stopped, the second optimization was started. The initial values of k_X were selected as sufficiently small values of 0.037 and 0.074. The initial values of d_Y were selected as about the half of the optimum parameter in Control



(a) Transition of d_y (b) Evaluation values

Figure 9. Optimization process of Control method 1 where "vertex1" is the best vertex in the simplex and "vertex2" is the second best



(a) Transition of k_x (b) Transition of d_y

(c) Evaluation values

Figure 10. Optimization process of Control method 2 where "vertex1" is the best vertex in the simplex, "vertex2" is second, and "vertex3" is the least.

method 1, since this value was expected to be safe enough. Fig. 10 (c) shows the transitions of the evaluation values. Finally, the force was reduced to 20.7 [N]. This value is about half of Control method 1. We can find that the countermeasure for X direction is also effective. In the first optimization of Control method 2, the simplex was deformed for 11 times with 28 parameters experimented. In the second optimization, simplex was deformed for 4 times with 9 parameters experimented.

We then evaluate the performance of each control methods using the optimum parameters. Fig. 11 shows the plot of the maximum force received during the assembly task with either one of the four conditions; 1) using the Control method 0, 2) using the Control method 1 with an optimum parameter, 3) using the Control method 2 with optimum parameters and 4) operated by a human. The maximum, average and minimum values of ten assembly experiments with each condition are plotted. We can see the effect of force reduction is considerable in the proposed methods where the difference between Control method 2 and human operation is only 6.4 [N]. Additionally, the dispersion of the force is not large.

Next, we compare the temporal changes of the force and the position of each control methods. These data clarify that the assembly skill of human is replicated well and what causes the small difference between the performance of the proposed method and the human operation. Fig. 12, Fig. 13 and Fig. 14 show examples of the force and the position data of Control method 0, Control method 1 and Control method 2, respectively. These are compared with Fig. 7 where this figure shows the force and the position data of the human operation. They show that the force in the Y direction is considerably reduced in Control method 1 and Control method 2, compared to Control method 0. Moreover, in Control method 2, the force in the X direction is reduced considerably like a human operation. They show the proposed countermeasures worked well. However, the force in the Y direction is not reduced enough. This is the main difference between Control method 2 and human operation. As for the position, the trends of proposed methods are similar to that of the human operation, but the amounts of displacement in the Y direction of the proposed methods are smaller than that of the human operation. This is an explanation of why the force reduction of the proposed methods in the Y direction is not enough.

There are three reasons why the performance of the proposed method differs from a human demonstration. One is the expression capability of the simplified force control law. NCC in the X direction (0.967) was quite high, but NCC in Y direction (0.788) was lower than it. Therefore, the force and position data in the Y direction is the source of difference between the proposed method and the human demonstration. The second is the hardware difference. From (1), it is expected that if the value of d_Y is increased, the velocity will increase, and the amount of movement will also be increased. It can improve the difference of displacement in the Y direction, and it can make the force in Y direction escape well. However, as d_Y is increased too much, the robot starts to oscillate and becomes unstable. This destabilization seems to be due to the response performance of the robot. When the force and the position data of the robot were examined in more detail, a time delay about 0.1 [s] was observed until the operation was actually started after the force was first sensed. In general, the dead time is a factor that makes the system unstable. The third is due to the coordinates used for the force control. The proposed method is applied only in X and Y directions and did

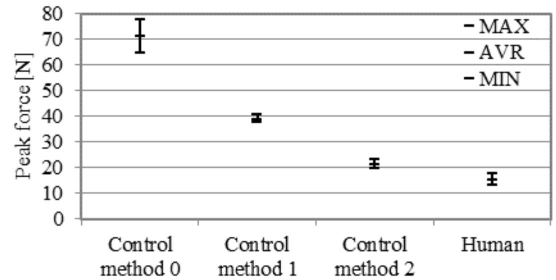


Figure 11. Peak forces of Control methods 0, 1 and 2, and human operation among ten trials.

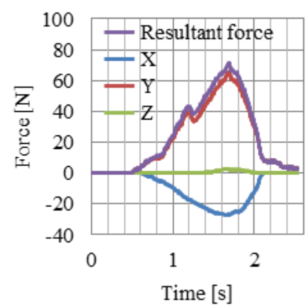
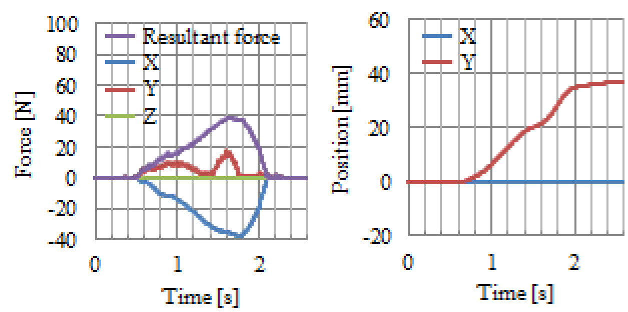
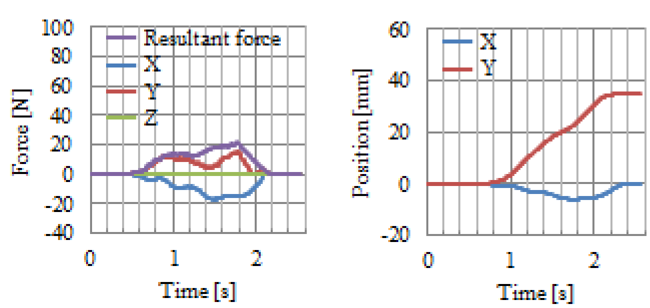


Figure 12. Example force data in Control 0 where a force control was not implemented to the robot and the position of the tool was fixed. Measured force is far larger than that of human of Fig. 7 (a).



(a) Force (b) Position

Figure 13. Example of force and position data in Control method 1. Compared with Control method 0 (shown in Fig. 12), the force value of Y direction is substantially reduced.



(a) Force (b) Position

Figure 14. Example of force and position data in Control method 2. The force value of X direction is reduced compared with Control method 1 shown in Fig. 13.

not applied in Z direction and rotation about the Z-axis. If we apply the proposed method also for Z direction and the rotation about the Z-axis, the performance of the proposed method can improve.

As described above, three kinds of control methods including the proposed method were implemented on a robot and their performances were evaluated. In particular, the performance was close to human, when the proposed method was implemented in both the X direction and the Y direction.

B. Experiment of the Other Force Control Laws

In the proposed method, the force control law is determined by NCC, and control strategies that give an arbitrary compliance and viscosity are implemented in the X and Y direction, respectively. Now, to confirm the validity of the control law selection, the other control laws are tested.

The cases where the force control law in the X direction was changed to (2) and (3) and the cases where the force control law in the Y direction was changed to (1) and (3) were implemented. The parameter optimizations of them were also carried out. The results of assembly experiments using the optimum parameters are shown in Fig. 15. The center of Fig. 15 is the result of ten trials by the proposed method, the left two are the results of changing the force control law in the Y direction, and the right two are the results of changing the force control law in the X direction. This figure shows that the peak force of the proposed method is the smallest, and it is confirmed that the force control law selection using the NCC analysis obtains an appropriate force control law.

VI. Conclusion

In this research, a robotic assembly of ring-shaped rubber packings to cylindrical workpieces is realized. To reduce the excessive force, we analyzed the position and force data of a human's hand with the normalized cross-correlation, and we constructed force control laws based on the human characteristics. The force control parameters were determined by an optimization using the downhill simplex method. The above framework realized a force control taking the characteristics of the robot into consideration, and it can be applied not only to the ring-shaped rubber packing assembly but also to other tasks which require a certain force control. Experiments were conducted, and the results confirmed that the performance was close to that of a human. Future works include further validation of the proposed force control design method. Especially, the number of the parameter of the force control law is limited to one in the proposed method. We will investigate how much is the influence when an additional stiffness, viscosity, or inertia parameter is implemented. Dealing with how to determine the coordinate system is also one of the future works. If the direction of the coordinate system is changed, the result can be changed, and the performance can be declined. The method such as principal component analysis will be effective to determine it.

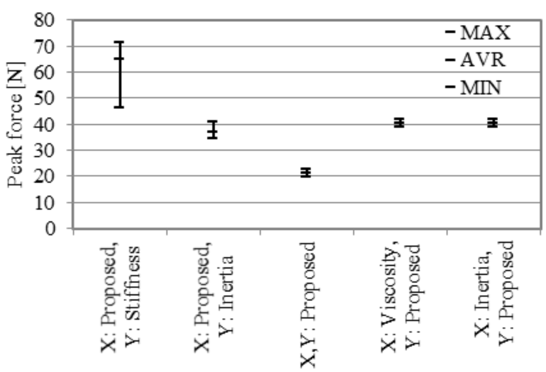


Figure 15. Comparison to the force control laws which are not selected by NCC analysis. The performance is the best when the control laws by proposed method are not changed both in the X and Y directions.

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