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Vision Based Compliant Motion Control for Part Assembly

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Abstract— **In this paper, we propose a vision based compliant motion control method for part assembly work. Some industrial parts are deformed during assembly of parts. If work progress continues, deformation of the part increases, humans check the deformation and adjust force corresponding to the progress state. The proposed method enables a robot manipulator to adjust force applied for assembly work like a human. In our proposed method, force applied for the work is generated by visual information from a camera reading the deformation of the parts. Processing the visual information quantifies the deformation and the data show the work progress. NCC is generally used for template matching, but in this paper we use it for quantifying deformation. Connectors are assembled by a robot manipulator using proposed method and impedance control in experiments. Experimental results are presented to verify the effectiveness of the proposed method.**

I. INTRODUCTION

The production lines are becoming increasingly automated. Industrial robots are used in painting, welding and sealing processes. Their works demand that the end-effector is controlled with high accuracy of trajectory (position and orientation). However if a manipulator assemble parts, the parts come in contact with each other, so the position control is not sufficient. Here parts are male and female parts for insertion. For processes which involve contact between parts, robotic compliant motion control is necessary. Robotic force control has been studied for over 30 years, for example, hybrid position/force control[1], stiffness control[2], damping control[3] and impedance control[4]. In force control, force information from force/torque sensor is fed back to the control loop. In recent years, Chen et al. proposed a robust impedance control method for the assembly process[5].

Using just force control enables robot to work on very few part assembly because of following problems; the control strategy and program become complex and it cannot judge whether the state is good or not from force information. If both force information and visual information are fed back into robot control system, the robot can be used in wider range part assembly tasks.

Method of visual information obtained from camera to control robot has been studied before. Many visual servoing systems have been reported[6][7][8]. In visual servoing system, visual information is fed back to closed-loop position control for end-effector. In the recent years, both force and vision based control methods have been proposed. Nelson et al. proposed three different strategies which combine force and vision within the feedback loop of manipulator; traded control, hybrid control, and shared control[9]. Morel et al. proposed control algorithm that combines visual servo control and force feedback within the impedance control approach[10]. In this control scheme, the reference trajectory generated by a vision based control loop is fed to impedance controller. Huang et al. proposed a method that control position of end-effector corresponding to the object posture which is changed by contact with robot[11]. Lippiello et al. proposed algorithm based on visual data for estimation of the pose of the object that interacts with the robot manipulator with force control[12]. This method considers that the environment is a rigid object of known geometry but of unknown and possibly time varying position and orientation. The previous works use visual information to know position, orientation and geometry of environment and to control position and orientation of the robot. However, assembly tasks still don't completely become automated and few researches use visual information to control force for part assembly. During part assembly processes, humans use visual sense to check the progress and control force: if the force is needed to carry on the task, the humans increase the force, till the task is completed. After the end of the task, they release the force. The approach prevents unnecessary load being applied to the parts. This approach is appropriate force control for part assembly.

In this paper, we propose a vision based force control method for part assembly work. We focus attention on the part deformation with force, for assembly processes. Proposed method checks the deformation and adjusts force corresponding to progress state. Examples of the deformable parts are stopper, latch and etc. This paper is organized as follows. Section II describes proposed method. Experiments are discussed in section III. Experimental results are presented to verify the effectiveness of the proposed method. Finally, section IV presents conclusions and discusses the further development direction.

II. PROPOSED METHOD

Some industrial parts are deformed during part assembly works. As the work progress, the deformation of part increase, human checks the deformation and adjusts force corresponding to the progress state. We proposed a method that uses force generated by visual information like a human. This proposed method judges the task progress by the deformation of the part, so this method is effective only if the task progress produces the deformation. Fig.1 shows the structure of proposed method. Images of the part deformation are taken from camera. The system processes the obtained image data, quantifies the deformation, judges whether the

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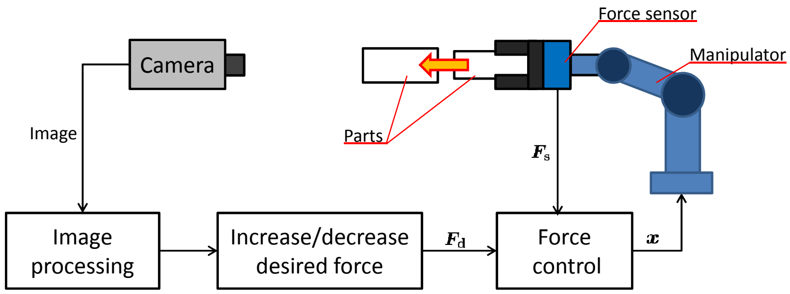


Fig. 1. Structure of proposed method

assembly task progresses or not. The force required assembly work (desired force : $\mathbf{F}_d$) is decided by the progress. Robot manipulator with force control can apply the desired force to the parts. Following are the components of proposed method.

A. Force Control

When a robot manipulator assembles parts, the parts come in contact with one other, so compliant motion control is necessary. In addition, a robot manipulator has to apply the desired force to the parts. The following equation is obtained by modification of impedance equation to meet the requirements

$$\mathbf{M}\Delta\ddot{\mathbf{x}}+\mathbf{D}\Delta\dot{\mathbf{x}}+\mathbf{K}\Delta\mathbf{x} \quad = \quad \mathbf{F}_s-\mathbf{F}_d, \tag{1}$$

where $\Delta\mathbf{x}=\mathbf{x}-\mathbf{x}_d$ is the position displacement from desired position, $\mathbf{F}_s \in \mathbf{R}^{6\times 1}$ is the force acquired from force/torque sensor, $\mathbf{F}_d \in \mathbf{R}^{6\times 1}$ is the desired force vary with visual information and $\mathbf{M} \in \mathbf{R}^{6}$, $\mathbf{D} \in \mathbf{R}^{6\times 6}$ and $\mathbf{K} \in \mathbf{R}^{6\times 6}$ are mass matrix, damping matrix and stiffness matrix, respectively.

During the parts is in contact with one other, stiffness coefficient (in $\mathbf{K}$) corresponding to the direction of the force applied is set 0, so $\mathbf{F}_s$ will approach $\mathbf{F}_d$. With respect to the other directions, this equation gives an effect similar to a RCC device to end-effector. The approach enable the robot manipulator to apply $\mathbf{F}_d$ in eq.(1), to the parts.

B. Use of Visual Information

When the robot using previous methods carry out assembly work, the force used in the work is set to an initial value. This force needed to complete the task must be known before hand. In those cases, the value has to be set in according to the type of parts. If the force value is fixed, the force applied to the parts may be more than necessary or the force may fall short of accomplishing the tasks depending on the condition of the parts. The force control that the large value is set to ensure the tasks be accomplished is not appropriate. In case that the parts deform as the task progresses, the workers use the corresponding force and carry out the task with observing the deformation, e.g. if the deformation becomes larger, they find the task progress smooth. When the deformation remains static, they make out stagnation of the progress. In this way, humans use sense of force as well as visual sense in the assembly work. If robot could use visual sense and estimate the task progress as smooth or static and the robot adjusts the force corresponding to the progress state, the task is completed like a human. In next section, the processing method to quantify the deformation of parts from vision is described. Preliminary experiment shows that the processing method can quantify the deformation appropriately.

1) Image Processing: To quantify the deformation, we use Normalized Cross-Correlation (NCC) that is a kind of image processing. Generally, NCC is used for template matching. NCC is calculated by the following equation and yields R_{NCC} as the similarity between two images

$$R_{NCC} = \frac{\sum_{j=0}^{N-1}\sum_{i=0}^{M-1} I(i,j)T(i,j)}{\sqrt{\sum_{j=0}^{N-1}\sum_{i=0}^{M-1} I(i,j)^2 \sum_{j=0}^{N-1}\sum_{i=0}^{M-1} T(i,j)^2}}, \tag{2}$$

where (i,j) is the coordinates of a pixel and M, N are the width and height of the images, respectively. Also, $T(i,j)$, $I(i,j)$ are the luminance value of template image and input image, respectively. NCC calculates R_{NCC} by comparing between template and input image. The higher R_{NCC} is, the more similar two image are. If input image matches up precisely with template, $R_{NCC}=1$ In the assembly task, a camera captures the image of the part deformation, and template is the image captured at the start of the task, R_{NCC} is calculated. In this way, the deformation is quantified.

In the method, simply setting the processing region that the deformation is in the region suffices in order to quantify the deformation of the parts. In addition, this method compares current image with initial image, so it can quantify the deformation, if the parts are distinguishable from background and the background remains nearly-unchanged. On the other hand, other method requires setting feature points accurately and each part has respective feature points. The proposed method is effective against the quantification of the deformation.

2) Preliminary Experiment: We verified that the task progress can be judged by the variation of R_{NCC} through a preliminary experiment. Fig.2 shows the experimental setup. Power connectors are used as an example of parts

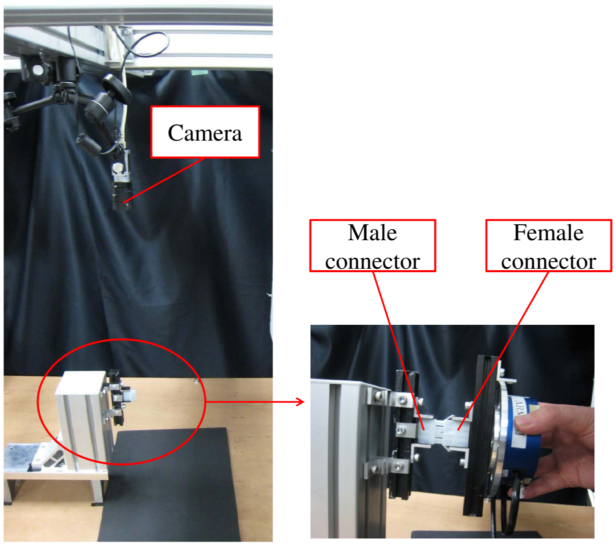
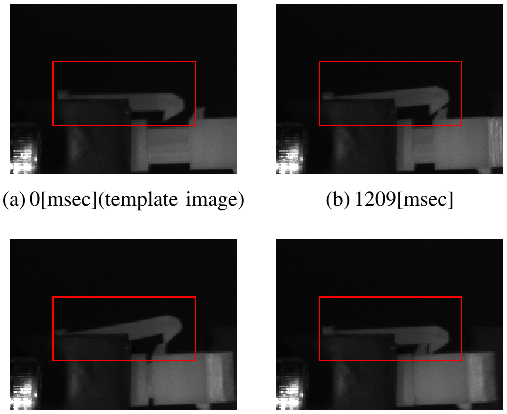


Fig. 2. Experimental framework of processing NCC



(a) 0[msec](template image) (b) 1209[msec]

(c) 2879[msec] (d) 2889[msec]

Fig. 3. Image of calculating R_{NCC}

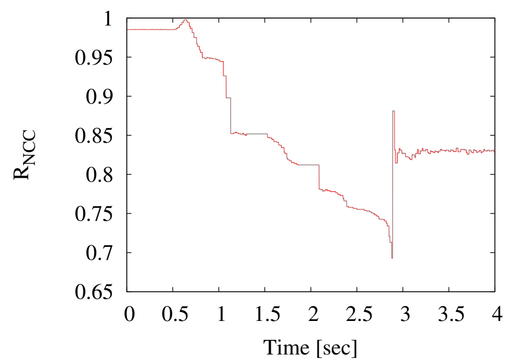


Fig. 4. The time variation of R_{NCC}

for assembly. The latch of male connector deforms with the assembly progress. The connector shows the following characteristic changes during the task; the deformation of the latch is increasing as task progresses and when the task is accomplished, the deformation returns to initial state. Industrial camera (basler : acA640-100gm) captures the image of the latch. The frame rate of this camera is 100[fps]. To clearly capture the image, the male connector is fixed, the region to calculate the similarity is set on the captured image. The assembly work is carried out by hand. The template image is the image captured at the start of the task and R_{NCC} is calculated every time the camera captures an image.

Fig.3 and Fig.4 show the captured images which are used for the calculation of R_{NCC} and the result of the calculation respectively. The size of the captured image is 160 x 120 pixel and the size of the calculating region, which is inside the rectangle in Fig.3, is 100 x 45 pixel. The results show that the larger the deformation is, the lower R_{NCC} is. Also, the latch returns to initial state between 2879[msec] and 2889[msec] and at the same time, R_{NCC} increase instantaneously. So, decreasing R_{NCC} represents the task going well, static R_{NCC} represents the task stagnation and instantaneous increase of R_{NCC} represents the completion of the task. The experimental result are presented to verify that NCC can quantify the deformation of the parts and the progress state can be judged by the time variation of R_{NCC}.

C. Desired Force

The visual information is obtained by camera reading the deformation with the assembly progress. Then, NCC calculates that how different the current image is from the initial image as R_{NCC}. The progress state is estimated from the time variation of R_{NCC}. In the progress state, go well, go backward, stop and completion exist.

In this section, method to decide the desired force $\mathbf{F}_{\mathrm{d}}$ from R_{NCC} is described. At first a small appropriate initial value of $\mathbf{F}_{\mathrm{d}}$ is set at the start of work. In term of R_{NCC}, previous value is $R_{\mathrm{NCC,pre}}$ and current value is $R_{\mathrm{NCC,cur}}$. At $R_{\mathrm{NCC,pre}} > R_{\mathrm{NCC,cur}}$, the task progress go well, so $\mathbf{F}_{\mathrm{d}}$ does not change and at $R_{\mathrm{NCC,pre}} \leqq R_{\mathrm{NCC,cur}}$, the task progress stop or go backward, so $\mathbf{F}_{\mathrm{d}}$ is increased. Then, when the task completion is detected from the time variation of R_{NCC}, $\mathbf{F}_{\mathrm{d}}$ is set to 0. The system updates the progress state at each time the image is captured and processed. The method enables robot to accomplish the assembly task without deciding the force necessary to accomplish the task and applying excess force to the parts.

III. EXPERIMENT

In this section, we describe the robot manipulator implementing proposed method do the part assembly works as experiments. In addition, the manipulator implementing impedance control without using visual information as traditional method do same works is compared. The experimental results are presented to verify the effectiveness of the proposed method.

A. Experimental setup

Fig.5 shows the experimental environment. As with preliminary experiment, power connectors are used as an exam-

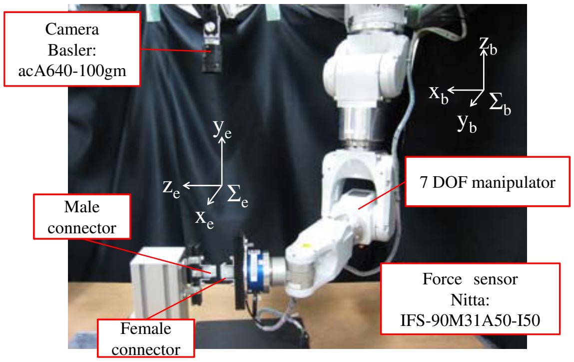


Fig. 5. Experimental environment

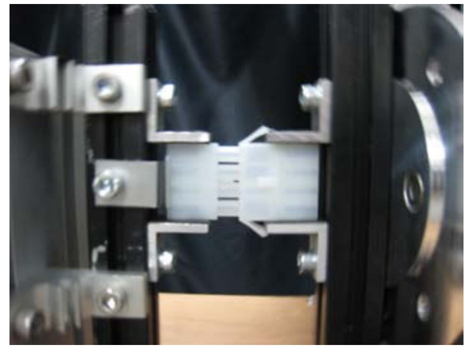


Fig. 6. Initial state

ple of parts for assembly. 7 DOF manipulator is fixed on steel plate located on top of aluminum frame. The manipulator has a force/torque sensor (Nitta : IFS-90M31A50-I50) mounted at the wrist. The female connector is fixed at the end-effector. The base coordinate system and the end-effector coordinate system are defined at the base of manipulator and at the tip of female connector, respectively. The male connector is fixed in such a way that the direction of assembly is along x-axis direction with respect to the base coordinate system. A industrial camera (basler : acA640-100gm) is mounted on the top of aluminum frame in order to capture the image of the latch clearly. The sampling frequency of the manipulator control is 1000[Hz]. The minimum time to capture and process an image is 10[msec] and then the calculated value is passed to the robot control loop.

B. Experimental Methodology

Fig.6 shows initial state that is set in order to accomplish the task certainly. The robot implements the impedance control modified to apply desired force and the applied force is set along z-axis direction with respect to end-effector coordinate system. In the proposed method, the size of the captured image set 160 x 120 pixel and the size of the calculating region set 100 x 45 pixel. The initial value of $|F_{\mathrm{d}}|$ set 2[N]. At $R_{\mathrm{NCC,pre}} > R_{\mathrm{NCC,cur}}$, F_{d} does't change and at $R_{\mathrm{NCC,pre}} \leqq R_{\mathrm{NCC,cur}}$, $|F_{\mathrm{d}}|$ is increased by 0.08[N]. If R_{NCC} is increased by 0.1, the system deems the task to finish and set F_{d} to 0. This value is determined from the preliminary experimental result. The limit of $|F_{\mathrm{d}}|$ is set 10[N] to protect the parts and the manipulator from applying too powerful force. If $|F_{\mathrm{d}}|$ exceeds the limit value, $|F_{\mathrm{d}}|$ is set to 0 as abnormal end.

Given technique is compared with, the manipulator implementing traditional impedance control without using visual information do same work. In traditional impedance control, we use eq.(1) with setting desired force $|F_{\mathrm{d}}|$ as follows previously. $|F_{\mathrm{d}}|$ is 2[N] at start, increase in proportion to time and finally becomes 7[N] in 1[sec]. This value is decided experimentally because the task requires approximately 6[N]. For assessing effectiveness, the experiments are done under the following three conditions respectively.

1) The manipulator with proposed and traditional method does the connector assembly work respectively. The impedance parameters are the following:

$$\begin{aligned}\mathbf{M}_{\mathrm{e}} &= \mathrm{diag}(10, 10, 50, 5, 5, 5)\\ \mathbf{D}_{\mathrm{e}} &= \mathrm{diag}(200, 200, 1000, 20, 20, 20)\\ \mathbf{K}_{\mathrm{e}} &= \mathrm{diag}(200, 200, 0, 5, 5, 5).\end{aligned}$$

These parameters are decided experimentally and are used in two methods.

2) To examine the effect of the change in the parameters, the impedance parameters are changed as the follows:

$$\begin{aligned}\mathbf{M}_{\mathrm{e}} &= \mathrm{diag}(10, 10, 35, 5, 5, 5)\\ \mathbf{D}_{\mathrm{e}} &= \mathrm{diag}(200, 200, 500, 20, 20, 20)\\ \mathbf{K}_{\mathrm{e}} &= \mathrm{diag}(200, 200, 0, 5, 5, 5)\end{aligned}$$

The smaller M,D along z-axis direction with respect to end-effector coordinate system enable end-effector to move fast. We compare the result between two methods and verify the effect of proposed method in fast assembly task.

3) This condition #3 requests larger force than the condition #1 and #2 to accomplish the task. To make the necessary force larger, sponges are put into female connector. The impedance parameters are same as the condition #1.

C. Experimental Results

Fig.7, Fig.8, Fig.9 and Fig.10 show the captured image under the condition #1 and the condition #3 and Fig.11, 12 and 13 show the experimental results under the each condition respectively. F_{s}, F_{d} represent the z-axis force obtained from force/torque sensor and desired force along the z-axis direction with respect to end-effector coordinate system. We made sure that the proposed method and the traditional method enable the robot to assemble the connectors.

In the condition #1, the maximal values of $|F_{\mathrm{s}}|$ are approx. 7.0[N] with the proposed method and approx. 9.3[N] with the traditional method (Fig.11). In the condition #2, the maximal values of $|F_{\mathrm{s}}|$ are approx. 6.7[N] with the proposed method and approx. 12.6[N] with the traditional method and the impact at finishing task is approx. 4.8[N] as absolute value

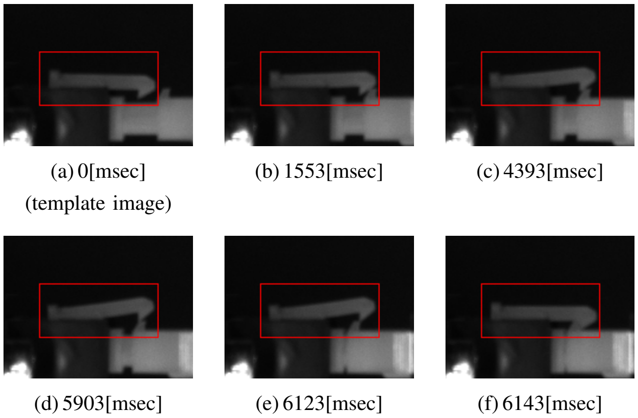


Fig. 7. Image of latch with proposed method under condition #1

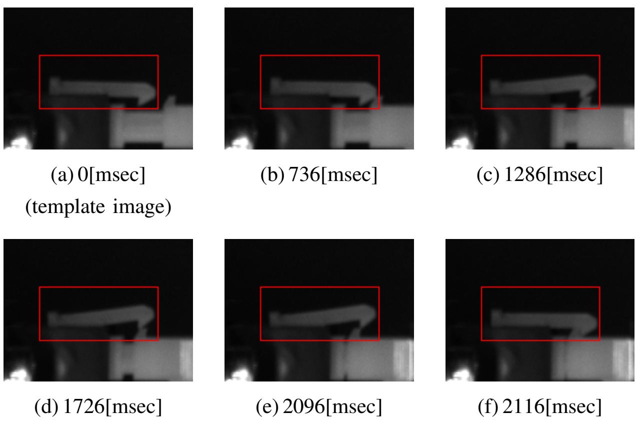


Fig. 8. Image of latch with impedance control under condition #1

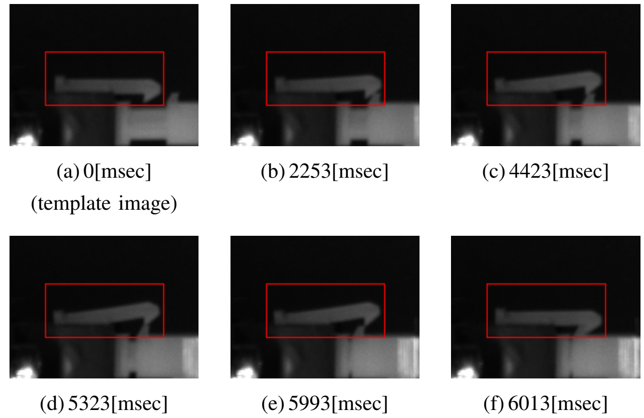


Fig. 9. Image of latch with proposed method under condition #3

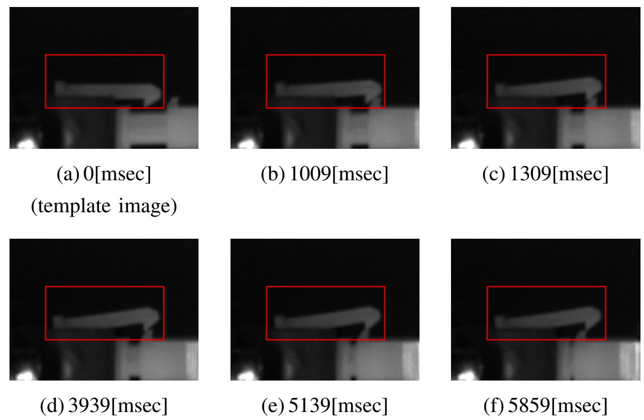


Fig. 10. Image of latch with impedance control under condition #3

with the proposed method (Fig.12). In the condition #3, the proposed method can accomplish the task but the traditional method cannot do because F_d is set to 7[N]. The maximal values of $|F_\mathrm{s}|$ are approx. 9.2[N] with the proposed method and approx. 7.9[N] with the traditional method (Fig.13).

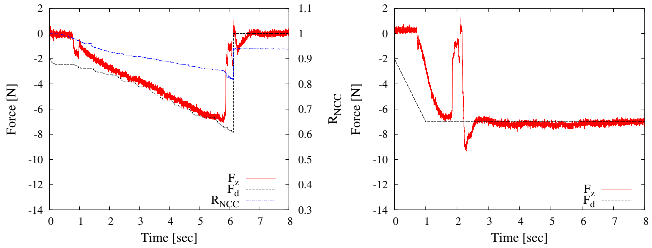
D. Discussion

This proposed method judged the task progress by using visual information, increase the desired force with the task progress. So this method did the assembly work without setting desired force previously. In addition, because this method can find the completion of the task, unnecessary force was not applied to the parts after end of the task.

When the impedance parameter is changed (condition #2), the impact force with both method became larger than in condition #1. The connector has a margin between the parts. The connector can move in margin after the latch locks. The reason why the impact arises is that when impedance parameter changed, the end-effector moved more speedily in the space. The traditional method cannot find the completion of the task, so the large impact as approx. 12.6[N] occurred. Excessive impacts have the potential to break the parts. On the other hand, the proposed method set the desired force to 0 as soon as the latch locked, hence this method was able to reduce the impact to approx. 4.8[N]. Also, from the result in condition #1 and #2, the proposed method is insusceptible to the impedance parameter as compared to the traditional method. Proposed method makes it easier to set the impedance parameter.

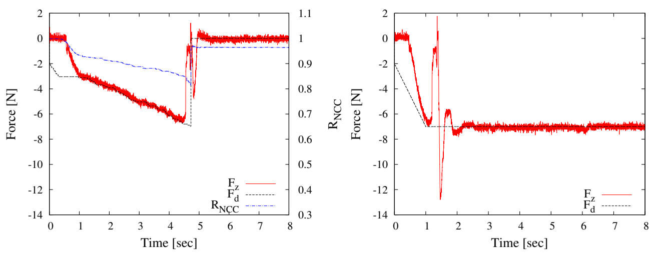
In the condition #3, that large force is needed for the task, it was assured that the proposed method accomplished the assembly work without setting the desired force corresponding to the condition preliminarily. However, the traditional method could not have done the work. The reason for the failure to complete the work is that the set value is not enough to meet requirement. If the robots with the traditional method try assembling the parts, it requires setting sufficiently large value. In this case, however, excessive force is used in the tasks requiring a small force. That approach is far from the appropriate motion control. In this regard, the proposed method has the advantage because it can set necessary value for each task by itself.

$|F_\mathrm{s}|$ decreases before the latch is locked. This character is especially prominent in Fig.13. The shape of the stopper causes this character. As shown in Fig.14, the shape of stopper is trapezoidal shape. When the latch reach on upper base of the stopper, the friction decrease, hence, F_s decreased temporarily. From this, we can conclude that using visual information is proper to judge whether the task is over for this task.



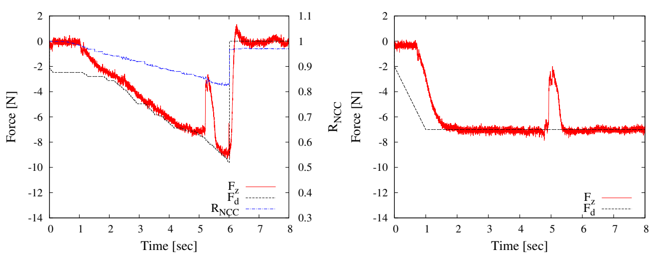
(a) Proposed method (b) Impedance control

Fig. 11. Result of experiment under condition #1



(a) Proposed method (b) Impedance control

Fig. 12. Result of experiment under condition #2



(a) Proposed method (b) Impedance control

Fig. 13. Result of experiment under condition #3

IV. CONCLUSIONS

Many part assemblies are difficult to work only with a sense of force. This paper proposes a new compliant motion control method using visual information for the part assembly.

Section II described the structure and the components of the proposed method respectively. To control the force applied to the parts, the proposed method uses the modified impedance control that operate with reference to the desired force. The desired force is decided by the progress state of the work. To find the progress state of the work from visual information, we focus on the deformation of the parts and quantify it with the use of NCC. This method judges the progress state from the time variation of R_{NCC}. Section III described experiments with robot manipulator with the proposed method assembled connectors under three conditions. For comparison, the manipulator with the traditional method did the same tasks. The effectiveness is proved by the experimental results. The experimental results prove that the proposed method has the following advantages,

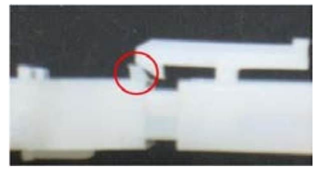


Fig. 14. Stopper of Female connector

- To apply the force corresponding to the condition without setting the desired force previously,
- To reduce the impact force at the end of the task,
- To be insusceptible to the impedance parameter as compared to the traditional method.

The proposed method can judge the progress state by observing the deformed parts. To clearly capture the image, the male connector is fixed. If a robot works on assembly of various kinds of parts, like humans, the robot has to grasp the parts with multiple arms without fixing the parts. Hence, the proposed method needs a system where camera can tracks the moving part. The effectiveness is proofed from the experimental results but proposed method is not fast in comparison to traditional method. In case that the deformation changes faster, high speed camera is effective. In the future, we will make system more agile and generalize this method. If the operating speed is improved and adaptability of assembly tasks increase, the proposed method will become more powerful control method.

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