The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Robot Motion Control Using Mechanical Load Adjuster with Motion Measurement Interface for Human-Robot Cooperation

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Abstract—**The development of a robot motion control scheme and a mechanical load adjuster with a motion measurement interface is addressed in this paper. To improve the efficiency of a task involving human-robot cooperation, we designed a novel robot control system, in which a multiple-load state can be provided for a human operator. This system also can provide a multiple-dynamics state during a task involving human-robot dynamical cooperation. The multiple-load state including its transition is effective and efficient in such a task. A single load state can be easily provided by the impedance control of the robot motion thus far; however, the multiple-load state and its transition are difficult to realize using a conventional control scheme. The proposed control scheme differs widely from a conventional impedance control scheme in that the multiple-load state as well as both active and passive states cannot be induced in the single robotic system. Under the proposed control scheme, the load state can be adjusted with the various dynamics in the active or passive state. To confirm the effectiveness of the proposed control system, human-robot cooperative experiments were carried out. Results showed that the proposed control scheme can provide the multiple-load state for use in a human-robot cooperative task system.**

I. Introduction

In a human-robot cooperative task system, an impedance and admittance control scheme for controlling robot motion has generally been used, as shown in Fig.1 [1-3]. Although such control schemes are effective for human-robot interaction systems that execute cooperative tasks such as carrying a load [1,4], tracking guidance (or tracking assistance) [5], and robot-assisted rehabilitation [6-8], it is difficult to provide a multiple-load state and its transition in an active or passive state. The realization of the multiple-load state and its transitions using a single robotic system is useful and effective for human-robot cooperation, because the load duty ratio between the human operator and robot can be adjusted arbitrarily to a suitable value.

In this study, we focus on providing various load states and their transitions to a human operator in a human-robot dynamical interaction system. From the inherent dynamics of human motion to artificial dynamics, such as impedance characteristics, the dynamics between human and robot motion can be adjusted using the proposed device, which we named "mechanical load adjuster".

Manuscript received August 1, 2009. This research was partially supported by the Academic Frontier Research Project on "New Frontier of Biomedical Engineering Research" and The Ministry of Education, Culture, Sports, Science and Technology (MEXT), "Grant-in-Aid for Scientific Research (B), 21360120, 2009".

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The objective of this study is to develop the mechanical load adjuster and an inherent-dynamics-based motion control scheme for a human-robot cooperative system. The proposed device and control scheme allow a human operator to select a suitable load state from various load states during the human-robot dynamical interaction [9-12]. The proposed system, which involves the use of a new type of human-machine hardware interface and a robot motion controller, uniquely differs from previous control schemes that allow a safe and easy-to-use interaction with a robot [1-6,9-12].

The proposed mechanical load adjuster with a motion-detecting interface is composed of (i) a motion-detecting system that can detect relative positional deflection data between the human and robot motion, and (ii) a load-adjusting mechanism that can be used to vary the dynamics between human and robot motion. The proposed system can provide a multiple-load state based on both inherent and impedance dynamics.

In the inherent dynamics control mode, the dynamics of the human motion is uncoupled and independent of that of the robot motion; hence, the human operator is free from the load derived from the robot motion, such as impedance characteristics and robot dynamics. On the basis of the relative positional deflection data obtained using the motion-detecting system, a robot motion controller can generate the motion of the robot so that it decreases the relative positional deflection. Assuming that the detected positional deflection coincides with the human motion, the generated motion simply follows the inherent dynamics of the human motion. We define "inherent dynamics" as the whole of the substantial dynamics of the target task and the object, which is derived from material characteristics such as mass, viscosity, stiffness, friction, and restitution coefficient as well as the task environment. It appears that human operators feel more familiar with and have a greater intuitive understanding of the inherent dynamics of the target task and object than they do with the dynamics of the impedance characteristics, because they are sensitive to the inherent dynamics of various tasks and objects, which might have been acquired as empirical knowledge or by experience through executing numerous tasks involving various objects.

In the impedance control mode, the dynamics of the human motion is coupled and dependent on that of the robot; there-

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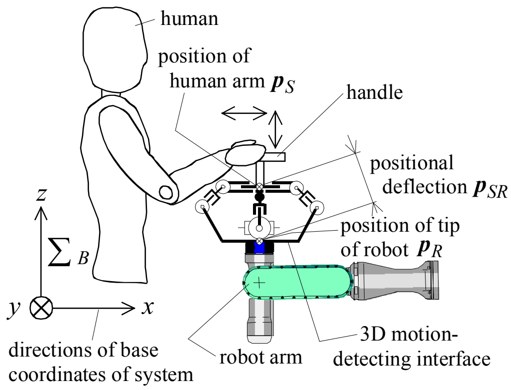


Fig.1 Human-robot cooperative motion control using mechanical load adjuster with motion-detecting interface

fore, the significant load derived from the dynamics of the robot motion, such as impedance characteristics (including mass, viscosity and stiffness) can be added to the human operator [1-3]. In the transition mode between the inherent control mode and the impedance mode, a hybrid-state of both dynamics can be provided.

This proposed concept makes the robot motion more adaptable for the cooperative task, because multiple-load states, which are useful for an efficient cooperative task but cannot be provided by using a robot motion controller based on the impedance control scheme [1-5], can be provided. Consequently, the concepts of the proposed scheme and system seem to be effective for a human-robot cooperative task system.

II. Inherent-Dynamics-Based Motion Control And Hybrid-Dynamics-Based Motion Control

We discuss the differences between the impedance control and inherent-dynamics-based motion control of the robot in this section. The dynamics of both models and a hybrid-dynamics-based control model are shown in Fig.2.

In the impedance control model, the human operator and handle are rigidly connected to the robot, as shown in Fig.2(a); thus, the dynamics of the motion of the object (i.e., the handle) is nearly equal to (or is defined as) that of the robot [1-3]. The virtual dynamics provided by impedance parameters replaces the inherent dynamics of the object as the motion dynamics. The dynamics of the motion of the object is coupled with and dependent on that of the robot; therefore, the significant load derived from the impedance characteristics can be added to the human operator. The impedance characteristics act as the significant load in the cooperative task.

On the other hand, in the inherent-dynamics-based motion control model, the motion of the object is uncoupled and free from that of the robot by using a purely passive element, such as a virtual wheel model at a contact point, as shown in Fig.2(b), so that the inherent dynamics of the object can be conserved. Although the dynamics of the object and robot are uncoupled and independent, their motion can be almost synchronized by simply controlling the robot motion to decrease the positional deflection between the robot and object, which is detected using the proposed motion-detecting interface. Under the uncoupled and independent dynamics, the human operator is free from the load of the impedance characteristics and robot dynamics, i.e., the human operator can move his/her arms freely. Therefore, the load of the cooperative

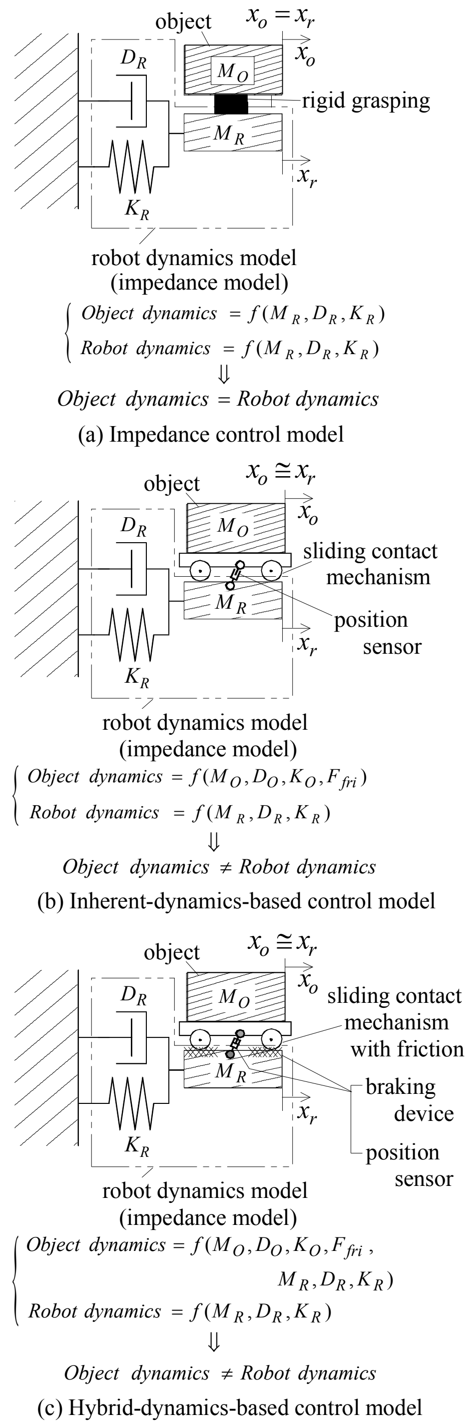


Fig.2 Dynamics models of impedance control, inherent-dynamics-based motion control and hybrid-dynamics-based motion control

task assigned to the human can be nearly zero without the friction element. The motion that follows the inherent dynamics of the object makes the object motion more intuitive and natural for the human operator than that resulting from impedance control, because the viscosity and stiffness characteristics of the impedance characteristics, which help provide a significant load but seem to generate unnatural motion for the human operator, are practically eliminated.

In the hybrid-dynamics-based motion control model, the motion of the object is partly coupled with (dependent on) that of the robot by using a purely passive element and friction between the robot and object, as shown in Fig.2(c), so that dynamics that is a hybrid of the inherent dynamics and impedance control is provided. The dependence rate between both dynamics, which is dependent on the frictional force between the robot and object, can be adjusted using the proposed mechanical load adjuster.

III. Mechanical Load Adjuster With Motion-Detecting Interface

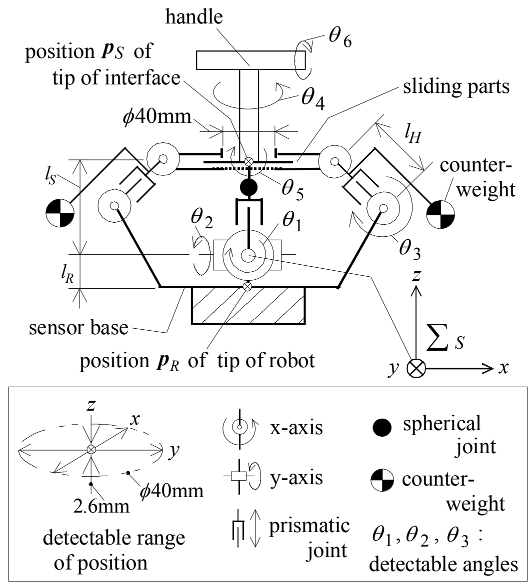
The proposed mechanical load adjuster with a motion-detecting interface is shown in Figs.3 and 4. The interface is composed of a link mechanism including passive joints, braking devices (electromagnetic brakes) and motion-detecting sensors (rotary encoders), and it can instantly detect the relative positional deflection between the present position of the object and that of the robot as well as adjust the magnitude of the load for the human.

This interface mechanism has an important role that allows the dynamics of the motion of the human to be mechanically uncoupled or coupled with (independent of or dependent on) that of the robot. The uncoupled or coupled state can be determined by adjusting the magnitude of the braking torques.

In the uncoupled state, the interface mechanism behaves as (i) a purely mechanical passive element between the robot and human, and (ii) an energy dissipation function, such as friction. The passive element and appropriate frictional interference are expected to contribute to improving the stability of robot motion control [12-17].

When the human arm is moved from its initial position to the tip of the motion-detecting interface $\boldsymbol{p}_S$, the motion detecting interface can detect the positional deflection $\boldsymbol{p}_{SR}$, which is fed back as a motion command to the robot. $\boldsymbol{p}_{SR}$ is calculated kinematically using the detected angles θ_1, θ_2, and θ_3, and lengths l_R, l_S, and l_H. To simplify the kinematics, the assumptions $l_S >> l_R$, $l_H \equiv const.$, $l_S \equiv const.$, $\theta_5 \approx 0$ are made. Taking this into account, $\boldsymbol{p}_{SR}$ is obtained as

$$\boldsymbol{p}_{SR} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} l_S \tan\theta_1 \\ l_S \tan\theta_2 \\ l_H \sin\theta_3 \end{bmatrix}, \qquad (1)$$



Note that θ_1, θ_2, θ_3, and θ_4 are equipped with braking devices. The fricitional torques of these joints can be adjusted.

Fig.3 Joint model of mechanical load adjuster with motion-detecting interface using braking device

where θ_1, θ_2, and θ_3 are the relative angles detected by the rotary encoders set on each joint. Therefore, 3-DOF (degrees-of-freedom) translational motion can be detected in the x-, y- and z-directions at the tip of the interface (the handle).

Note that the angles of rotation θ_4, θ_5, and θ_6 are derived from the free joint motion when the braking device is free. These angles are not detected and are irrelevant to the motion control of the robot; however, 6-DOF motion is provided at the tip of the interface because of their contribution.

The position of the tip of the interface can be moved in the x-, y-, and z-directions within its mechanical limit, and rotated freely around the y- and z-axes. The detectable range of the interface is restricted to within ±20mm in the x- and

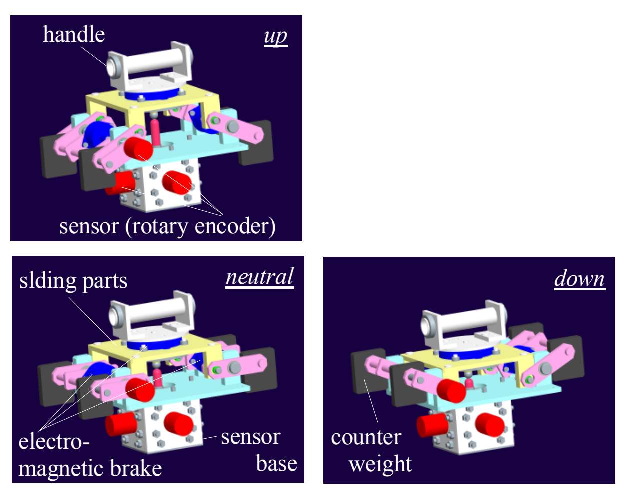


Fig.4 Overview of mechanical load adjuster

y-directions and $\pm 1.3\,\text{mm}$ in the z-direction from the equilibrium position (i.e., the initial position) owing to the mechanical limitation of the link mechanism. The accuracy of the positional detection of the interface is 0.17 mm in the x- and y-directions and 0.1 mm in the z-direction.

The deadweight of the moving parts of the interface is compensated using a counterweight. It is assumed that this extra weight will not impose a significant burden on the human or significantly affect the inherent dynamics of the motion of the object.

At the tip of the motion-detecting interface, an appropriate frictional force, derived from the friction torques of the rotary joints and the translational friction of the sliding parts, enables a smooth interaction with the human. It also contributes to significantly improving the stability of the impedance control, as mentioned above.

In the coupled state, the mechanical load adjuster behaves as the binder between the dynamics of the human and robot motion. The dynamics of the human motion coincides with that of the robot motion in the coupled state. To couple both dynamics, some rotary joints and sliding parts are equipped with rotary braking devices. These braking devices can restrict the motion of the motion-detecting interface through the braking torques; therefore, allowing the dynamics of the object motion to be mechanically coupled with (dependent on) that of the robot motion (i.e., impedance control).

IV. Robot Motion Controller

The control scheme for the robot motion is described in this section. In the inherent dynamics control state, the robot motion controller generates motion commands relative to the positional deflection data. The controller has a feedback loop that decreases the horizontal and vertical positional deflections, as shown in Fig.5. The positional deflection $\boldsymbol{p}_{SR}$ is transformed into a motion command. The motion of the robot is controlled to nearly coincide with that of the object, so that the human can voluntarily move the object simultaneously with the robot.

The motion of the robot can be described as

$$\boldsymbol{M}_R \ddot{\boldsymbol{p}}_R + \boldsymbol{D}_R \dot{\boldsymbol{p}}_R = \alpha \boldsymbol{K}_V \boldsymbol{p}_{SR} + (1-\alpha)\boldsymbol{F}_H , \quad (2)$$

where $\boldsymbol{M}_R$ and $\boldsymbol{D}_R$ are the mass and damping matrices, respectively. $\boldsymbol{p}_R$ is the position vector of the tip of the robot (i.e., the end effector) relative to the base coordinates $\sum_B$. $\ddot{\boldsymbol{p}}_R$ and $\dot{\boldsymbol{p}}_R$ are the acceleration and velocity vectors, respectively. $\boldsymbol{K}_V$ is the gain matrix for the positional deflection vector. $\boldsymbol{p}_{SR}$ is the positional deflection vector and is detected by the motion-detecting interface. $\boldsymbol{F}_H$ is the force vector applied to the tip of the motion-detecting device by the human. α $(\in 0 \le \alpha \le 1)$ is the weight coefficient that determines the weight of the two input signals for the robot motion control.

The robot motion control states are described as follows.

IF $\alpha = 1$ [Inherent dynamics control state]

The braking torques derived from the braking devices are set to zero in this state. When the positional deflection $\boldsymbol{p}_{SR}$ is detected by the proposed motion controller, the robot motion is controlled to decrease $\boldsymbol{p}_{SR}$ by the input $\boldsymbol{K}_V \boldsymbol{p}_{SR}$. Consequently, the position of the tip of the robot $\boldsymbol{p}_R$ coincides with that of the object $\boldsymbol{p}_S$. The cooperative task load for the human can be nearly zero without the friction of the motion-detecting interface; however, the robot motion is controlled to follow the human motion by decreasing the detected positional deflection.

IF $\alpha = 0$ [Impedance control state]

In this state, the braking torques are set to the maximum of the braking devices to control the position of the tip of the robot $\boldsymbol{p}_R$ to rigidly coincide with that of the object $\boldsymbol{p}_S$. This control state is equivalent to a conventional impedance control scheme. The robot motion is controlled to decrease the detected force $\boldsymbol{F}_H$ applied by the human and the environment. The robot motion is controlled to follow the human motion with a significant load generated by impedance characteristics such as the mass and damper characteristics described in eq.(2).

IF $0 < \alpha < 1$ [Hybrid control state]

The braking torques are set to an appropriate value set between zero and maximum in proportion to the weight coefficient α in this state. The weight coefficient is adjusted arbitrarily in this control state, so that the proposed motion controller can provide variable load states with multiple-dynamics and their transitions. Therefore, the cooperative task load for the human operator can be regulated arbitrarily in accordance with the weight coefficient.

V. Experimental System

As shown in Fig.6, the experimental system consists of a 7-DOF PA-10 manipulator (Mitsubishi Heavy Industries, Ltd.), a 6-DOF IFS-67M25A50-I40 force sensor (Nitta Corporation), which is mounted on the tip of the robot to measure the magnitude of the force applied by the human, and the mechanical load adjuster with the motion-detecting interface, which is mounted on the force sensor.

In the case that the impedance parameters in eq.(2) are correctly chosen, the robot's motion can avoid excessive overshooting when obeying each command. The desired velocity $\dot{\boldsymbol{p}}_R$ is computed using the input term $\alpha \boldsymbol{K}_V \boldsymbol{p}_{SR} + (1-\alpha)\boldsymbol{F}_H$.

The robot is controlled by position-control-based admittance control. Therefore, our system becomes unstable when the robot comes in contact with a high-stiffness environment without the proposed interface, because our system has a serious problem of controller contact stability owing to hardware performance characteristics, such as the large sampling time required for the force control [17].

VI. EXPERIMENT AND OBSERVATION

A. Human-Robot Cooperative Task

To investigate the performance of the mechanical load adjuster with the motion-detecting interface and robot motion controller, an experiment based on a tentative cooperative task involving the arm motion of the human operator is carried out, as shown in Fig.6. The human operator grasps the handle on the tip of the interface and moves it from the start position to the target position with an arbitrary trajectory. It is expected that the robot will add and adjust the load to the arm motion (i.e., the object motion) as well as smoothly follow the planned motion of the human.

The impedance parameters of the robot motion controller in eq.(2) for the experiment are as follows: $\boldsymbol{M}_R = diag[3 \quad 3 \quad 3]$, $\boldsymbol{D}_R = diag[150 \quad 150 \quad 150]$, and $\boldsymbol{K}_V = diag[800 \quad 800 \quad 800]$. The weight coefficient, which determines the magnitude of the the human load, is set at $\alpha = 0$, 0.5, and 1.

B. Experimental Results and Observations

The results of the experiment are shown in Figs.7 and 8. The trajectory of p_{Sz} shows the position of the tip of the mechanical load adjuster. Force is measured at the tip of the robot, and is applied directly by the human to the robot while the human moves his/her arm. Note that the measurement directions of the force are based on the base coordinates Σ_B, as shown in Fig.6.

First, we discuss the experimental results of the motion control of the robot shown in Fig.7. It appears that the motion of the robot during the experiment is smooth without problems. No significant overshooting of the motion of the robot is observed, and the system appears to be stable. This result demonstrates that the human was able to smoothly work in collaboration with the robot.

When the weight coefficient α is zero, the control input of the robot motion is equivalent to the detected force $\boldsymbol{F}_H$, because $\alpha \boldsymbol{K}_V \boldsymbol{p}_{SR}$ tends to zero. As shown in Fig.7(a), the robot motion is regulated by the impedance dynamics described by mass and viscosity coefficient.

When the weight coefficient α is 0.5, the control input consists of two terms, namely, $\alpha \boldsymbol{K}_V \boldsymbol{p}_{SR}$ and $(1-\alpha)\boldsymbol{F}_H$. The positional deflection detected by the motion-detecting interface and the detected force generate the robot motion, as shown in Fig.7(b). The dynamics of the robot motion contains both inherent and impedance dynamics.

When the weight coefficient α is 1, the control input is the positional deflection $\alpha \boldsymbol{K}_V \boldsymbol{p}_{SR}$, because $(1-\alpha)\boldsymbol{F}_H$ tends to zero. As shown in Fig.7(c), the motion of the robot is regulated by the inherent dynamics. The detected force appears to be derived from the friction of the sliding mechanisms of the motion-detecting interface. However, this can be reduced by decreasing the friction of the sleeves of the interface. Note that such a frictional force does not affect the stability of the system, because the friction tends to attenuate the oscillation of the system and provides more natural dynamics than impedance characteristics for the human. Consequently, the position of the tip of the robot coincides with that of the object. It is clear that the interface isolates the dynamics of the arm (i.e., the object) from that of the robot. These results show that the motion of the arm is nearly independent of the impedance characteristics that describe the motion of the robot under impedance control.

As shown in Figs.7(a)-(c) and Fig.8, although the profiles and maximum magnitudes of the control input term derived from $\alpha \boldsymbol{K}_V \boldsymbol{p}_{SR} + (1-\alpha)\boldsymbol{F}_H$ are similar, the detected force when $\alpha = 1$ is approximately four-fifths or much smaller in magnitude than of those when $\alpha = 0$ and 0.5. This shows that the robot motion controller can provide an appropriate multiple-load state for the human in accordance with the weight coefficient α.

These experimental results reveal that the human was able to carry out a cooperative task involving arm motion in cooperation with the robot. It is also concluded that the mechanical load adjuster with the motion-detecting interface and the robot motion controller operate well and stably during the human-robot interaction.

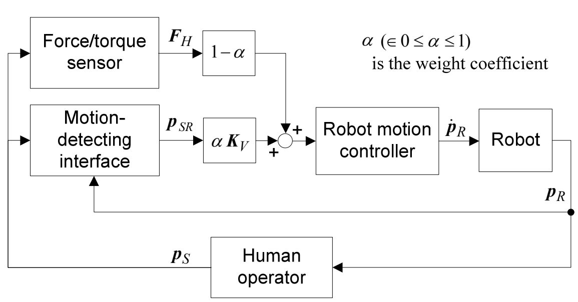


Fig.5 Block diagram of robot motion controller using mechanical load adjuster with motion detecting interface

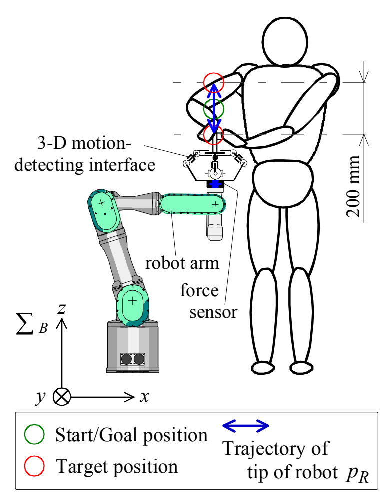
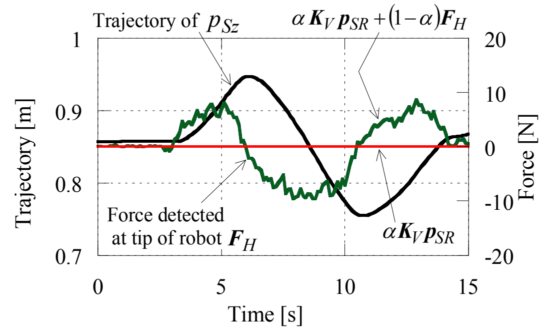


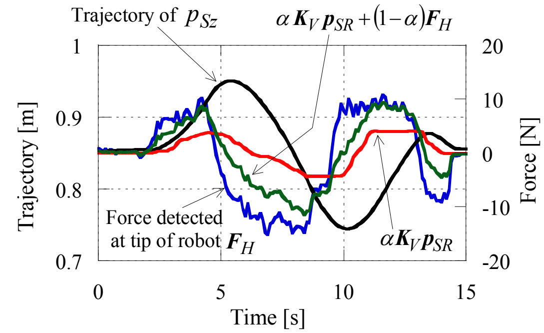
Fig.6 Start and target positions of human-robot cooperative motion

VII. CONCLUSIONS

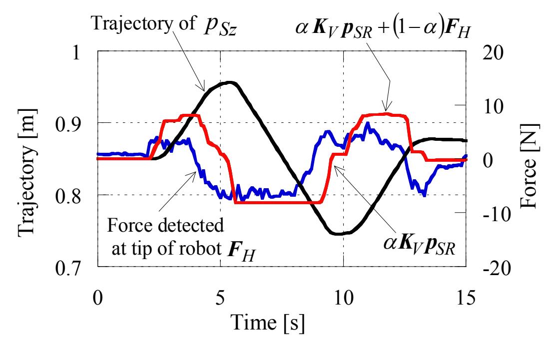
In this paper, we propose a mechanical load adjuster with a motion measurement device for a human-robot cooperative task system. The proposed interface can be used to adjust the cooperative task load as well as detect the positional deflection between the object and robot, and the robot motion controller causes the robot motion to follow the inherent dynamics of the object. To investigate the performance of the proposed control scheme, tentative cooperative tasks involving human arm motion are being carried out. Experimental results show that the proposed system can provide a variable-dynamics-based motion control scheme with a multiple-load state that is effective for a human-robot cooperative task system.



(a) $\alpha = 0$ [Impedance control state]



(b) $\alpha = 0.5$ [Hybrid control state]



(c) $\alpha = 1$ [Inherent dynamics control state]

Fig.7 Experimental results of human-robot cooperative motion

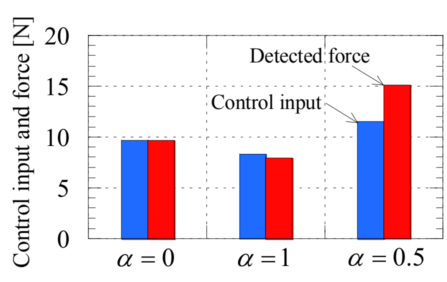


Fig.8 Maximum magnitudes of control input and detected force in each control state

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