Human Robot Physical Interaction Utilizing Force Detectable Tactile Covers

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Abstract. In the paper, we describe a tactile sensor mechanism design and motion control methods for human-robot physical interaction (physical interference (PIF) with human, viewed from the robot side). Robots performing tasks in the neighborhood with human have to behave not only compliantly adapting to human motion but also strictly performing given tasks in PIF. First, to detect tactile and force information on entire surfaces of robot's body in PIF, considering PIF will occur on various parts of the body, we propose whole-arm sensitive covers composed of a force-torque sensor and touch sensors. Next, motion control methods for realizing both force following and task fulfillment by utilizing redundancy according to distinction of the attribute of given tasks are presented. Finally, from evaluation experiments, it was confirmed that the covers are effective for accurately sensing PIF and control methods proposed are useful for realizing force following and task fulfillment in physical interaction.

1 Introduction

Human Symbiotic Robots that can co-exist with human for supporting and enhancing human life in the fields of Medicare, welfare and households in the 21st century are likely to physically contact and collide with human. The robots are required to recognize such situations and behave appropriately adapting to the situations. The authors have comprehensively called such various situations 'Physical InterFerence' (PIF)[1]. PIF, which is a form of physical interaction viewed from the robot side, includes all the contact situations such as tactile, sliding, pinching, gripping, striking, and collision situations, etc. concerning human. PIF actively or passively occurs between robots and human on the entire surfaces of robot's body as shown in Fig.1, producing physical interactive force over zero.

PIF occurrence causes various influences into/onto human and robots interactively such as psychological, physiological, mental, physical, informational and emotional ones. Among these influences, physical influence onto robots and human, which is of quite importance, are especially focused on, since interference force caused by PIF in co-operating with human may hurt human or disturb robots' performing tasks. As examples concerning physical influences, robot recognizes the existence of environments (including human), human feels physical pains, robot may topple, robot might spill milk out of the handled cup by impacts in PIF, etc.

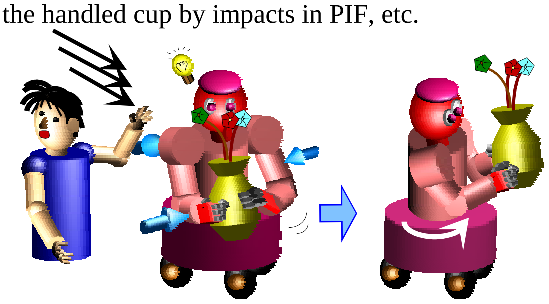


Fig.1. An Image of Human-Robot Physical Interaction in cooperation. This shows PIF may occur on various and several parts of entire surfaces of robots' body. In cases of any PIF, robots have to behave appropriately adapting to human motions and force applied from human

In these situations, it is important for robots to comprehend physical influences onto not only human body but also robots' performing tasks and behave to simultaneously attenuate these two physical influences. We call such robots' behaviors 'PIF Adapting Behaviors'. Such robotic technologies, which a few researches have been done so far, are highly important to realize high-level human-robot symbiosis. It is apparent that only conventional collision avoidance techniques using optical, ultrasonic sensors, etc. are not enough for securing high reliability of robotic system in PIF [2][3].

In the paper, we hence aim to realize the PIF Adapting Behaviors, which are dexterous task-fulfilling manipulation with compliantly adapting to human motions and force in any PIF by whole body cooperation utilizing redundancy. In the following, PIF sensing hardware systems and motion control methods necessary for realizing the PIF Adapting Behaviors are described, which are implemented into an actual humanoid robot and evaluated by some experiments.

2 PIF Adapting Behaviors

In order to realize the complicated PIF Adapting Behaviors, first, robots have to detect PIF with human directly through the sense of touch. Then, PIF sensing hardware systems that can detect tactile and force information (PIF information) in PIF are required. Next, based on the detected PIF information, robots have to plan their behaviors to attenuate physical influence onto human body as, i.e. force following (to reduce external force by following human motions with the robot's body continuously in touch with human), PIF-parry (to move its body away from human), and emergency stop, etc. In addition, robots have to simultaneously comprehend and attenuate physical influence on task performance, and behave to realize high task performance, i.e. (robustly) dexterous manipulation, and task fulfilling manipulations, etc. In the cases of co-operating with human in the narrow space, it is important for robots to have the ability of following force and human motion as well as performing the given task adroitly. Therefore, it is essential for robots to generate the PIF Adapting Behaviors considering both force following and task-fulfilling manipulation.

2.1 Previous Researches

Conventional researches have mainly focused on PIF-sensing limited only at the wrist of the robot's arm using a force/torque sensor [4]. A humanoid sensor suit that covers the entire body of the robot has been proposed [5], however, it cannot detect force information representing interactive physical influences but distributed patterns and on/off information of PIF with environments. These PIF sensing hardware systems are not enough to recognize physical influences in detail onto human and robots on the entire surface of robots' body in PIF with human.

Many researches that deal with PIF occurring between environments (including human) and robots have mainly focused on only efficient task execution or only securing of high human safety. Some methods of collision force reduction have been proposed [6][7]. These methods, however, are difficult to be implemented into actual systems because a prior knowledge of collisions is required. Many researches have reported the active compliance control approaches using a force/torque sensor mounted only on the wrist of the robot's arm [4][8]. However, few researches have applied such control methods to issues concerning PIF especially with human occurring on entire parts of robot's body, not only at the wrist. This is the reason there have been no useful PIF sensing hardware systems that can detect force information on the entire parts of the body as well as at the wrist as mentioned above.

In order to both secure human safety and maintain task performance in collisions with human, a control method is proposed, in which the configuration of the robot arm with no redundancy is modified to the target to compensate for deviations of end-effector's position caused by the passive trunk deformation [9]. Since contact position is fixed because of the restriction of the PIF sensing hardware system utilized in this research, contact position that is changing in real time has never been detected. In addition, in this method, the role of each joint of some limbs playing in force following and position compensation has been divided respectively. Actually, the role of each joint needs to change in force following or/and task-fulfilling manipulations, if attribute and constraint form of the task are changed or utilization of redundancy is needed for task fulfillment. Therefore, it is difficult to realize both force following and task fulfillment by only implementing this method into humanoid type robots cooperating with human.

2.2 Target of The Study

Targets of the study are represented as four images concerning the PIF Adapting Behaviors are illustrated in Fig.2. Fig.2 (a) shows that following force applied from human onto various parts of robot's body by whole body cooperative manipulations (force following) is a useful method for attenuating physical influences onto human body. This can be a base control method for reduction of physical influences of PIF. With only this method, however, the robot can never fulfill the task to perform as shown in Fig.2 (b). Only force following is insufficient in the situation of carrying coffee where such a task with the attribute is saddled on the robot because human may be scalded with the spilled hot milk as the result. This example implies that loss of robots' task fulfillment has human injured. No researches have focused on this significant issue about human safety so far.

Thus, as shown in both Fig.2 (c) and (d), realization of both force following and task fulfillment in PIF at the same time is required for the robot. Fig.2 (c) shows that the robot has to move its arm forward to follow human motions without changing the hand posture. In this case, the robot has to behave maintaining the orientation of the hand vertically in disregard of large deviation of the hand position. Fig.2 (d) shows that a type of the task saddled on the robot is distinct from that in Fig.2 (c). The position as well as the orientation of the hand has to be unmoved strictly. Under such a situation, the robot cannot move its arm forward as in Fig.2 (c). In this case, the robot has to behave adroitly revolving the elbow by utilizing the redundancy for force following with the hand position unmoved as shown in Fig.6 (b). This means that the processed motions to adapt to PIF will be also changed according to constraint conditions and attribute of the given tasks and the necessity of utilizing redundancy for task fulfillment. In addition, the role of each joint is changed and may be different from each other according to types of the given task. It is required for the robot to understand the meaning of the given task such as the attribute and the constraint condition that restrict manipulations.

The target of the study is to realize both force following and task-fulfilling manipulations according to attribute and constraint condition of various given tasks and necessity of utilizing redundancy for task fulfillment as in Fig.2 (c) and (d).

2.3 Requirements for PIF Adapting Behaviors

In order to realize such behaviors considering both force following and task fulfilling manipulation as shown in Fig.2, requirements for the PIF Adapting Behaviors have been deduced as follows, as the results of the analysis of various PIF between human and robots.

(a) PIF Sensing Hardware System

PIF sensing hardware system that can detect force information such as PIF occurrence or not (PIF On/Off), PIF Position, Force Magnitude, Force Orientation, and Duration Time on the entire parts of the robot's body.

(b) PIF Adapting Motion

Force Following. Force following motion using several redundancy of whole body for reducing interference force applied on several parts of the body surfaces; As one of the behaviors for attenuating physical influences onto human body.

Task fulfillment. Task-fulfilling manipulations appropriate for the attribute and constraint conditions of given tasks by utilizing one or several redundancy; As one of the behaviors for attenuating physical influences on robots' performing tasks.

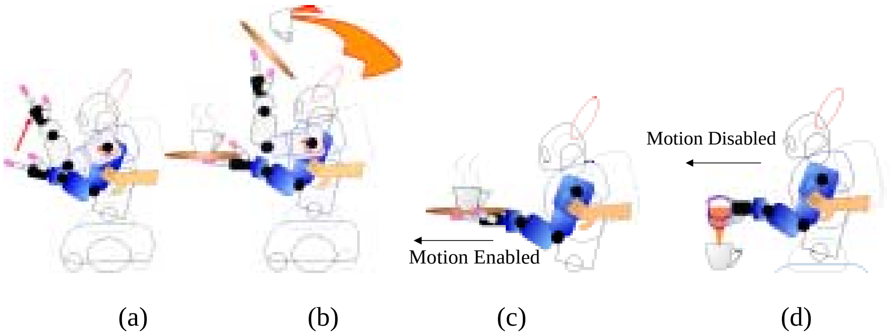


Fig.2. The images as the target of the study. These images show that the form of PIF Adapting Behaviors for realizing both task-fulfillment and high compliance to human needs to change according to the constraint condition and attribute of the task saddled on the robot at the moment in PIF. The figure (a) shows only force following by whole body cooperative manipulation utilizing redundancy is useful for attenuating physical influence on human under the condition no target tasks are given. The figure (b) shows only force following such as in figure (a) never fail to spill the coffee out of the cup without considering performing the given task. The figure (c) shows in order not to spill the coffee, maintaining the hand posture constantly in addition to following human motion is required. In the case of the situation where the task with the attribute as in the figure (c) is saddled on the robot, the arm is permitted to move forward. However, in the case of the figure (d), the robot cannot move its arm forward in order to continue pouring coffee into the cup. The figure (d) shows another task-fulfilling manipulation distinct from the task in the figure (c) is required because of the difference in the attribute of the given task. The manipulation needs the redundancy of the elbow for unmoving the position of the hand

3 Mechanism Design of PIF Sensing Hardware System

In order to detect PIF occurrence or not (PIF On/Off), PIF Position, Force Magnitude, Force Orientation, and Duration Time even on several parts of the body at the same time by utilizing hardware systems, we have developed a PIF sensing surface cover that can detect the five indexes on the surfaces of robot' body. The mechanism design is as follows.

3.1 Design of PIF Sensing Surface Covers

In order to satisfy the requirements for PIF sensing hardware systems, we have proposed a sensitive sensor structure that is designed to cover the robot body as shown in Fig.3 [1] [10]. This PIF sensing cover is composed of a six-axis force-torque sensor and FSR sensors (touch sensors) inside for realizing high PIF sensitivity. Since the interference force is concentrated to the force-torque sensor, accurate PIF sensing of Force Magnitude, Force Orientation, and Duration Time is realized. FSR sensors are equipped between two plates on each surface of the cover for detecting accurate on/off information of touch, and specify the plate where PIF is occurring in order to calculate the PIF position by combination of moments detected by the force-torque sensor. The box-typed sensor structure can expand PIF sensing areas of one force/torque sensor much larger than the conventional usage way of a force-torque sensor. Several cover modules with this structure can cover most of the surfaces of the entire robot's body.

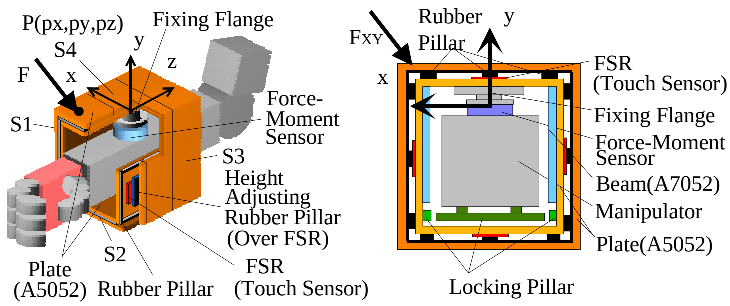


Fig.3. Design of Surface Cover. This shows since the box-typed cover is connected with a robot body at a single position for concentrating external force applied onto the cover surfaces to the force/torque sensor. In addition, FSR sensors on the surfaces accurately detect touch information concerning the existence of environments including human

3.2 Implementation onto Actual Humanoid Robot

To date, we have developed a prototype of Human Symbiotic Robot that has 52 DOF in total composed of head, arms, hands, trunk, waist, and vehicle part for securing both vertical and horizontal task spaces and realizing dexterous tasks stably in various co-operations with human [11]. The anthropomorphic dual arms of WENDY are focused on as the subjects onto which the PIF sensing cover is implemented.

The surface covers are divided into five modules for actually implementing onto the humanoid robot that is in complicated form, considering no interference to motion of the arm by equipment of the covers in any motions and optional configurations. Each cover module has been designed under considerations of lightening, low volume, high friendliness for human, and no interference between covers, cover and cables. The assembly design and overview of the forearm cover developed based on the concepts are illustrated in Fig.4 as an example. In addition, the assembly design and overview of WENDY equipped with the developed dual arm surface covers are illustrated in Fig.5. Memoryfoam M-38 as a viscoelastic material is equipped on the outer surfaces for impulsive force absorption. A total of six six-axis force-torque sensors are installed in dual arms in order for the robot to precisely recognize interference force on the entire and several parts of the body at the same time as shown in Fig.5. Thus, the robot can detect tactile and force information in detail on several parts of dual arms. The cover modules where a force/torque sensor is installed are upper shoulder (Nitta Corp.: IFS-67M25A-I40), upper arm, and forearm cover module (Nitta Corp.: IFS-67M25A-I40) of dual arms. A few FSR sensors are equipped on the surfaces of all the modules. The weight of each cover including a force-torque sensor and FSR sensors is 2.72 [kgf] (upper shoulder), 0.32 [kgf] (lower shoulder), 1.06 [kgf] (upper arm), 0.35 [kgf] (elbow), and 0.68 [kgf] (forearm) respectively.

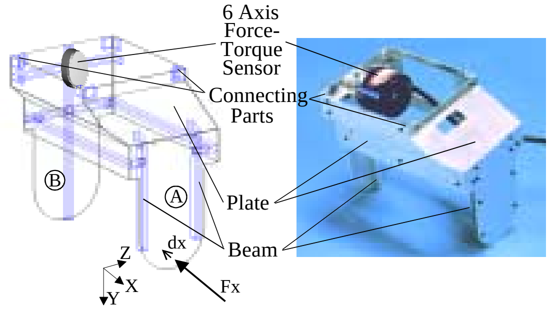


Fig.4 (i.e.) The Designed and Developed Forearm Surface Cover Module. As a material of the surface cover, 1[mm] light and highly stiff A5052 plate is used. Four plates of A5052 are constructed with L-type connecting parts at the four corners. The surface cover becomes box-typed and each plate is stiffly strengthened with a few beams of which material is YH75

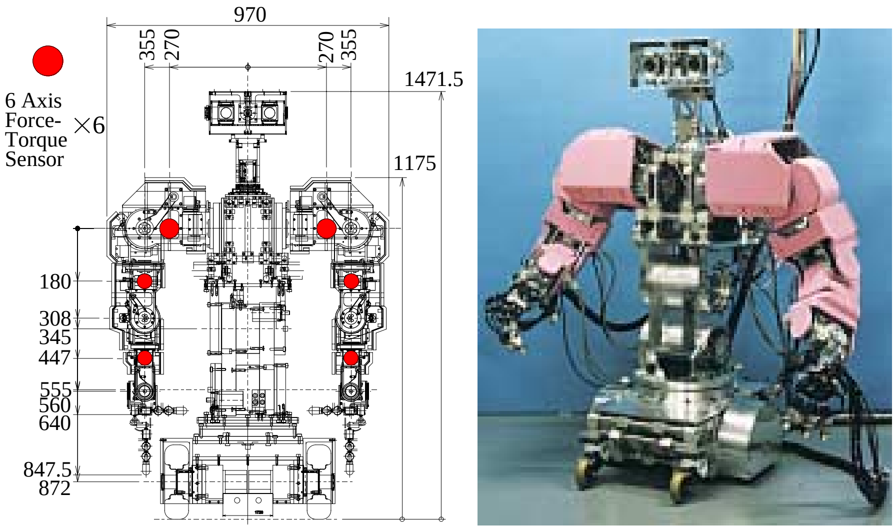


Fig.5. Assembly Design and Overview of WENDY with Humanoid Dual Arm Surface Covers

3.3 Analysis

The method used to measure force position, magnitude and orientation is as follows.

Analysis Condition. A Simple PIF force is applied onto a plate of the surface cover from the outside. The plate of PIF force being applied is specified based on on/off information by FSR.

Analysis Condition. The coordinate system is described in Fig.3. The magnitude and orientation of applied force f, θ, ϕ in the polar coordinate system are calculated by Eq. (1). The contact position $\vec{p} = (p_x, p_y, p_z)^T$ is calculated using information of detected plates and force information $\vec{f} = (f_x, f_y, f_z, m_x, m_y, m_z)^T$ by Eq. (2), (3). Duration time is calculated by setting a threshold value of PIF force magnitude as approximately 70[gf]-200[gf].

$$\begin{cases} \left|\vec{f}\right| = \sqrt{f_x^{\ 2} + f_y^{\ 2} + f_z^{\ 2}} \\ \theta = Arc\tan(f_y / f_x) \\ \phi = Arc\tan(\sqrt{f_x^{\ 2} + f_y^{\ 2}} / f_z) \end{cases} . \tag{1}$$

(a) S1, S3 plate $(S1: f_x < 0, i = 1,\ \ S3: f_x > 0, i = 2)$

$$\begin{cases} p_x = (-1)^{i+1} \cdot L \\ p_y = ((-1)^{i+1} \cdot L \cdot f_y - m_z) / f_x \\ p_z = (m_y + (-1)^{i+1} \cdot L \cdot f_z) / f_x \end{cases} . \tag{2}$$

(b) S2, S4 plate $(S2: f_y < 0, i = 1,\ \ S4: f_y > 0, i = 2)$

$$\begin{cases} p_x = (m_z + (-1)^i \cdot h_i \cdot f_x) / f_y \\ p_y = (-1)^i \cdot h_i \\ p_z = ((-1)^i \cdot h_i \cdot f_z - m_x) / f_y \end{cases} . \tag{3}$$

Each PIF force applied onto distinct cover modules is independently processed. If two or more plates in a cover module detect the touch with environments, a force vector calculated by the summation of force applied onto a cover module is virtually regarded as a simple force.

4 Control Method

In this section, motion-processing methods for realizing PIF Adapting Behaviors are presented. First, a basic motion processing method for compliantly following force and human motion is described. Based on it, a method for following PIF occurring on several parts of the dual arms at the same time utilizing redundancy is proposed. Next, a motion control method of both realizing force following and task fulfillment at the same time utilizing redundancy is presented considering the distinction of the attribute of the given task. The details are as follows.

4.1 Force Following Control

To realize the PIF Adapting Behaviors considering attenuation of physical influences onto human body, first, a virtual compliance control method [12] is adopted because this method is considered effective for reducing interference force applied. A compliance control equation of a PIF position where PIF is occurring on a surface of the body is expressed as Eq. (4).

$$\mathbf{M_0}\ddot{\mathbf{x}} + \mathbf{D_0}\dot{\mathbf{x}} + \mathbf{K_0}\mathbf{x} = \mathbf{F} \,. \tag{4}$$

Moreover, force following motions without storing kinetic energy given in PIF are required to effectively reduce PIF force. Thus, the stiffness component may be disregarded. In addition, since the motions are processed in most short time 1[ms], we may regard the virtual mass as equal to zero. Eq. (4) is thereby rewritten as denoted in Eq. (5). This equation means that robots have to behave to realize a desirable mobility $\mathbf{D_0}^{-1}$ on a PIF position. Based on this method, each joint is controlled as denoted in Eq. (6). The mobility $\mathbf{D_0}^{-1}$ is decided by a (transpose) Jacobean at the PIF position $\mathbf{J_c}$, $\mathbf{J_c}^{\mathbf{T}}$ representing configurations of the robot and mobility of each joint $\mathbf{D}^{-1}$ as denoted in Eq. (7).

$$\dot{\mathbf{x}} = \mathbf{D_0}^{-1}\mathbf{F} \,. \tag{5}$$

$$\dot{\mathbf{q}} = \mathbf{D}^{-1}\mathbf{J_c}^{\mathbf{T}}\mathbf{F} \,. \tag{6}$$

$$\mathbf{D_0}^{-1} = \mathbf{J_c}\mathbf{D}^{-1}\mathbf{J_c}^{\mathbf{T}} \,. \tag{7}$$

Furthermore, we have to consider PIF force is applied on several parts of robot's body at the same time, not only on one part. It is required for robots to process force following by whole body cooperative manipulations that combine arms, trunk, waist, and vehicles in order to efficiently realize a desirable mobility.

Thus, a new control method for processing force following utilizing dual seven-DOF arms and a trunk is proposed to cope with several PIF simultaneously occurring on several parts of dual arms at the same time. In order to reduce all the interference force produced on several and entire parts of arms, robots have to behave to reduce all the torques generated by the force to each joint. In the case of the robot with the link structure as WENDY, the control method is denoted as Eq. (8) based on Eq. (6).

The trunk is actuated by the summation of the torques generated by each force independently detected on several parts of the arms. For example, if PIF occurs onto a right forearm, force following utilizing the trunk and the arm.

$\mathbf{D_0}^{-1} \in \mathfrak{R}^{6\times 6}$ denotes a mobility diagonal matrix at a PIF position, $\mathbf{x} \in \mathfrak{R}^{\mathbf{6\times 1}}$ a position vector of the PIF position, and $\dot{\mathbf{x}} \in \mathfrak{R}^{\mathbf{6\times 1}}$ a velocity vector of the PIF position respectively. In addition, $\dot{\mathbf{q}}_\mathbf{T} \in \mathfrak{R}^{\mathbf{6\times 1}}$, $\dot{\mathbf{q}}_\mathbf{R} \in \mathfrak{R}^{\mathbf{6\times 1}}$, $\dot{\mathbf{q}}_\mathbf{L} \in \mathfrak{R}^{\mathbf{6\times 1}}$ denote a joint velocity reference vector of trunk, right arm, and left arm respectively. N_R and N_L denote the number of force independently detected on right and left arm respectively. In the case of WENDY's hardware systems, they are both three. $\mathbf{D}^{-1}_{\mathbf{R\_i}} \in \mathfrak{R}^{\mathbf{6\times 6}}$ denotes mobility diagonal matrices of right arm, $\mathbf{D}^{-1}{}_{\mathbf{L\_i}} \in \Re^{\mathbf{6\times6}}$ those of left arm, $\mathbf{J_c}^{\mathbf{T}}{}_{\mathbf{R\_i}} \in \Re^{\mathbf{6\times6}}$ transpose Jacobean matrices of right arm, $\mathbf{J_c}^{\mathbf{T}}{}_{\mathbf{L\_i}} \in \Re^{\mathbf{6\times6}}$ those of left arm, $\mathbf{F_{R\_i}} \in \Re^{\mathbf{6\times1}}$ interference force vectors onto right arm, and $\mathbf{F_{L\_i}} \in \Re^{\mathbf{6\times1}}$ those onto left arm respectively. The marks **R**, **L** denote right and left arm respectively. In addition, the mark **i** denotes a symbol for distinguishing six surface covers respectively that have a six-axis force-torque sensor inside. If **i** is equal to one, this denotes upper shoulder, as the same, two upper arm, and three forearm cover of dual arms. Each vector and matrix is based on the common coordinate system.

$$\left.\begin{aligned}\dot{\mathbf{q}}_{\mathbf{T}} &= \sum_{\mathbf{i}=1}^{\mathbf{N\_R}} \mathbf{D}^{-1}{}_{\mathbf{R\_i}} \mathbf{J_c}^{\mathbf{T}}{}_{\mathbf{R\_i}} \mathbf{F_{R\_i}} + \sum_{\mathbf{i}=1}^{\mathbf{N\_L}} \mathbf{D}^{-1}{}_{\mathbf{L\_i}} \mathbf{J_c}^{\mathbf{T}}{}_{\mathbf{L\_i}} \mathbf{F_{L\_i}} \\ \dot{\mathbf{q}}_{\mathbf{R}} &= \sum_{\mathbf{i}=1}^{\mathbf{N\_R}} \mathbf{D}^{-1}{}_{\mathbf{R\_i}} \mathbf{J_c}^{\mathbf{T}}{}_{\mathbf{R\_i}} \mathbf{F_{R\_i}} \\ \dot{\mathbf{q}}_{\mathbf{L}} &= \sum_{\mathbf{i}=1}^{\mathbf{N\_L}} \mathbf{D}^{-1}{}_{\mathbf{L\_i}} \mathbf{J_c}^{\mathbf{T}}{}_{\mathbf{L\_i}} \mathbf{F_{L\_i}}\end{aligned}\right\} . \tag{8}$$

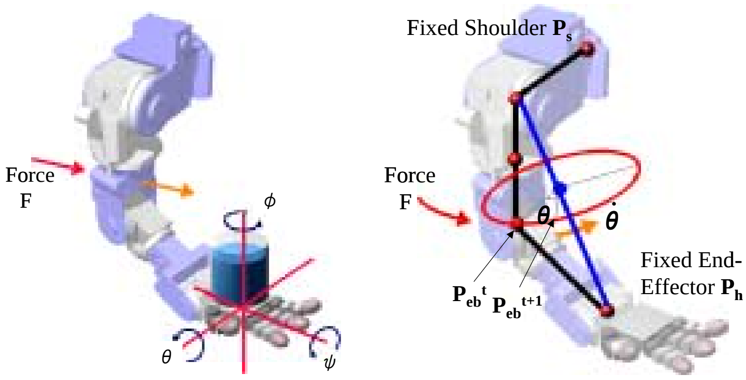
Since the dimension of $\mathbf{J_c}$, $\mathbf{J_c}^{\mathbf{T}}, \mathbf{D}^{-1}, \dot{\mathbf{q}}$ actually changes according to the link where PIF occurs, we introduce a denotation **pos** for distinguishing the dimension of them according to the position of the link. The relationship between **pos** number and parts of the body is as follows. Upper shoulder is one, upper arm four, elbow five, and forearm six. For example, if the PIF position is on the upper arm cover, the dimensions actually become $\mathbf{J_c} \in \Re^{\mathbf{6\times4}}$, $\mathbf{J_c}^{\mathbf{T}} \in \Re^{\mathbf{4\times6}}$, $\mathbf{D}^{-1} \in \Re^{\mathbf{4\times4}}$, $\dot{\mathbf{q}} \in \Re^{\mathbf{4\times1}}$ respectively. Thus, the dimension of the vector and matrices is in general denoted as, $\mathbf{J_c} \in \Re^{\mathbf{6\times pos}}$, $\mathbf{J_c}^{\mathbf{T}} \in \Re^{\mathbf{pos\times6}}$, $\mathbf{D}^{-1} \in \Re^{\mathbf{pos\times pos}}$, $\dot{\mathbf{q}} \in \Re^{\mathbf{pos\times1}}$ respectively. In the aforementioned explanations, the dimension of all the vectors and matrices is adjusted to make **pos** become six by adding zero elements.

When PIF occurrence is detected on surface covers by FSR sensors and several six-axis force-torque sensors, each PIF position is strictly calculated by utilizing Eq.(2), (3), the detected plates, and elements of force and moment [1]. In addition, each Jacobean at each PIF position is calculated utilizing joint angles and the PIF position. Finally, the reference velocity of each joint for force following, calculated by Eq. (8), is transmitted to each servo system. These processes are conducted in real time. As the result, the robot can realize force following compliantly adapting to human motion, even if any PIF producing various amounts of force from various directions occur on several and any parts of robot's body in any robot's configuration.

4.2 Force Following and Task Fulfillment Control

Representation of Tasks

In order to let robots behave compliantly adapting to human motions without losing the significant tasks to perform as shown in Fig.2 (c) and (d), control methods for both force following and task fulfillment are proposed in the paragraph. Two types of task with a distinct attribute and constraint with each other are focused on in the paper. One of them is the orientation constraint of the hand where the hand posture has to be maintained in any PIF in disregard of large deviation of the hand position as shown in Fig.6 (a). The other is the position constraint condition of the grip where the grip position has to be strictly unmoved at a desirable point by utilizing redundancy in any PIF as shown in Fig.6 (b).



(a) Orientation Constraint (b) Position Constraint

Fig.6. Force-following and task-fulfilling manipulation in each task. This shows the form of each manipulation for realizing both task-fulfillment and high compliance to human is quite different because the attribute of each task is essentially distinct. In the case of the task as in the figure (a), since maintaining the hand orientation in any PIF is saddled on the robot, the role of each joint is independently distinguished only for force following or only for orientation compensation. On the other hand, in the case of the figure (b), since unmoving the grip position by utilizing redundancy in any PIF is saddled on the robot, some joints as shoulders and upper arms have to play two roles as both force following and position-unmoving at the same time

PIF Adaptation According to Attribute of Given Task

Hand Orientation-Constrained Force Following.

First, a motion control method in the case where the hand orientation constraint in the common coordinate system is saddled on a robot as shown in Fig.6 (a) is described. The robot has a seven-DOF redundant arm with a hand, and three joints of the grip are rectangular one another. If PIF occurs on the upper arm of the arm whose hand is holding a cup with contents inside, first, force following is processed based on Eq. (6) to reduce the force applied from human. The hand orientation is changed according to the manipulation by force following. All the joints closer to the arm base from the PIF position are used only for processing force following, whereas rest joints closer to the hand are used only for maintaining a desirable hand orientation. If the desirable hand orientation is a perpendicular to the ground, each joint angle of the grip is decided based on Eq. (9).

$$ {}^{3}\mathbf{R}_{7} = {}^{0}\mathbf{R}_{3}^{-1} \cdot {}^{0}\mathbf{O}_{\text{hand}} \cdot {}^{h}\mathbf{O}_{\text{hand}}^{-1} \ . \tag{9} $$

${}^{h}O_{hand} = {}^{h}(x, y, z)^{T} = (0,1,0)^{T}$ is a direction vector of the hand in the hand coordinate system, ${}^{0}O_{hand} = {}^{0}(x, y, z)^{T} = (0,0,1)^{T}$ in the common coordinate system. If PIF directly occurs on the grip, or extremely large amount of force is applied to the arm, the task will not be fulfilled, as humans would not execute the task under the same situation, either, since the physical influence by acceleration is extremely large.

Grip Position-Constrained Force Following Utilizing Redundancy. Next, a motion control method in the case where a grip position constraint in the shoulder coordinate system is saddled on the robot is described. In the case of orientation constraint mentioned in the previous paragraph, joints used for force following are distinguished from those used for stabling hand orientation. In other words, the role of each joint is independently distinguished only for force following or only for orientation compensation.

In performing the task in which a robot has to completely unmoved the hand position of seven-DOF arm at the desirable point by utilizing the redundancy, the role of each joint is distinct from in cases of orientation constraint. Some joints are needed to play two roles in both force following and grip position maintenance at the same time. Because of the distinction in the intrinsic attribute of each task, a motion control method appropriate for each attribute is needed.

As shown in Fig.6 (b), when positions of grip and shoulder are decided, a plane, which includes the elbow position, perpendicular to the line that links grip with shoulder is calculated. The plane forms a redundant space. In addition, a circle along which the elbow has to follow for unmoving the grip position is calculated and virtually drawn on the plane in the redundant space. Under such a condition, if PIF occurs on upper arm, elbow, or forearm, the arm has to be manipulated to make the elbow move along the circle on the plane. This manipulation enables the robot to precisely maintain the grip position if position control gains have been appropriately decided. In addition to the manipulation, following PIF compliantly to adapt to human force with the elbow moving along the constrained circle is also needed. Then, three joints closer to the arm base from the PIF position have to play two roles in force following as well as grip position maintenance at the same time. This means that the task with position constraint needs more complicated motion control methods than that with orientation constraint. The control method for realizing both force following and maintenance of the grip position is as follows. We introduce a new method expressed as Eq. (10).

$$ \dot{\theta} = \frac{\mathbf{D_0}^{-1}}{\|\mathbf{r}\|}\mathbf{F} \ . \tag{10} $$

$$ \dot{\theta} = \mathbf{D_{eb}}^{-1}\tau \ . \tag{11} $$

Eq. (10) means that robots have to behave to compliantly follow PIF revolving the elbow. Eq. (10) is appropriately converted according to the task attribute based on Eq. (5) in order to realize a desirable mobility $\mathbf{D_0}^{-1}$. $\dot{\boldsymbol{\theta}}$ denotes an angular velocity vector on an axis that links positions of a grip and the shoulder. The axis is called Redundant Axis afterwards in the paper. Thereby, the direction vector of the axis may be changed if the desired position of the grip and the shoulder is renewed according to the given task. $\mathbf{r}$ denotes a radius vector of the circle formed in the redundant space of the elbow. It also changes according to the configuration of the arm and the desirable grip position. These are based on the common coordinate system.

As a hypothesis, Eq. (10) might be rewritten as Eq. (11) for a rule in the rotating coordinate system based on Eq. (5) in the translation coordinate system. $\boldsymbol{\tau}$ denotes a virtual torque vector on the axis, which is calculated by $\mathbf{r}$ and an external force $\mathbf{F}$. $\mathbf{D_{eb}}^{-1}$ denotes a virtual rotating mobility diagonal matrix on Redundant Axis. If PIF occurs on the arm, an angular velocity $\dot{\boldsymbol{\theta}}$ on the axis to compliantly follow human force and motion is calculated by Eq. (10). In addition, since a slight displacement $\dot{\boldsymbol{\theta}}\Delta t$ on the circle in a sampling time Δt is calculated, the next position of the elbow $\mathbf{P_{eb}}^{t+1}$ on the circle in a redundant space is decided utilizing $\dot{\boldsymbol{\theta}}\Delta t$ and the present position of the elbow $\mathbf{P_{eb}}^{t}$. Each joint angle is calculated to realize $\mathbf{P_{eb}}^{t+1}$ by solving the inverse kinematics based on the next elbow position.

The adroit motions revolving the elbow on Redundant Axis are processed to compliantly adapting to the force applied from human as well as strictly unmoving the grip position. This means that the robot can behave to realize a mobility at a PIF position as well as fulfill the task, considering the difference in the attribute of task. In addition to the grip position maintenance, the rest joints closer to the hand from the PIF position can be used for compensating for deviations of the hand orientation at the same time, if necessary.

5 Experiment

5.1 Basic PIF Sensing Characteristics of the Developed Hardware System

In order to verify the basic sensing characteristics of the developed surface covers, two experiments were carried out. They are static measurement of PIF position sensing accuracy and PIF force sensing accuracy of the proposed cover. The data were sampled from a force-torque sensor in the forearm surface cover by an A/D board at a rate of 100 [Hz] for two seconds in each experiment. The manipulator with the cover was kept level with the ground by measuring the posture with a spirit level placed on the plate. Memoryfoam M-38 was removed from the surface to draw checked patterns on each surface of the cover for position measurement as shown in Fig.8.

For experiments, a PIF sensing system and a PIF adapting motion-processing system have been developed as shown in Fig.7. In the PIF sensing system, PIF information such as force information from six force-torque sensors and numbers of on/off information of touch from FSR sensors installed in the covers are sampled at a rate of 1[ms]. In the PIF adapting motion-processing system, joint angles of dual arms, trunk, waist, vehicle, and head are sampled from encoders mounted on each joint.

Since all these information are shared among all the consoles (four personal computers) linked with Dual Port RAM one another, PIF Adapting motions are processed at approximately a rate of 1[ms] based on all the PIF information, the configuration information of the robot and task information.

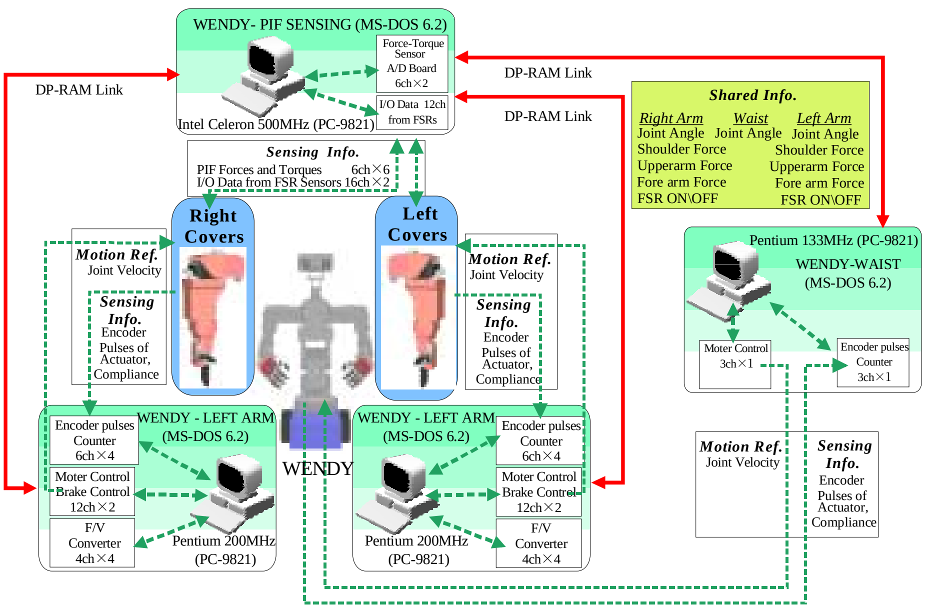


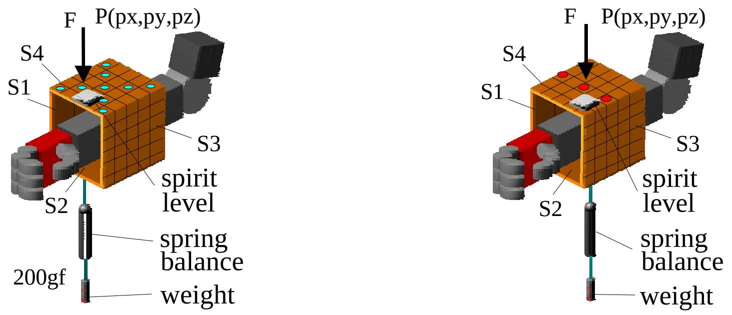
Fig.7. PIF Adapting System and Flow of Several Information. The total system is integrated by a host computer and all the processes are conducted at a rate of 1[ms]

Exp.1: Static measurement of position accuracy

A point weight of 200[gf], measured with a spring balance, was added on several points of the surface cover. This process was conducted on seventeen points (on $z = \pm x$) on the surface of the S4 plate (Fig.3) five times respectively as shown in Fig.8 (a). PIF positions calculated are shown in Fig.9 (a).

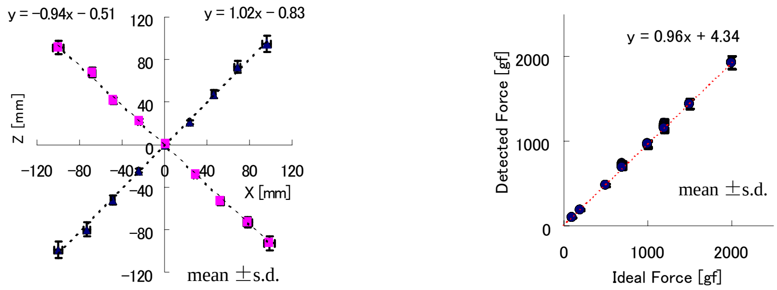
Exp.2: Static measurement of force accuracy

Force loads of 0.1, 0.2, 0.5, 0.7, 1.0, 1.2, 1.5, 2.0 [kgf] were applied on a point (x,z) = (0, 0) of the S4 plate on the surface cover five times respectively as shown in Fig.8(b). The detected forces are shown in Fig.9 (b).



(a) Position Measuring System in Exp.1 (b) Force Measuring System in Exp.2

Fig.8. Experimental Equipments for Position and Force Measurement



(a) Position Measurement Characteristics (b) Force Measurement Characteristics

Fig.9. Experiment Results

Fig.9 (a) shows the average errors in calculation of contact position, depending on the detection accuracy of force, were approximately 5[mm]. Fig.9 (b) shows the average errors in detection of applied force were approximately 4%. From the result of these experiments, it was confirmed that the surface cover having the proposed structure as shown in Fig. (3) has the ability of sensing the state of PIF accurately enough to specify the contact position and applied force information.

5.2 Only Force Following Utilizing Arms and Trunk

In this section, some experiments were carried out in order to evaluate the effectiveness of the proposed control methods for force following mentioned in the section 4.1. In these experiments, only force following utilizing 7-DOF arms and the trunk of WENDY was processed in various PIF from human one-sidedly. There are two ways to adjust motion compliance to PIF by control; one of them is mobility adjustment and the other adjustment of combining joints to move. In the following, first, the effect on force reduction by mobility adjustment of each joint is described. Next, the effect on it by adjustment of combining joints to move is described.

Force Reduction by Mobility Adjustment

The effect on force reduction by adjusting joint mobility is investigated in this paragraph. A simple force is gradually applied on a PIF position on the upper shoulder cover from the front of it. Only a trunk is actuated to follow PIF by utilizing Eq. (6). A device that can produce force increasing at a constant rate was newly developed for experiments. Mobility of the trunk is set five steps of values. Mobility of the joint $\mathbf{D}^{-1}$ is newly expressed as $\mathbf{G}$, and a base mobility is also expressed as $\mathbf{G_0}$ for easily comparing the results of each condition. The rate of force increase is set 5 [N/s].

As shown in Fig.11 (a), in the case of no control, the interactive force is simply increasing. In addition, the larger the mobility is set, the smaller the force peak becomes and the quicker the force reduction begins. However, as shown in the fifth curve, the setting of too large mobility produces oscillation that may cause highly significant inconvenience for realizing high task performance. Thereby, the mobility of each joint should be set as large as possible, as long as no oscillations occur. For example, in this case, the mobility of the trunk should be set $1.5\mathbf{G_0}$ as shown in the fourth curve in order to realize the efficient force reduction without oscillations.

Force Reduction by Combining Moving Joints

The effect on force reduction by combining moving joints is investigated in this paragraph. First, two experiments were carried out, where WENDY behaves to process force following motions in order to reduce interference force applied from one or several human on one/ several and various parts of dual arms at random. As one of the experiments, only an arm was set as the moving joints for force following, and human applied force onto the surface of the forearm cover from the left side and top of the arm. As the result, it was confirmed that the robot can recognize PIF onto the part not the wrist and adapt to follow human motion compliantly as shown in Fig.10 and following motion using only an arm processed based on the Eq. (8) is basically useful for reduction of force applied from human. As the other, nine joints of arms and the trunk of WENDY were set as the moving joints, and several human applied force onto the surface of several parts of WENDY. As the result, it was confirmed that WENDY can behave compliantly adapting to several interference force applied from humans on several parts of the body by combining the dual arms and the trunk based on Eq. (8).

Next, another experiment was carried out for verifying the effect of combining some body parts on force reduction. PIF force is gradually applied by utilizing the same device above on a PIF position on the upper arm cover from the front of it. The right arm and the trunk of WENDY are chosen as moving joints for force following. As shown in Fig.11 (b), it was confirmed that following motion by both the arm and the trunk is more effective for force reduction than that by only the arm. These results mean whole body coordinative manipulations by combining several joints are effective for force reduction and combination of each limb needs to change appropriately according to PIF conditions.

(a) Force Following to PIF from the Left Side of the Forearm

(b) Force Following to PIF from the Top of the Forearm

Fig.10. Force Following utilizing only an Arm

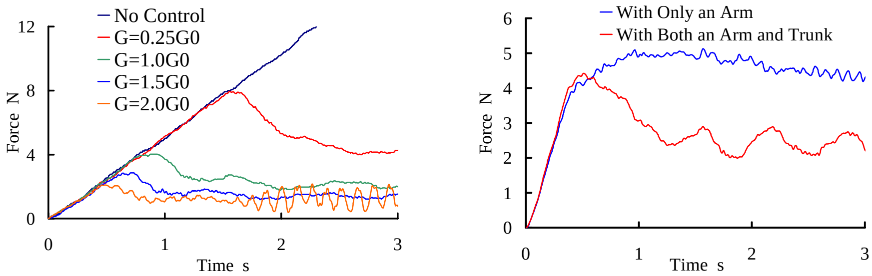


Fig.11. Force Reduction by Adjustment of Mobility or Moving Joints Combination

5.3 Realization of Both Force Following and Task Fulfillment

The aforementioned experiments were carried out for verification of only force following. In this section, the effectiveness of the proposed control methods for realizing both task fulfillment and force following at the same time mentioned in the section 4.2 is evaluated. Two experiments were carried out, where PIF occurs on the upper arm cover of WENDY from human one-sidedly. First, WENDY has to behave to follow PIF without spilling contents out of the cup holding in the hand as shown in

Fig.6 (a) by utilizing Eq. (8) and Eq. (9). The desirable errors on rolling and pitching axes in the hand coordinate system are set zero. Next, WENDY has to behave to both follow PIF with the hand position strictly unmoved as shown in Fig.6 (b) by utilizing the method mentioned in the last of the paragraph 4.2. The desirable error of the grip position is set zero.

Orientation Errors in Force Following

As shown in Fig.12 (a), (b), the arm moves in the direction of which human applies force to and at the speed in proportion to the magnitude of applied force with maintaining the posture of the cup constantly. As shown in Fig.13, the hand posture is maintained constantly. (the orientation of the hand direction vector is maintained vertically to a horizontal plane.) Fig.14 illustrates the absolute magnitude of the detected force and errors of the hand orientation on two axes. Although each joint is changing to compliantly adapt to human motions, the deviations of the hand orientation become almost zero as shown in Fig.14. The maximum of the hand orientation errors is under ±0.017[rad]{±3.0[deg]}, which is the slight error we cannot recognize within our vision. From the result, it was confirmed that the control method utilizing Eq. (8) and Eq. (9) is useful for realizing the task concerning hand orientation stability as well as force following at the same time.

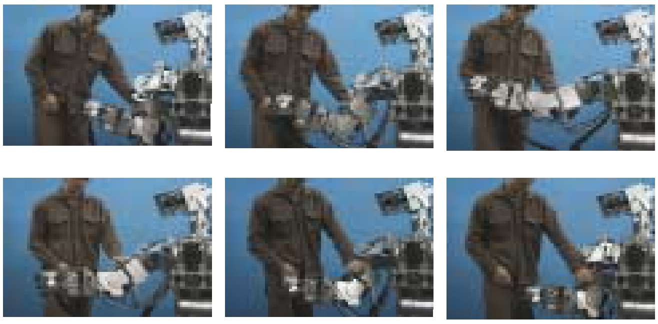


Fig.12. PIF Adapting Motions with Hand Posture maintained

Position Errors in Force Following

In the experiment, WENDY moved its arm to revolve the elbow on Redundant Axis for strictly unmoving the grip position by efficiently utilizing redundancy. Fig.15 illustrates the absolute magnitude of the detected force, absolute errors of the grip position, and changes of joint angles. Although each joint changes to compliantly adapt to human motions, deviations of the grip position become almost zero. The maximum of the grip position error is under 5[mm], which is a slight error, too. From the result, it was confirmed that the control method based on Eq. (10) is useful for strictly unmoving the grip position by utilizing the redundancy as well as force following at the same time.

Fig.13. Close-ups of the Hand. This shows the hand posture is maintained constant

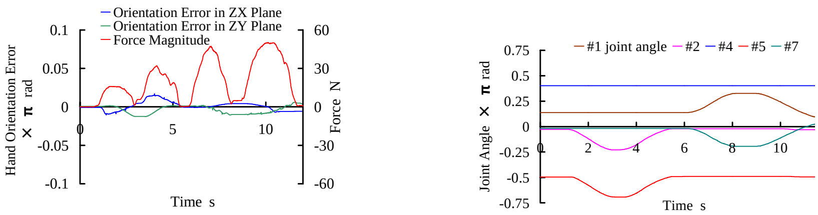


Fig.14. Measured Force and Hand Orientation Errors, Joint Angle Changes under Hand Orientation Constraint. This shows the hand orientation errors are slight in spite of large angle change of each joint

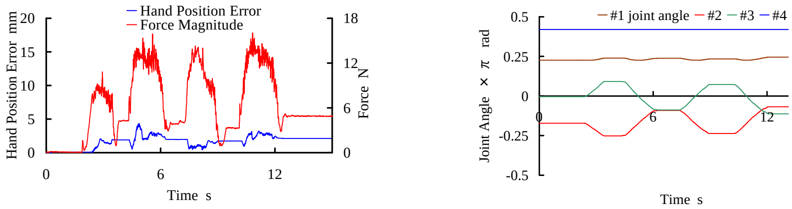


Fig.15. Measured Force and Grip Position Errors, Joint Angle Changes under Grip Position Constraint. This shows the grip position error is slight but large amount of force is applied

6 Conclusion

In the paper, we describe a mechanism design of surface covers for recognizing tactile and force information on the entire body surfaces and control methods for robot compliantly following human motion and fulfilling diversely given tasks in Physical InterFerence (PIF) with human. PIF is a form of physical interaction viewed from the robot side. In cases of PIF occurrence, PIF Adapting Behaviors for attenuating physical influences caused by PIF onto both human body and task performance are required. First, to detect tactile and force information on entire surfaces of robot's body in PIF, we propose whole-arm sensitive covers composed of a force-torque sensor and touch sensors. Next, a base control method for compliantly following human motion by coordinating multiple joints to effectively reduce external force produced on several body surfaces is presented. In addition, control methods for fulfilling given tasks as well as following PIF at the same time are proposed. The methods enable robots to behave to adapt to human motion by utilizing redundancy adroitly for task fulfillment according to the constraint condition and the attribute of given tasks. Finally, from evaluation experiments, it was confirmed that the covers are effective for accurately sensing PIF and by utilizing the tactile and force information detected by the covers, the motion control methods proposed in the paper realize humanoid's capability of compliantly following human motion with fulfilling given tasks by efficiently utilizing the redundancy.

References

1. H.Iwata, H.Hoshino, Y.Adachi, S.Sugano: "Robot Arm Surface Covers for Physical Interference Adapting Motion", In Proc. Of IEEE/ASME AIM'99, pp.671-676, 1999
2. V.J.Lumelsky, E.Cheung: "Real-time collision avoidance in teleoperated whole-sensitive robot arm manipulations," IEEE Trans. Syst., Man, Cysbern., Vol.23, pp.194-203, 1993
3. J.L.Novak, J.T.Feddema: "A capacitance-based proximity sensor for whole arm obstacle avoidance," In Proc. Of IEEE ICRA'92, pp.1307-1314, 1992
4. M.Koga, K.Kosuge, K.Furuta, K.Nosaki: "Coordinated motion control of robot arms based on the virtual internal model," IEEE Trans. Robot. Automat., Vol.8, pp.77-85, 1992
5. M.Inaba, Y.Hoshino, H.Inoue: "A Full-Body Tactile Sensor Suit Using Electrically Conductive Fabric and Strings", IEEE International workshop on IROS'96, pp.450-457, 1996
6. R.Volpe, P.Khosla: "Experimental verification of a strategy for impact control," In Proc. Of IEEE ICRA'91, pp.1854-1860, 1991
7. I.D.Walker: "The use of kinematic redundancy in reducing impact and contact effects in manipulation," In Proc. Of IEEE ICRA'90, pp.434-446, 1990
8. S. Setiawan, S. H.Hyon, J. Yamaguchi, A.Takanishi: "Physical Interaction between Human And a Bipedal Humanoid Robot –Realization of Human-follow Walking-, In CD-ROM Proc. Of IEEE ICRA'99, pp.361-367, 1999
9. H.Lim, K.Tanie: "Collision-Tolerant Control of Human- Friendly Robot With Viscoelastic Trunk", IEEE/ASME Trans. Of Mechatronics, Vol.4, No.4, pp.417-427, 1999
10. H.Iwata, S.Kayaba, T.Morita, S.Sugano: "Design of Humanoid Surface Sensor for Tactile Interference with Human", In Proc. Of IEEE ROMAN'98, pp.549-554, 1998
11. T.Morita, H.Iwata, S.Sugano: "Development of Human Symbiotic Robot: WENDY", In CD-ROM Proc. Of IEEE ICRA'99, 1999
12. H.Hirabayashi, K.Sugimoto, S.Arai, S.Sakaue: "Virtual Compliance Control of Multiple Degree of Freedom Robot", In Proc. Of SICE'85, pp.343-350, 1985 (in Japanese)