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Assist Control for Dual Arm Cooperative Manipulation by Remote Controlled Robot

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Abstract— **In this paper, we propose an assist control system that improves the efficiency of double arm cooperative tasks. The system estimates the type of task intended by an operator by detecting time-series changes in the movement of the operator's hands. Next, the corresponding assist control is executed based on impedance control. Experimental results show the effectiveness of the proposed method in real-time dual arm cooperative tasks.**

I. INTRODUCTION

In recent years, there has been a growing tendency to apply remote controlled robots to tasks that are dangerous for human beings, such as work at disaster sites, and handling of radioactive substances and highly toxic substances. Since such a robot needs to perform various kinds of complex work, a master-slave system is suitable (Fig. 1). In a master-slave system, the structure of the robot (slave) main body is similar to that of the operator (master), allowing the operator to operate it intuitively.

On the other hand, conventionally, in master-slave control, there are various problems such as time delays due to delays in communication between the master and slave, operation delays due to the dynamic characteristics of the robot itself, spatial calibration errors due to differences between the master and slave mechanisms, and an inadequate sense of operability due to insufficient presentation of visual and tactile sensations. These have been the cause of low working efficiency of the robot. Therefore, in order to solve these problems, assist control that predicts human intent and guarantees operation on the slave side has been investigated [1].

Our group has also been conducting research on assist control, and we have proposed a method of semi-autonomously controlling the slave robot by measuring the target object with a vision sensor of the slave robot [2]-[4]. In the method, however, only reaching movements, i.e. movements for picking up an object, are taken into account, and other operations are not considered. Therefore, the target of assist control in this research is dual arm cooperative manipulation for freely manipulating a object with both hands. Dual arm cooperative manipulation includes not only the work of lifting objects with both hands but also various tasks such as turning valves with both hands or holding a rod, such as a mop handle, with both hands. In this research, the aim is to automatically detect the moment at which to switch to dual arm cooperative manipulation and to shift to appropriate assist control.

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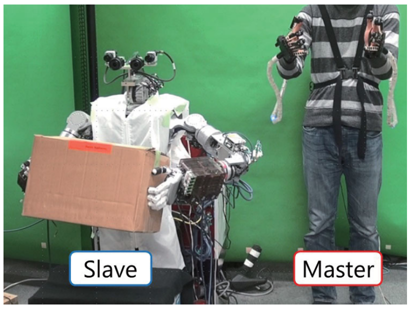

Fig. 1: Master-slave system.

II. RELATED WORKS

A. Dual Arm Cooperative Work

Kruse et al. proposed a system that performs dual arm cooperative work with hybrid control using a depth sensor as an input device [5]. Bjerkeng et al. proposed dual arm cooperative control related to industrial robots that move in a narrow space [6].

In this research, emphasis is placed on intention estimation of dual arm cooperation, and the aim is to achieve a smooth shift to assist control based on this estimation.

B. Detection of Operator's Action in Remote Control System

Mori et al. proposed algorithms for classifying human motion with pre-prepared motion pattern templates [7]. Yu et al. detected the motion by determining the route of the operator's work in advance [8].

In this research, we also a method which does not need to set the route of work or pattern template in advance.

III. SYSTEM CONFIGURATION

Fig. 2 shows the configuration of the master-slave system used in this research [4].

The system does two things: master-slave control and visual presentation. Movement of the master is measured by the flexible sensor tube (FST) which is one of the master devices. The measured movement is sent to the slave devices, then the master-slave control is performed. The visual presentation in this research is to present the image of the camera mounted on the slave's head to the master by head mounted display (HMD).

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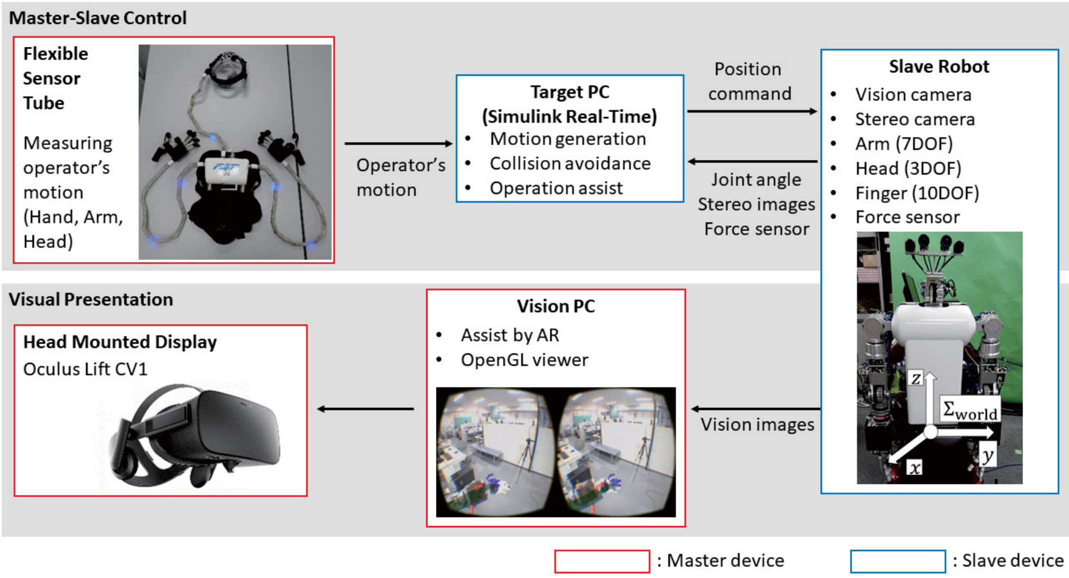


Fig. 2: System configuration.

A. *Master Devices*

1) FST: The FST is a tubular sensor composed of 23 joints and a potentiometer is installed at each joint so that the angle can be measured. In this research, FST is used to measure the movement of the hand and head of the master.

The FST sends sensor information to the target PC every 10 ms so that the target PC can calculate the hand position and orientation and the head orientation of the master. In this research, only sensor information for calculating the hand position and orientation are sent.

2) Vision PC: The vision PC performs image processing on the images sent from two visual presentation cameras of the slave in order to assist the master's work with augmented reality. For example, the vision PC draws the state of the FST and the simulation of the robot arm of the slave with OpenGL.

3) HMD: Rift CV 1 is used as a HMD. Rift CV 1 is developed by Oculus Corporation for virtual reality applications.

The images processed on the vision PC are displayed on two liquid crystal panels of Rift CV 1.

B. *Slave Devices*

1) Target PC: The target PC performs the following three processes to remotely control the slave. Firstly, based on the information sent from FST, the hand position and orientation and the head orientation of the master are calculated by forward kinematics of FST. Secondly, based on the result of the last process, the target joint angles of the arm and the head of the slave are calculated by inverse kinematics of the slave. Finally, position command of the target joint angles is sent to the slave. The calculation is performed at 200 Hz on Matlab Simulink Real-Time.

2) Slave Robot: The slave is an upper-body-type humanoid robot, and the arm, the hand, and the head are driven. Σ_{world} in Fig. 2 is the world coordinate system in this research. The arm is a redundant manipulator with 7 degrees of freedom (DOF), each hand has 10 DOF, and the head has 3 DOF. Four cameras are mounted on the head: two inside are visual presentation cameras and the other two are stereo cameras. A capacitive six-axis force sensor manufactured by WACHO-TECH Inc. is attached to the forearm part.

The slave sends the values of the force sensors, the values of the joint angles and the images of the stereo cameras to the target PC, and sends the images of the visual presentation cameras to the vision PC.

IV. ASSIST CONTROL SYSTEM FOR DUAL ARM COOPERATIVE MOTION

The proposed assist control system for dual arm cooperative work is shown in Fig. 3. As a premise, it is assumed that the slave already holds an object to be handled in the dual arm cooperative work. In this research, a detector and an assist controller to support the master so that he/she can smoothly perform dual arm cooperative work are developed.

The detector determines whether or not the work being performed by the master is classified as a dual arm cooperative work that is the subject of the assist control. The work to be assisted is chosen in advance. The dual arm cooperative work to be assisted in this paper is as follows (Fig. 4):

Work I
: Work to move the box back and forth (along the x-axis of the world coordinate system)

Work II
: Work to move the box left and right (along the y-axis of the world coordinate system)

Work III
: Work to move the box up and down (along the z-axis of the world coordinate system)

Work IV
: Work to rotate the box (around the x-axis of the

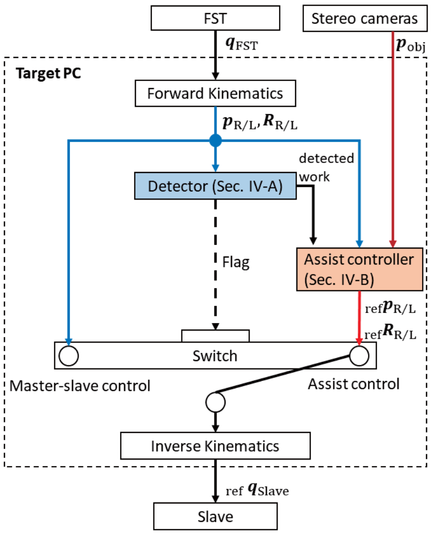


Fig. 3: Overview of assist control system.

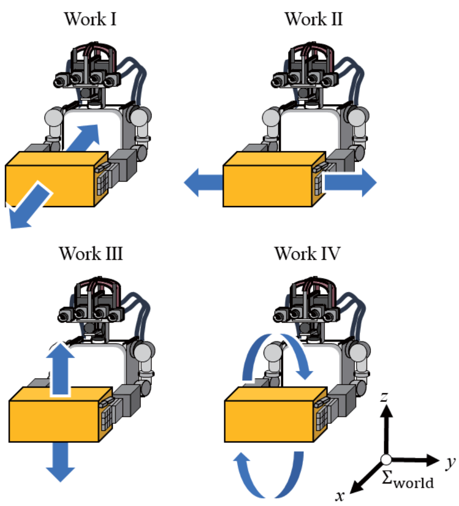


Fig. 4: Work to be assisted in this paper.

world coordinate system)

The determination of the detector is made based on the hand position and orientation of the master obtained by the FST and its forward kinematics.

If the work currently being performed by the master is the subject of assist control, the detector tells the assist controller which of the work to be assisted is being performed. Also, the detector outputs a flag indicating that work to be assisted is being performed. While this flag is being output, the assist controller performs appropriate assist according to the work and generates a new target hand position and orientation. The new target values is generated based on the contents of the work transmitted from the detector, the hand position and orientation of the master, and the position of the object acquired from the stereo cameras of the slave.

If the work currently being performed by the master is not the subject of assist control, the detector outputs a flag for instructing to execute master-slave control. In other words, the hand position and orientation of the master are passed directly to the inverse kinematics of the slave.

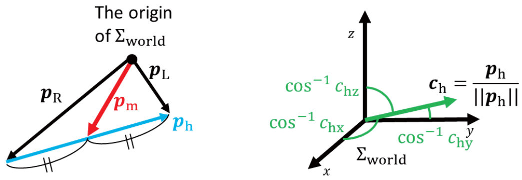


Fig. 5: Control variables for assist control: vector $\boldsymbol{p}_{\rm h}$ from the right hand to the left hand of the master, vector $\boldsymbol{p}_{\rm m}$ from the origin of the world coordinate system to the midpoint of $\boldsymbol{p}_{\rm h}$, and vector $\boldsymbol{c}_{\rm h}$ which is the direction cosine of $\boldsymbol{p}_{\rm h}$.

A. Detector

It is determined whether or not the work being performed is the subject of the assist control by the following three processes.

- Firstly, the vectors shown in Fig. 5 are calculated based on the hand position of the master, then time-series data of the vectors are obtained.
- Secondly, if there is a change in the average of the time-series obtained in the first process, it is detected.
- Finally, based on the result of the second process, the determination is performed.

1) Obtaining Time-Series Data: Three vectors $\boldsymbol{p}_{\rm h}$, $\boldsymbol{p}_{\rm m}$, $\boldsymbol{c}_{\rm h} \in \mathbb{R}^3$ are shown in Fig. 5. $\boldsymbol{p}_{\rm h} = \boldsymbol{p}_{\rm L} - \boldsymbol{p}_{\rm R}$ is a vector from the right hand to the left hand of the master. $\boldsymbol{p}_{\rm R/L} \in \mathbb{R}^3$ is the hand position of the master. The subscript R represents the right hand, and L represents the left hand. $\boldsymbol{p}_{\rm m} = \boldsymbol{p}_{\rm R} + \boldsymbol{p}_{\rm h}/2$ is a vector from the origin of the world coordinate system to the midpoint of $\boldsymbol{p}_{\rm h}$. $\boldsymbol{c}_{\rm h} = \boldsymbol{p}_{\rm h}/\|\boldsymbol{p}_{\rm h}\|$ is a unit vector of the $\boldsymbol{p}_{\rm h}$. These vectors are described in the world coordinate system.

The vector $\boldsymbol{c}_{\rm h} = [c_{\rm hx}, c_{\rm hy}, c_{\rm hz}]^{\rm T}$ is also known as direction cosine of $\boldsymbol{p}_{\rm h}$. Therefore, angles α, β, γ between $\boldsymbol{c}_{\rm h}$ and the x, y, z-axes of the world coordinate system can be expressed as $\alpha = \cos^{-1} c_{\rm hx}$, $\beta = \cos^{-1} c_{\rm hy}$, $\gamma = \cos^{-1} c_{\rm hz}$ respectively.

Using the time series data of each element of $\boldsymbol{p}_{\rm m} = [p_{\rm mx}, p_{\rm my}, p_{\rm mz}]^{\rm T}$ and $\boldsymbol{c}_{\rm h} = [c_{\rm hx}, c_{\rm hy}, c_{\rm hz}]^{\rm T}$, the detector performs the determination. Therefore, the detector receives six sets of time-series data $\{p_{\rm mx1}, \ldots, p_{\rm mxn}\}$, $\{p_{\rm my1}, \ldots, p_{\rm myn}\}$, $\{p_{\rm mz1}, \ldots, p_{\rm mzn}\}$, $\{c_{\rm hx1}, \ldots, c_{\rm hxn}\}$, $\{c_{\rm hy1}, \ldots, c_{\rm hyn}\}$, $\{c_{\rm hz1}, \ldots, c_{\rm hzn}\}$ as the input, where n is the number of data included in one time-series data. In the time-series data, data from the present to n steps before is stored, and the newest data is the nth element and the oldest is the first element.

2) Detection of a Change in the Average: In order to detect a change in the average of the time-series data $\{x_1, \ldots, x_n\}$, for each element $x_i\,(i = 1, \ldots, n)$ the upper cumulative sum U_i and the lower cumulative sum L_i are

TABLE I: The correspondence between the detection result of the change in the average and the determination result of the detector.

The detection result	The determination result
Change of p_{mx} is detected	Work to move the box back and forth (Work I)
Change of p_{my} is detected	Work to move the box up and down (Work II)
Change of p_{mz} is detected	Work to move the box left and right (Work III)
Change of c_{hy} and c_{hz} is detected at the same time	Work to rotate the box (Work IV)

defined in [9] by

$$U_i = \begin{cases} 0 & \text{if } i = 1 \\ \max(0, U_{i-1} + f(x_i)) & \text{if } i > 1 \end{cases}, \tag{1}$$

$$L_i = \begin{cases} 0 & \text{if } i = 1 \\ \min(0, L_{i-1} + g(x_i)) & \text{if } i > 1 \end{cases}, \tag{2}$$

$$f(x_i) = x_i - (\mu_x + \nu\sigma), \tag{3}$$

$$g(x_i) = x_i - (\mu_x - \nu\sigma). \tag{4}$$

$\mu_x = (\sum_{i=1}^{25} x_i)/25$ is estimated average (note that μ_x is not the actual average of the time-series data) and σ and ν are parameters. The parameter σ is called estimated standard deviation and the parameter ν decides how much x_i needs to be away from the estimated average μ_x in order to increase the upper cumulative sum or to decrease the lower cumulative sum. The function $f(x_i)$ evaluates how much x_i is greater than the average and the function $g(x_i)$ evaluates how much x_i is less than the average.

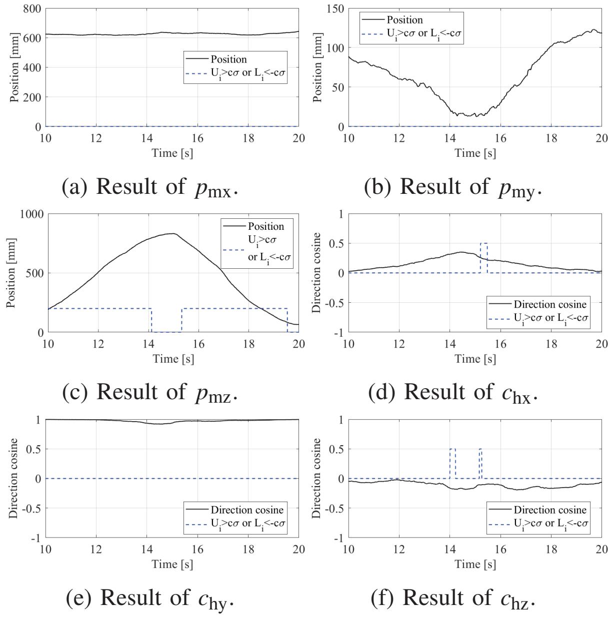
Every time the upper cumulative sum and the lower cumulative sum are calculated for each x_i, it is checked whether $U_i > c\sigma$ or $L_i < -c\sigma$ is satisfied. c is a parameter for determining easiness (or difficulty) to detect a change in the average. If either condition is satisfied, it means that the average of the time-series data is changing. Therefore, a change in the average can be detected. In order to detect a change in the average, the mean and the standard deviation of the time-series data are not the actual values but the estimated values.

For the six time-series data mentioned in Sec. IV-A.1, it is detected whether there is a change in the average. The upper cumulative sum and the lower cumulative sum are calculated individually for each time-series data.

3) Determination: The detector determines whether or not the work being performed is the subject of the assist control based on the results of Sec. IV-A.2.

In this paper, the correspondence between the detection result of the change in the average and the determination result of the detector is as shown in Table I

The detection result of the change in the average is shown in Fig. 6. The solid black line is the data value. The blue dashed line is whether $U_i > c\sigma$ or $L_i < -c\sigma$ are satisfied. If the blue line is 0, the conditions are not satisfied. Otherwise, either of the conditions is satisified. The work III is performed. It can be confirmed that the change of the



(a) Result of p_{mx}. (b) Result of p_{my}.

(c) Result of p_{mz}. (d) Result of c_{hx}.

(e) Result of c_{hy}. (f) Result of c_{hz}.

Fig. 6: The detection result of the change in the average when the work to move the box up and down (Work III) is performed.

average is detected for p_{mz}. Although it is a slight time compared to the case of p_{mz}, the change is also detected for c_{hx} and c_{hz}. Therefore, when the detector performs the determination, it is also considered whether the change is continuously detected for t_{th} seconds or more in order to prevent erroneous determination.

B. Assist Controller

Assist control is performed by limiting the movement of the slave robot to a specific direction or specific directions according to the work. For example, when the work to move the box up and down is being performed, the assist controller limits the movement of the hand of the slave to the vertical direction.

At first, the assist controller calculates the target value of the hand of the slave that limits movement. After that, the target value is calculated again by impedance control in order to prevent the grasping object from falling.

1) First Calculation of the Target Value: The target position ${}_{\mathrm{ref}}\boldsymbol{p}_{\mathrm{R/L}} \in \mathbb{R}^3$ and orientation ${}_{\mathrm{ref}}\boldsymbol{R}_{\mathrm{R/L}} \in \mathbb{R}^{3\times 3}$ of the hand of the slave are obtained from $\boldsymbol{p}_{\mathrm{m}}$, $\boldsymbol{c}_{\mathrm{h}}$ and the position of the object $\boldsymbol{p}_{\mathrm{obj}} \in \mathbb{R}^3$ by

$$\begin{bmatrix} {}_{\mathrm{ref}}\boldsymbol{R}_{\mathrm{R/L}} & {}_{\mathrm{ref}}\boldsymbol{p}_{\mathrm{R/L}} \\ \boldsymbol{0} & 1 \end{bmatrix} = \begin{bmatrix} {}_{\mathrm{ref}}\boldsymbol{R}_{\mathrm{obj}} & {}_{\mathrm{ref}}\boldsymbol{p}_{\mathrm{obj}} \\ \boldsymbol{0} & 1 \end{bmatrix} {}^{\mathrm{o}}\boldsymbol{T}_{\mathrm{R/L}}, \tag{5}$$

$$\begin{bmatrix} {}_{\mathrm{ref}}\boldsymbol{R}_{\mathrm{obj}} & {}_{\mathrm{ref}}\boldsymbol{p}_{\mathrm{obj}} \\ \boldsymbol{0} & 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}\boldsymbol{R}(\boldsymbol{c}_{\mathrm{h}}) & \boldsymbol{B}\boldsymbol{p}_{\mathrm{m}} + \boldsymbol{C}\boldsymbol{p}_{\mathrm{obj}} \\ \boldsymbol{0} & 1 \end{bmatrix}, \tag{6}$$

$$\boldsymbol{R}(\boldsymbol{c}_{\mathrm{h}}) = \begin{bmatrix} c_{\mathrm{hy}} & -c_{\mathrm{hx}} & 0 \\ c_{\mathrm{hx}} & c_{\mathrm{hy}} & -c_{\mathrm{hz}} \\ 0 & c_{\mathrm{hz}} & c_{\mathrm{hy}} \end{bmatrix}, \tag{7}$$

where ${}_{\mathrm{ref}}\boldsymbol{p}_{\mathrm{obj}} \in \mathbb{R}^3$ is the target position of the object, ${}_{\mathrm{ref}}\boldsymbol{R}_{\mathrm{obj}} \in \mathbb{R}^{3\times 3}$ is the rotation matrix representing the target orientation of the object, $\boldsymbol{A}, \boldsymbol{B}$ and $\boldsymbol{C} \in \mathbb{R}^{3\times 3}$ are suitable

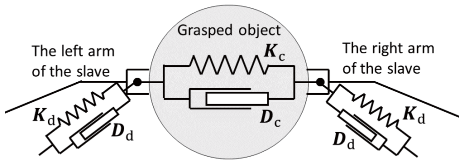


Fig. 7: Virtual springs and dmapers installed in impedance control.

transformation matrices, $\boldsymbol{R}(\boldsymbol{c}_{\rm h}) \in \mathbb{R}^{3\times3}$ is a rotation matrix corresponding to the direction cosine $\boldsymbol{c}_{\rm h}$, and ${}^{\rm o}\boldsymbol{T}_{\rm R/L} \in \mathbb{R}^{4\times4}$ is a homogeneous transformation matrix from the coordinate system of the object to the coordinate system of the hand of the slave.

$\boldsymbol{A}, \boldsymbol{B}$ and $\boldsymbol{C}$ are determined corresponding to the detected work by the detector and limits the direction in which the slave moves.

2) Impedance Control: Impedance control is performed by installing virtual springs and dampers in each hand of the slave as shown in Fig. 7 [10]. The spring (spring constant $\boldsymbol{K}_c \in \mathbb{R}^{3\times3}$) and damper (damping coefficient $\boldsymbol{D}_c \in \mathbb{R}^{3\times3}$) connecting both hands of the slave generate a virtual force for constantly grasping the object. Therefore, the equilibrium length of the spring is set shorter than the width of the object. Another spring (spring constant $\boldsymbol{K}_d \in \mathbb{R}^{3\times3}$) and damper (damping coefficient $\boldsymbol{D}_d \in \mathbb{R}^{3\times3}$) on the hand of the slave fix the position of the hand to the target value. The length of the spring becomes the equilibrium length, when the position of the hand coincides with the target value. By adjusting the equilibrium point where these springs are balanced so as to be inside the object, it is possible to always apply a force to the object.

The impedance control is expressed by

$$\boldsymbol{M}\Delta_{\rm ref}\ddot{\boldsymbol{p}}_{\rm R/L} + \boldsymbol{D}\Delta_{\rm ref}\dot{\boldsymbol{p}}_{\rm R/L} + \boldsymbol{K}\Delta_{\rm ref}\boldsymbol{p}_{\rm R/L} = \boldsymbol{f}_{v,{\rm R/L}}, \qquad (8)$$

where $\boldsymbol{M}, \boldsymbol{D}$ and $\boldsymbol{K} \in \mathbb{R}^{3\times3}$ are desired mass, desired damping coefficient and desired spring constant respectively, $\Delta_{\rm ref}\boldsymbol{p}_{\rm R/L}$ is the difference between the value of ${}_{\rm ref}\boldsymbol{p}_{\rm R/L}$ of this step and that one step before and $\boldsymbol{f}_{v,{\rm R/L}} \in \mathbb{R}^3$ is force generated by the virtual spring sand dampers.

As a result, by performing the impedance control on the target position of the hand of the slave obtained in Sec. IV-B.1, it is possible for the slave to grasp the object appropriately.

V. Experiments

A. Verification of Detector

Verification by simulation was conducted in order to confirm how accurately the detector can classify the dual arm cooperative work being performed by the master and how much time does the classification require from the start of the work. Dual arm cooperative work to be classified is the four mentioned in Sec. IV.

1) Methods: The master wearing the FST put the two hands forward and carried out the work I from the stationary state. Note that the master did not have any object during the verification in order to reproduce the actual situation of remote control. The data of the position and orientation of the hand of the master were given to the detector. Then, classification result and time required for the classification were confirmed. The same method was done for work II to IV. These were done by four masters A, B, C and D.

TABLE II: Result of the classification by the detector.

	Work I	Work II	Work III	Work IV
Master A	Succeed 2.36 s	Succeed 1.72 s	Succeed 2.42 s	Failure
Master B	Succeed 1.645 s	Succeed 1.66 s	Succeed 1.62 s	Succeed 5.585 s
Master C	Succeed 1.51 s	Succeed 1.55 s	Succeed 1.215 s	Succeed 1.665 s
Master D	Succeed 1.78 s	Succeed 1.64 s	Succeed 1.58 s	Succeed 4.99 s

TABLE III: Average time of the classification.

	Work I	Work II	Work III	Work IV
Average Time	1.82 s	1.64 s	1.71 s	4.08 s

The parameters of the detector in this verification are $n = 100$, $\sigma = 50$ mm (for $p_{\rm mx}, p_{\rm my}, p_{\rm mz}$), $\sigma = 0.1$ (for $c_{\rm hx}$, $c_{\rm hy}$, $c_{\rm hz}$), $\nu = 1/2$, $c = 5$ and $t_{th} = 0.7$ s.

2) Results and Discussion: The result is shown in Table II. Each row shows the classification result for each master, and each column shows the classification result for each work. The time written in the same place as "Success" indicates the required time from the start of the work to the classification . For example, for the work I by the master B, the detector successfully classified and it took 1.645 s to make the determination. These results show that the accuracy of the proposed detector is enough high because it only failed in the classification for the work IV by the master A.

In Table III, the average time required for the classification is shown for each work. Since the remote control is performed in real-time, it is better that the time from the start of the work until the detector classifies the work is shorter. However, it takes more than 1 s in all classifications, and it is not short enough to realize assist control. In particular, the classification for work IV takes 4.08 s on average. The work I to III can be classified by detecting a change in the average of one set of time-series data, whereas in order to classify into work IV, changes in the average of two sets of time-series data must be detected at the same time. Therefore, it shows that the classification into the work IV is more difficult than that into the other work. As a result, the classification into the work IV took more time.

B. Verification of Assist Controller

1) Methods: As shown in Fig. 1, the master operated the slave, and the slave moved the box up and down (Work III) with both hands with assist control.

The parameters of the impedance control in this verification are $\boldsymbol{M} = 0.01\boldsymbol{I}_3$, $\boldsymbol{D} = 500\boldsymbol{I}_3$, $\boldsymbol{K} = 1000\boldsymbol{I}_3$, $\boldsymbol{K}_c = 1000\boldsymbol{I}_3$, $\boldsymbol{D}_c = 100\boldsymbol{I}_3$, $\boldsymbol{K}_d = 500\boldsymbol{I}_3$ and $\boldsymbol{D}_d = 50\boldsymbol{I}_3$.

The transformation matrices $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ in (6) are set as

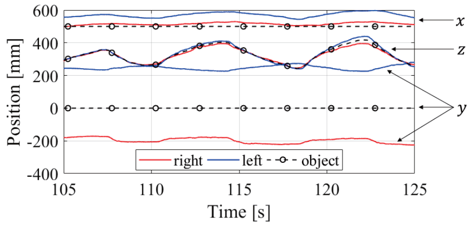


Fig. 8: Target position of object and master's right and left hands.

follows:

$$\boldsymbol{A} = \boldsymbol{R}^{-1}(\boldsymbol{c}_\mathrm{h}),\ \boldsymbol{B} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix},\ \boldsymbol{C} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

With this procedure, the motion of the object is limited to translational motion along the z-axis.

2) Results and Discussion: The target position of the object during the assist control and the position of the both hands of the master used for the input to the assist controller are shown in Fig. 8. The lines indicated by 0 mm, -200 mm, and 250 mm are the values of the target position of the object and the position of the both hands of the master in the y-axis direction (horizontal direction) of the world coordinate system. The three lines oscillating around 300 mm are values in the z-axis direction (vertical direction) of the world coordinate system. The three lines from 500 mm to 600 mm are values in the x-axis direction (depth direction) of the world coordinate system. Fig. 8 shows that the target position of the object in the x-axis direction is constant and not influenced by the input, i.e. the position of the both hands of the master. This also applies to the y-axis direction. It can be confirmed that the target position of the object in the z-axis direction changes corresponding to the movement of the both hands of the master.

The black solid line in Fig. 9 is the distance between the right and left hand of the slave during the assist control, the blue dashed line is the distance between the right and left hand of the slave before the assist control starts, and the red dotted line is the equilibrium length of a virtual spring that connects the both hands of the slave. The distance of the black line was measured with reference to the palms. The distance between the hands is beyond the blue line. This indicates that the correction by the impedance control was insufficient. Therefore, it is necessary to improve the impedance control.

VI. CONCLUSIONS

In this research, in order to enable a smooth dual arm cooperative operation in a master-slave system, we proposed an assist control method based on a detector and an assist controller. The detector detects dual arm cooperative motion from a change in the motion of the operator's two arms. The assist control can be performed while the object is grasped stably with both hands. The proposed method was shown to be effective by an experiment. However, the detector can be considered to take too much time to detect the

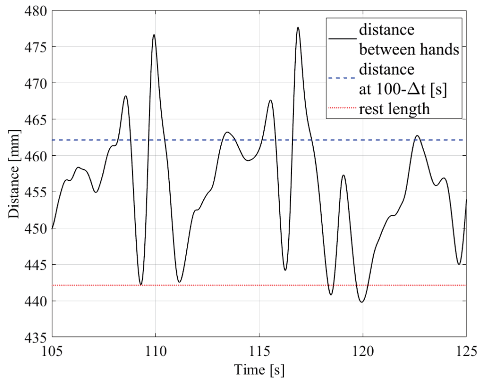


Fig. 9: Distance between slave hands.

change in order to perform assist control in real-time remote control. Therefore, reducing the detection time is required in the future. Additionally, in the assist control proposed here, impedance control was performed only between the two robot hands so as not to drop the object, and was not performed on the origin of the object coordinate system. Therefore, the force control performance was insufficient, and assist control will need to be improved in the future.

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