2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Whole-body Cooperative Force Control for a Two-Armed and Two-Wheeled Mobile Robot Using Generalized Inverse Dynamics and Idealized Joint Units

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Abstract— **This paper proposes a control framework for a two-armed and two-wheeled mobile robot that can coordinate all the joint forces to achieve diverse motion objectives such as position, velocity, acceleration, force and impedance at any part of the body. The framework comprises two components: 1) Generalized Inverse Dynamics (GID) that determines joint forces satisfying multiple objectives considering task priorities and various constraints and 2) the Idealized Joint Unit (IJU) that generates accurate torque with assigned apparent inertia and viscosity. GID treats the robot as a single manipulator with multiple branches using a joint model with 2-DOF motion subspace equivalent to two opposing wheels. A 21-DOF mobile robot equipped with IJUs is set up and GID is applied to it. The result shows that GID works well in the examples of physical human-robot interaction and object manipulation where motion objectives are attained coordinating the whole body while keeping passivity due to the redundancy and the assigned impedance property.**

I. INTRODUCTION

It is preferable for a human-symbiotic robot to be able to interact with a human and the environment not only at the end of the limbs, such as a hand or a sole, but also at any part of the body to provide services safely around us. Generalized Inverse Dynamics (GID) we proposed in [1] is believed to be an effective way of control for such a service robot because it can determine joint forces to realize various motion objectives considering their priorities and various constraints. For instance, it can control position, velocity, acceleration, force, impedance and angular correspondences in Cartesian space at any point of the body and equivalents of these values in the joint and momentum spaces of the whole body. It can also consider the constraints such as maximum allowed force to accomplish them, unipolar contacts, friction cones and contact polygons. Using the interactive dynamics simulator equipped with two-armed multi-fingered haptic devices, we have verified that GID can enhance the physical interaction abilities of a virtual humanoid.

In [2], we proposed the Idealized Joint Unit (IJU) that can make accurate response to the required torque and external torque according to the specified virtual impedance properties (inertia and viscosity). IJU enabled us to apply GID to real robots by eliminating errors in the joint model caused by unknown friction and inertial properties. The effectiveness of coupling GID and IJU was verified by applying them to the control problem of keeping balance of a simple 4-DOF manipulator on moving terrain.

In this paper, we propose the whole-body cooperative force control method using GID and IJU for the integrated mobile robot platform with two arms and wheels. On most of the conventional wheeled mobile robots, the dynamics of the mobile base and the upper body have been separately treated. In this research, the opposing two wheels are modeled as their equivalent 2-DOF joint, which enables GID to control the whole body as a single manipulator considering the non-holonomic constraints. IJUs are used in major joints to reduce errors in generated force and acceleration. The proposed method realizes the compliant whole-body motions such as force-based interactions, grasping and manipulation coordinating the mobile base and the upper body.

In Section II, related works are surveyed. In Section III, a summary of GID, the equivalent joint model to two-wheeled mobile base, and the optimal grasping/manipulation force determination method using GID is provided. In Section IV, the principle and the control algorithm of IJU are described. Section V explains the hardware construction of IJU and the two-armed and two-wheeled robot equipped with it. In Section VI, the experimental results are presented.

II. RELATED WORKS

A number of researches have dealt with robots with arms and a mobile base from different points of view. Iwata[3] and Mukai[4] focused on the physical interaction with a human. Inamura[6], Yamazaki[5], Wyrobek[7] and Nguyen[8] reported prototypes of daily assistive robots. However, physical interaction on any part of the body or dynamic cooperative control of the mobile base and the upper body have been rarely considered. Khatib[9] proposed a dynamic control model for incorporating a mobile base and a single manipulator, where object manipulation incorporating multiple omni-wheeled mobile manipulators with 6-DOF was realized based on the concept of augmented object model and virtual linkage. Kosuge[10] realized handling an object by a two-armed mobile manipulator in cooperation with a human by controlling the apparent impedances of arms and the mobile base so that they are connected sequentially.

Manuscript received September 15, 2009. This work was supported by Sony Corporation.

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However, in either case, the action points for interation and manipulation were restricted to the specific parts because 6-DOF force/moment sensors were used to detect external force/moment. Borst[11] realized precise impedance control in Cartesian space and coordination of the mobile base and the upper body on the humanoid robot with torque sensors in the joints, but they did not mention generalization such as task control in various motion spaces or task priority control.

In the literature of biped humanoid robots, generalized control framework based on operational space formulation was proposed by Sentis[12], but it has been verified only in dynamics simulation. Hyon [13] has worked on whole-body cooperative force control of a hydraulic biped humanoid robot, but the discussion was mainly focused on the problem of maintaining balance.

Compared with prior research, this paper provides 1) a generalized framework of the whole-body cooperative force control for a two-armed and two-wheeled mobile robot, and 2) hardware configuration to realize it on a real robot, which enables to give various motion objectives such as position, velocity, acceleration, force, impedance and angular correspondences in Cartesian space at any point of the body and equivalents of these values in the joint and momentum spaces while considering their priorities and various constraints.

The key feature of the hardware configuration we propose is a joint unit equipped with a built-in torque sensor. Wu[14] and Pfeffer [15] controlled joint torque using torque sensors. Albu-Shäffer[16] achieved passivity based impedance control in Cartesian space considering the elastic deformation of a flexure. In contrast to these researches, this paper provides the actuator unit that can accelerate precisely in response to the target torque and the external torque measured by the torque sensor according to the specified virtual impedance properties (inertia and viscosity).

III. WHOLE-BODY COOPERATIVE FORCE CONTROL BY GID

A. Generalized Inverse Dynamics

GID is a basis of the whole-body cooperative force control that determines joint forces for simultaneously realizing multiple motion objectives such as acceleration, force, velocity, position at any portion of the robot, and the total momentum. It can also consider task priorities and inequality constraints such as maximum force, uni-polar contacts, friction cones and support polygons. GID consists of two phases: 1) virtual force determination to achieve motion objectives and 2) its transformation into real forces such as joint/contact forces.

1) Virtual Force Determination: An operational space[17] $\boldsymbol{x}$ is defined by the equation $\dot{\boldsymbol{x}} = \boldsymbol{J}\dot{\boldsymbol{q}}$ using a joint value $\boldsymbol{q}$ and a Jacobian $\boldsymbol{J}$. A motion equation about an operational space is generally expressed as

$$\ddot{\boldsymbol{x}} = \boldsymbol{\Lambda}^{-1}\boldsymbol{f} + \boldsymbol{c} \ , \tag{1}$$

where $\boldsymbol{\Lambda}^{-1} = \boldsymbol{J}\boldsymbol{H}^{-1}\boldsymbol{J}^T$ and $\boldsymbol{c} = \boldsymbol{J}\boldsymbol{H}^{-1}(\boldsymbol{\tau} - \boldsymbol{b}) + \dot{\boldsymbol{J}}\dot{\boldsymbol{q}}$ are inverse inertia and bias acceleration in the operational space respectively. $\boldsymbol{H}$ is an inertia matrix in a joint space. $\boldsymbol{\tau}$ is a joint force, and $\boldsymbol{b}$ is a nonlinear force including gravity, coriolis and centrifugal forces. $\boldsymbol{f}$ is a force applied to the operational space.

Motion objectives about position, velocity, acceleration and impedance in the operational space $\boldsymbol{x}$ can be transformed into the target operational acceleration $\ddot{\boldsymbol{x}}$. According to (1), the virtual force $\boldsymbol{f_v}$ that should be applied in the operational space $\boldsymbol{x}$ to achieve the operational acceleration $\ddot{\boldsymbol{x}}$ can be determined by solving the following LCP (Linear Complementary Problem).

$$\begin{aligned} &\boldsymbol{w} + \ddot{\boldsymbol{x}} = \boldsymbol{\Lambda}^{-1}\boldsymbol{f_v} + \boldsymbol{c} \\ &\text{s.t.} \begin{cases} ((w_i < 0) \wedge (f_{v_i} = U_i)) \vee \\ ((w_i > 0) \wedge (f_{v_i} = L_i)) \vee \\ ((w_i = 0) \wedge (L_i < f_{v_i} < U_i)) \ , \end{cases} \end{aligned} \tag{2}$$

where $\boldsymbol{w}$ is a slack variable. L_i and U_i are the negative lower and the positive upper boundary of f_{v_i} that can be $-\infty$ and ∞, respectively. For example, the condition to attain the target acceleration $\bar{\ddot{x}}_i$ within the absolute value F_i of operational force f_{v_i} can be expressed as

$$L_i = -F_i, \ U_i = F_i, \ \ddot{x}_i = \bar{\ddot{x}}_i \ . \tag{3}$$

The target impedance can be simply expressed by setting the target acceleration as

$$\ddot{x}_i = K_p(\bar{x}_i - x_i) - K_v\dot{x}_i \ . \tag{4}$$

To apply an operational force/moment as a motion objective, you have only to add it to virtual forces $\boldsymbol{f_v}$ obtained by solving the LCP.

We should be able to specify a task priority in case that some motion objectives conflict with each other. In our method, LCP (2) is solved for every priority, where virtual forces for lower priorities are determined in the former LCP and they are exerted as known external forces in the latter LCP for the higher priorities. Especially, we can compensate the gravity effect by applying the joint force obtained by Newton/Euler method to realize $\ddot{\boldsymbol{q}} = \boldsymbol{0}$ in the lowest priority.

2) Real Force Transformation: In the second phase of GID, virtual forces $\boldsymbol{f_v}$ determined in the previous section are transformed into real forces such as joint torques and contact forces. The condition to realize virtual forces $\boldsymbol{\tau_v} = \boldsymbol{J_v^T}\boldsymbol{f_v}$ by external forces $\boldsymbol{f_e}$ and joint forces $\boldsymbol{\tau_a}$ in actuated joints allowing a minimum adjustment $\boldsymbol{\Delta f_v}$ on $\boldsymbol{f_v}$ is described as (5) with two rows about an actuated joint set (index a) and an unactuated joint set (index u).

$$\begin{bmatrix} \boldsymbol{J_{vu}^T} \\ \boldsymbol{J_{va}^T} \end{bmatrix} (\boldsymbol{f_v} - \boldsymbol{\Delta f_v}) = \begin{bmatrix} \boldsymbol{J_{eu}^T} \\ \boldsymbol{J_{ea}^T} \end{bmatrix} \boldsymbol{f_e} + \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau_a} \end{bmatrix} \ , \tag{5}$$

where $\boldsymbol{J_{vu}}$ and $\boldsymbol{J_{va}}$ are unactuated and actuated components of the Jacobian concerning the operational space $\boldsymbol{f_v}$ acts on, respectively. $\boldsymbol{J_{eu}}$ and $\boldsymbol{J_{ea}}$ are unactuated and actuated components of the Jacobian concerning the operational space $\boldsymbol{f_e}$ acts on, respectively. As (5) is indeterminate, $\boldsymbol{f_e}$ and $\boldsymbol{\Delta f_v}$ are determined by the following QP (Quadratic Programming).

$$\begin{aligned} \min \quad & \tfrac{1}{2}\boldsymbol{\varepsilon}^T\boldsymbol{Q_1}\boldsymbol{\varepsilon} + \tfrac{1}{2}\boldsymbol{\xi}^T\boldsymbol{Q_2}\boldsymbol{\xi} \\ \text{s.t.} \quad & \boldsymbol{U}\boldsymbol{\xi} \geq \boldsymbol{v} \ , \end{aligned} \tag{6}$$

where ε is the difference between the sides of the upper row of (5), which gives the error of the equality of (5). $\boldsymbol{\xi}$ is the augmented vector of $\boldsymbol{f_e}$ and $\boldsymbol{\Delta f_v}$. $\boldsymbol{Q_1}$ and $\boldsymbol{Q_2}$ are positive semidefinite matrices that define criteria of minimizing these variables. Inequalities in (6) are used to impose constraints on friction cones, uni-polar contacts, the maxima of the real forces and support polygons, such as (10) shown later. The solution of (6) can give $\boldsymbol{\Delta f_v}$ and $\boldsymbol{f_e}$, satisfying (5) with a minimum norm. We can get the active joint forces $\boldsymbol{\tau_a}$ to realize objective motions by substituting $\boldsymbol{\Delta f_v}$ and $\boldsymbol{f_e}$ obtained above into the lower row of (5).

In a fully actuated system, all virtual forces are realized by joint forces. In such a case, we can simply get $\boldsymbol{\tau_a}$ by the following equation derived from (5) by substituting $\boldsymbol{\Delta f_v = 0}$ and $\boldsymbol{f_e = 0}$,

$$\boldsymbol{\tau_a} = \boldsymbol{J_{va}^T f_v}. \tag{7}$$

B. Wheel Equivalent Joint Model

In this research, the two-armed and two-wheeled robot is controlled by GID using the integrated dynamics model of the mobile base and the upper body, where the robot is modeled as a single manipulator with multiple branches. A mobile base with two wheels can move forward and rotate around the vertical axis with respect to the local coordinate system attached to itself. Therefore, the degrees of freedom that the mobile base has are equivalent to those of a 2-DOF joint with the following motion sub-space[19].

$$\hat{\boldsymbol{S}}_{\boldsymbol{0}} = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}^T, \tag{8}$$

where 6 rows of $\hat{\boldsymbol{S}}_{\boldsymbol{0}}$ correspond to rotational(x,y,z), and translational(x,y,z) respectively.

To control the robot by GID according to the above model, 1) we need to reflect the state of the wheels to that of the wheel equivalent 2-DOF joint, and 2) the target joint force for the 2-DOF joint must be transformed into that for the wheels. For the former, we just reflect the results of odometry to the position and the velocity of the wheel equivalent joint. Regarding the latter transformation, we can use the following equilibrium condition between the joint force of the equivalent joint (f_x, m_z), and wheel torque (τ_L, τ_R),

$$\begin{pmatrix} \tau_L \\ \tau_R \end{pmatrix} = \frac{R}{2W} \begin{pmatrix} W & -1 \\ W & 1 \end{pmatrix} \begin{pmatrix} f_x \\ m_z \end{pmatrix}. \tag{9}$$

Here, W is the half distance between the wheels, and R is the radius of the wheel.

C. Grasping Force Determination

GID can also determine the optimal grasping/manipulation force if the inertial properties of the grasped object are given. Although we proposed to attain the optimal grasping force by determining the internal force between the robot and the object using a single GID[1], this paper proposes another way that can reduce the computational cost by using the small-scale GID for the object that is independent from the GID for the robot.

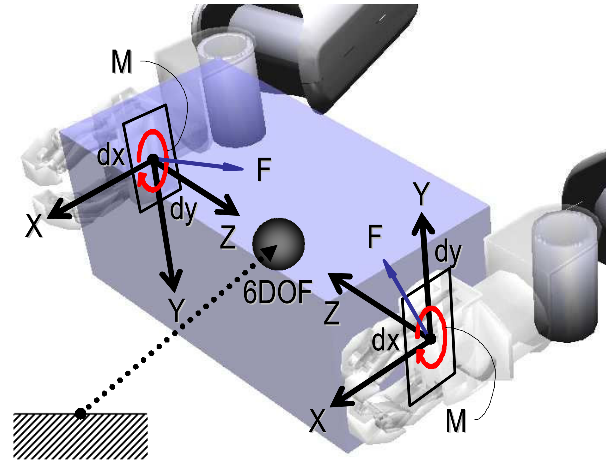

Fig. 1. Definitions for grasping force determination by GID

The grasped object can be regarded as a kind of robot that has only a 6-DOF unactuated joint with translational 3-DOF and spherical 3-DOF as shown in Fig.1. We can assign motion objectives regarding manipulation to the object and define the unknown external forces at the action points of grasping in the same way as a robot. Therefore the grasping forces can be obtained as the external force determined by QP (6), where the following inequality constraints expressing the support polygon at each action point are taken into consideration.

$$\begin{aligned} &|F_x| \le \mu_t F_z, \quad |F_y| \le \mu_t F_z, \quad F_z \ge 0, \\ &|M_x| \le d_y F_z, \quad |M_y| \le d_x F_z, \quad |M_z| \le \mu_r F_z \ , \end{aligned} \tag{10}$$

where z is the normal direction, x and y are tangential direction orthogonal to it, (F_x, F_y, F_z) and (M_x, M_y, M_z) are the force and moment acting on the contact point, μ_t and μ_r are the translational and rotational coefficients of friction, and (d_x, d_y) represents the rectangular size approximating the support polygon.

IV. PRINCIPLE OF IDEALIZED JOINT UNIT

In GID described in the previous section, dynamics of each joint is modeled as the following second order system.

$$I_a \ddot{q} = \tau_a + \tau_e - \nu_a \dot{q}, \tag{11}$$

where, in the case of a revolving joint, I_a is its inertia, q is its angle, τ_a is the torque it generates, τ_e is the external torque applied to it, and ν_a is the coefficient of viscosity. However, most of the actuators do not make response according to the theoretical model due to unknown friction and inertia in them. That is, the inconsistency in the impedance properties (inertia and viscosity) between the real joints and the theoretical model causes the response errors. Without any care, the motion objective would not be achieved even if the joint forces obtained by GID are applied to them. In this research, the response of the actuator is corrected so that it can make the ideal response according to the theoretical dynamics in (11) by adding an active controller. The external torque τ_e

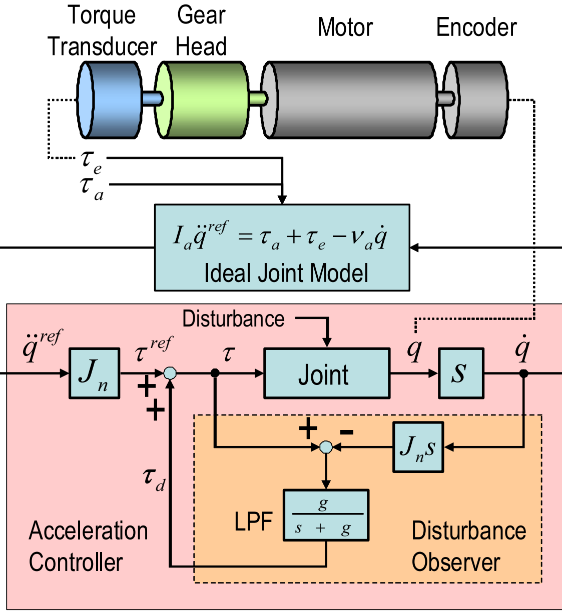

Fig. 2. Control scheme of Idealized Joint Unit

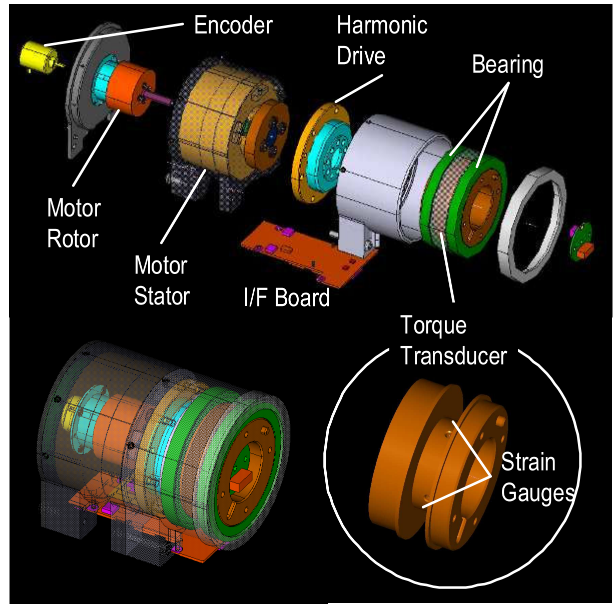

Fig. 3. Mechanical structure of Idealized Joint Unit

must be measured to correct the response since (11) contains it. Therefore the torque transducer is mounted outside the reduction gear as shown in Fig.2.

Achieving the ideal response according to (11) means that the joint acceleration $\ddot{q}$ in the left side of the equation is achieved when its right side is given. In this research, the disturbance observer[18] is applied to realize such an acceleration controller. The disturbance observer estimates the disturbance torque τ_d caused by unknown friction and inertia in the joint using input torque τ and observed joint acceleration $\ddot{q}$ passed through the low-pass filter to make the system stable as shown in the dashed line in Fig.2. The disturbance torque τ_d is added to the target torque τ^{ref} that is a product of the target acceleration $\ddot{q}^{ref}$ and nominal inertia J_n, which enables the actuator to accelerate in accordance with the target acceleration even though disturbances such as internal friction exist.

Finally, the joint acceleration $\ddot{q}$ determined by τ_a, τ_e, I_a, ν_a and $\dot{q}$ in (11) is used as the reference acceleration $\ddot{q}^{ref}$ of the above acceleration controller, which enables the joint to accelerate precisely according to the virtual impedance properties (I_a and ν_a) that GID assumes.

V. EXPERIMENTAL SETUP

A. Idealized Joint Unit

To set up the experimental two-armed and two-wheeled mobile robot, a few kinds of IJUs with different powers were developed. The mechanical structure of the typical model is shown in Fig.3.

IJU consists of an encoder, a motor, a reduction gear and a torque transducer, and they are sequentially connected. A Harmonic Drive gear, a frame-less BLDC motor, and an incremental encoder are used as a reduction gear, a motor and an encoder, respectively.

The torque transducer has a torsion structure whose ends are both supported by the housing via bearings. Four strain gauges are mounted on the torsion cylinder so that the effects of thermal and cross-axis sensitivity are reduced using Wheatstone bridge. Strain amplifiers are mounted on the circuit board under the IJU.

B. Two-armed and Two-wheeled Mobile Robot

An experimental two-armed and two-wheeled robot was developed using IJUs described in the previous section. Fig.4 shows its external appearance. It has 21 DOF in total, and its height is 67 [cm]. Each arm has 7 DOF in total with 3 DOF (pitch/roll/yaw) joints in the shoulder, 2 DOF (pitch/yaw) joints in the elbow and 2 DOF (roll/pitch) joints in the wrist. A 1 DOF gripper is connected to the end of each arm. The payload per one arm is 5[N]. The neck has 2 DOF (yaw/pitch) joints. The waist has a 1 DOF (pitch) joint. The mobile base has 2 DOF (pitch) joints in the wheels. IJUs are used in major joints except the gripper, the waist and the wheel joints. Reduction gears with small reduction ratio are used in the wheel joints to reduce friction.

Control boards, each controlling two set of motor driver and IJU which are operating every $250[\mu s]$, are distributed over the body. They are wired in a daisy chain fashion via real-time LAN to the main controller mounted on the base where computation for GID is carried out with a control cycle of 1 [ms]. A PC powered by Intel Core 2 Duo processor (2.66GHz) and operated by a real-time OS (Linux+RTAI) is used as a main controller. Although a 6-axis force/moment sensor is mounted in the wrist, it is not used for control but just for evaluation. Stereo vision system and an omnidirectional camera are mounted on the head for future use, and they are wired to another computer for cognitive processing on the base. The robot is also equipped

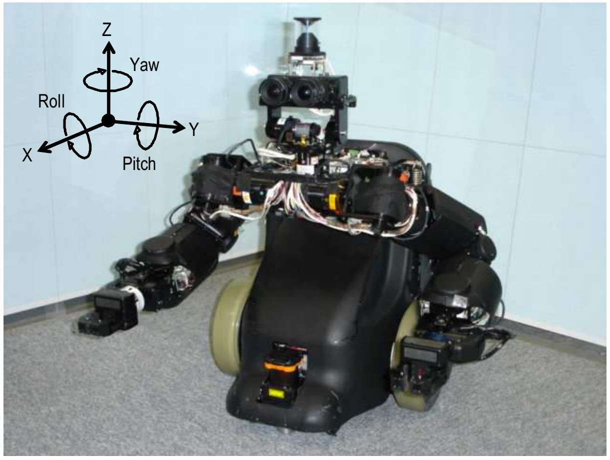

Fig. 4. Appearance of experimental two-armed and two-wheeled robot

with a wireless LAN and a lithium ion battery on the base so that it can operate stand-alone.

The inertial properties of those parts are calculated in CAD, and they are used as those for GID.

VI. EXPERIMENTAL RESULTS

Short videos regarding the following experiments are provided. They are helpful in understanding the results.

A. Evaluation of IJU

Before applying GID to the robot, the IJU mentioned in Section IV was evaluated. Fig.5(a) shows the comparison between the numerical solution of the differential equation (11) and the angle response of the developed IJU under the condition of $I_a = 0.015[kg \cdot m^2]$, $\nu_a = 0.1[Nm \cdot s]$, $\tau_a = 1[Nm]$ and $\tau_e = 0[Nm]$. The cutoff frequency of the LPF in the disturbance observer is set as $g = 630[rad/s]$. Both are almost identical within the limitation of the velocity of the motor, which confirms IJU can make theoretically correct response. Fig.5(b) shows the torque step response measured by the torque sensor when the target torque is changed from $0.1[Nm]$ to $0.2[Nm]$ with IJU stalled. The response whose time constant and settling time are $10[ms]$ and $50[ms]$ respectively is achieved without steady-state error, which means that the IJU is a favorable torque controlled joint.

B. Whole-body cooperative physical interaction

Secondly, we verified if the whole-body cooperative force control by GID enables the robot to have flexible physical interaction with a human. In the experiment, the position and the posture of the head and the hands in the global Cartesian space are softly fixed by impedance control, and external force is applied on various part of the body by a human. At the same time, the gravity compensation and the weak position control in the joint space are executed as the lower priority tasks so that the redundancy converges in the neutral posture. Hereupon, we see if both of the passivity caused by the redundancy and the above-mentioned compliant motion objective are attained.

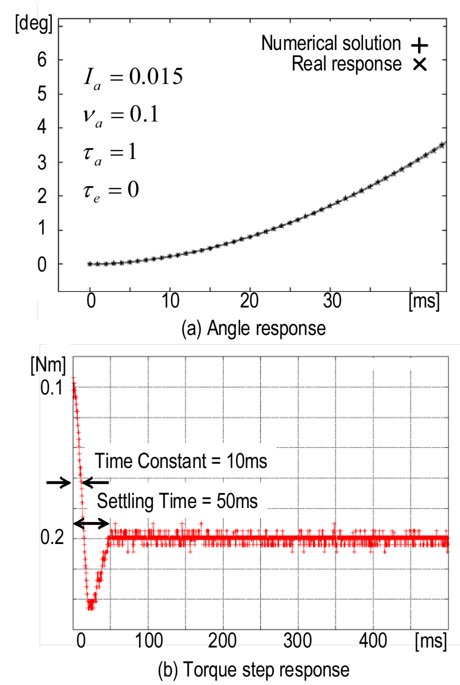

Fig. 5. Angle/torque responses of IJU

As shown in Fig.6, when the mobile base was pushed and rotated by a human, it behaved passively while softly keeping the position and the posture of the hands and the posture of the head. On the other hand, when the hands were pulled, the hands and the base were passively moved while maintaining the position and the posture of the head softly. This shows that compliant physical interaction on any part of the body while maintaining the task softly was realized.

C. Whole-body cooperative grasping/manipulation

Finally, we verified the effectiveness of the whole-body cooperative force control in grasping/manipulation task. After approaching from some distance and grasping the object (a box weighing 300[g]) with both hands, the robot is commanded to keep it at the specified global position with weak impedance control. In approaching, only the trajectories of both hands are specified without specifying the base motion. Grasping force/moment is determined by the method mentioned in Section III-C. Grasping is achieved by generating the force/moment on the hand link while controlling the impedance of the hand to match that of the object. Hereupon, we see if the robot can grasp the distance object incorporating the mobile base and verify if it can keep the position of the object compliantly while holding it even if external forces are applied on various parts of the body and the object.

As shown in Fig.7, in the reaching phase, the base moved automatically, without specifying its motion, to grasp the object. After the robot held up the object to the specified position, its base was pushed and twisted several times by a human. Meanwhile the position and the posture of the object and both hands were softly maintained. Lastly the

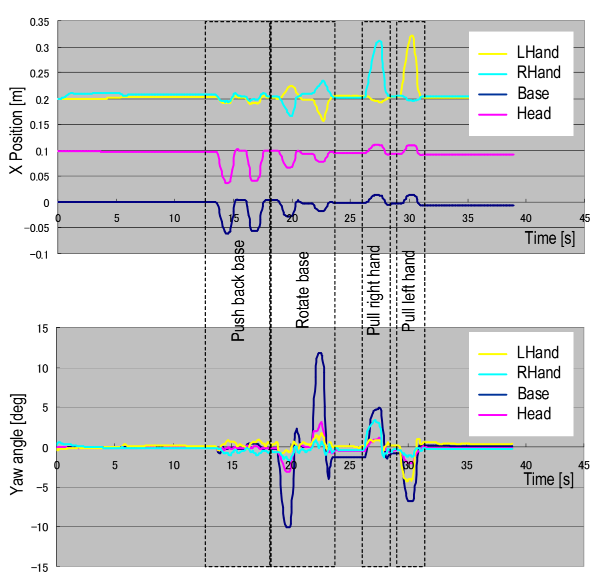

Fig. 6. Results of whole-body cooperative physical interaction

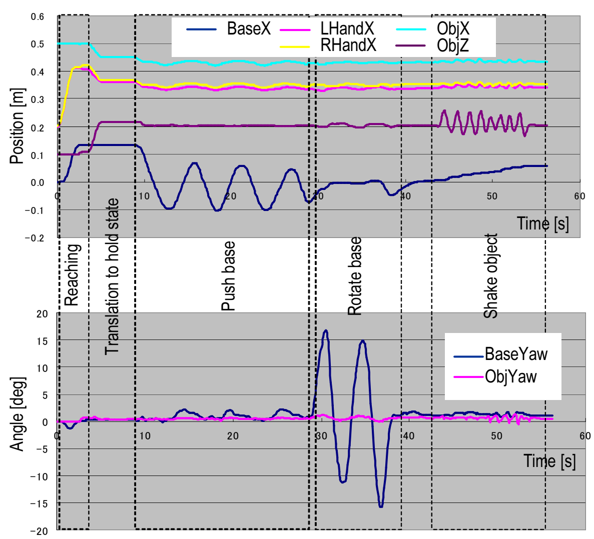

Fig. 7. Results of whole-body cooperative grasping/manipulation

object was moved vertically by a human, but the robot could hold the object passively and make it return to the target position gradually afterward. Here the position of the object is estimated as the middle of both hands'. Thereby we can say that the whole-body cooperative force control by GID is effective in flexible and human-safe grasping/manipulation as well.

VII. CONCLUSIONS AND FUTURE WORK

This paper proposed a methodology to realize whole-body cooperative force control on a two-armed and two-wheeled mobile robot using GID that can transform diverse motion objectives into the target joint forces. It was pointed out that modeling errors in the joint dynamics cause problems in applying GID to the robot, and the principle and the design of IJU that can force the joint to accelerate accurately according to the theoretical model considering the target/external torque in spite of the unknown friction/inertia in the joint were explained. Whole-body cooperative physical interaction with a human and object manipulation were realized on an experimental two-armed and two-wheeled robot with IJUs. The experiments show that the proposed control framework works effectively on a real two-armed and two-wheeled mobile robot.

Although parameter uncertainties and unmodeled dynamical parameters did not cause the significant errors in the above experiments, the proposed controller could be influenced by them. The improvement on wiring and the combination with adaptive control will be effective to reduce these errors and to achieve better performance. The torque transducer taking account of the detailed factors such as thermal effect, cross-axis sensitivity and hysteresis can also enhance the performance. These more practical issues will be discussed in another paper.

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