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Motion Control of Passive Robot Porter with Variable Motion Characteristics for Handling a Single Object

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Abstract— **In this paper, we introduce omni-directional object handling robot system developed based on passive robotics and propose its motion control algorithm for realizing variable motion characteristics of the handling object. Passive object handling robot called PRP (Passive Robot Porter) is controlled by servo brakes attached to the wheels of the robot. By designing the control algorithms of the servo brakes appropriately, the PRP has many functions such as navigation function and collision avoidance. In this paper, we especially focus on a motion control of the PRP for realizing variable motion characteristics of the handling object. If we can change the motion characteristics of it arbitrarily based on the servo brake control of the PRP, the maneuverability of the human operator would be improved. In this paper, we design the motion control algorithm and implement it to the PRP experimentally. Experimental results of the object handling illustrate the validity of the proposed method.**

Index Terms— **Passive Mobile Robot, Object Handling, Variable Motion Characteristics of Object, Servo Brake Control**

I. INTRODUCTION

For practical use of intelligent robot systems for supporting humans in the real world, we need to consider two main points: achieving high performance and user safety. Most conventional intelligent robot systems have servo motors that are controlled based on sensory information from sensors such as force/torque and ultrasonic sensors. The high performance of intelligent robot systems is realized in the form of functions such as power assistance, collision avoidance, navigation, and variable motion.

However, if we cannot appropriately control the servo motors, they can move unintentionally and might be dangerous for a human being. In particular, in Japan, legislation must be formulated for using them in a living environment. In addition, these intelligent robot systems tend to be heavy and complex because they require servo motors, reduction gears, sensors, a controller, and rechargeable batteries. Batteries present a significant problem for long-term use because servo motors require a lot of electricity.

From the safety point of view of the intelligent robot systems, passive robot systems have been proposed, which do not have servo motors for driving them and are moved based on the external force/moment applied. Initially, Goswami et al. proposed the concept of passive robotics [1], in which a system moves passively based on external force/moment without the use of actuators, and used a passive wrist comprising springs, hydraulic cylinders, and dampers. The passive wrist responds to an applied force by computing a particular motion and changing the physical parameters of the components to realize the desired motion.

Peshkin et al. also developed an object handling system referred to as Cobot [2] consisting of a caster and a servo motor for steering the caster based on passive robotics. Wasson et al. [3] and Rentschler et al. [4] proposed passive intelligent walkers for supporting the locomotion function of the elderly. In most of these walkers, a servo motor is attached to the steering wheel, similar to the Cobot system, and the steering angle is controlled depending on environmental information. These passive systems are intrinsically safe because they cannot move unintentionally.

We also developed a passive intelligent walker called RT Walker (Robot Technology Walker) [5] and an object handling system called PRP (Passive Robot Porter) [6]. The RT Walker and The PRP have passive dynamics with respect to the force/moment applied. They differ from other passive intelligent robot systems in that they control servo brakes appropriately without using any servo motors. By controlling the servo brakes attached to the wheels of the robot systems, we could realize not only the navigation function realized in the conventional passive robot but also other functions such as variable motion characteristics and gravity compensation function.

In this paper, we especially focus on the motion control of the omni-directional type passive mobile robot called PRP and its motion control algorithm for realizing the variable motion characteristics of the handling object. If we can change the motion characteristics of the handling object arbitrarily based on the servo brake control of the PRP, the maneuverability of the human operator would be improved. In the following part of this paper, first, we introduce the passive object handling system and propose its motion control algorithm that allows the robot to change the motion characteristics of the object. Finally, we implement it to the PRP and evaluate its validity through several experiments.

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II. PASSIVE OBJECT HANDLING ROBOT SYSTEM

A. *Hardware of PRP*

We have developed passive robot porter called PRP as shown in Fig.1 based on the concept of the passive robotics [6]. The PRP consists of three omni-directional wheels with servo brakes, some sensors such as force/torque sensor and encoder, a controller, and batteries. The omni-directional wheel consists of several small rollers so that the wheel can move in all directions.

Each omni-directional wheel is directly connected to a servo-brake, and the three wheels are equally spaced with axes set spaced apart by $2\pi/3$ radians. Three encoders are also installed on three wheels for odometry. The brake systems of the whole wheels are powered by batteries. The force/torque sensor is utilized for measuring the force/moment applied by the human to evaluate the performance of the robot. It should be noted that the force/torque sensor is not utilized for controlling the brake system directly, because the passive-type system moves based on the actual force/moment applied by the human without using the servo motors.

The control performance of the PRP depends on the characteristics of servo brakes. In the first prototype of the PRP, we used MR Brake (Magneto-Rheological fluid Brake: Load Corp., MRB-2107-3, Maximum on-state Torque: 5.6[Nm]) as the passive actuator. Braking torque of MR Brake is generated by chain mechanisms of iron powder from free flow state which are reacting to the applied magnetic field. This provides high responsibility and good linearity on controlling the braking torque of wheels. In addition, it consumes relatively small amount of power comparing with servo motors, and its weight is similar to a motor-gear component with the same output torque.

In addition to the previous version of the PRP [6], we attach a free joint and carry an object through it as shown in Fig.2. By using the free joint, the human operator could change the orientation of the object easily by applying the intentional moment to it. In this case, the PRP controls only the position of the object without considering its orientation. This means that the brake toques of wheels are only used for controlling the position of the object and the required force applied by the human operator for transporting the object could be reduced. This characteristics is explained in [7].

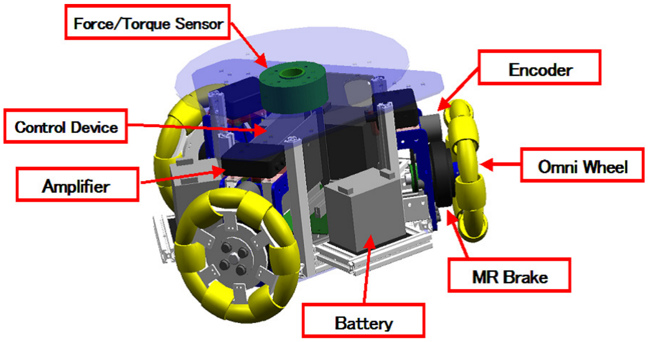


Fig. 1. Components of Omni-directional Passive Mobile Robot Called PRP

B. *Control of Servo Brake*

In this section, we explain the relationships among brake torque, angular velocity, and applied torque of the wheels with servo brakes. The PRP moves based on only the external force/moment applied to it, because it does not have any actuators such as servo motors. To control the motion of the PRP based on the external force f_{ew} applied to the wheel with a servo brake, we can derive the following relationships with respect to the angular velocity of the wheel with servo brakes ω_w:

for $\omega_w \neq 0$

$$t_{bw} = -k_b I_b \mathrm{sgn}(\omega_w) \tag{1}$$

for $\omega_w = 0$

$$t_{bw} = \begin{cases} -f_{ew} R_w & |f_{ew}| R_w \leq k_b I_b \\ -k_b I_b \mathrm{sgn}(f_{ew}) & |f_{ew}| R_w > k_b I_b \end{cases} \tag{2}$$

where t_{bw} is the brake torque generated by the servo brake, R_w is the radius of the wheel, I_b is the input current for the servo brakes, and k_b is the positive coefficient expressing the relationship between the brake torque and the input current. Unlike servo motor control, we can control the motion of the PRP by considering only these relationships.

It is obvious that the characteristics of the brake system of wheel are complicated compared to a motor-wheel system. The characteristics of brake system depend on the wheel rotational direction. The sign of output torque of the wheel is decided by the direction of the wheel rotation and magnitude of the torque is proportional to the input current of the brake. From Eq.(1), we have the following condition between the angular velocity of the wheel and the braking torque of a brake-wheel system.

$$t_{bw}\omega_w \leq 0 \tag{3}$$

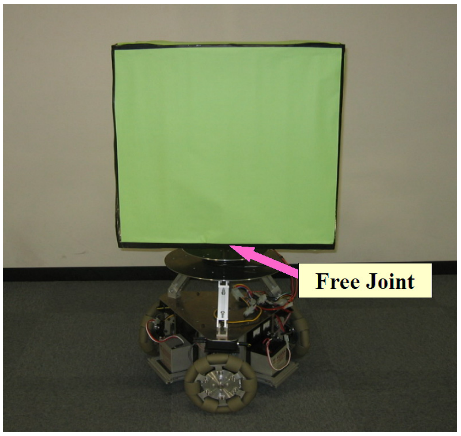


Fig. 2. Handling an Object by PRP with Free Joint

This condition is the servo brake control constraint of the system and indicates that one cannot have arbitrary torque from a servo brake. Therefore we need to consider the feasible brake torque t_{bw} during motion control of a robot. Noted that we do not consider the case that a wheel does not rotate during the transportation expressed in Eq.(2), because this case is the very short period.

III. MOTION CONTROL OF PRP FOR REALIZING VARIABLE MOTION CHARACTERISTICS OF AN OBJECT

A. Fundamental Motion Control Algorithm

If we can change the motion characteristics of the handling object arbitrarily based on the servo brake control of the PRP, the maneuverability of the human operator would be improved. In this section, we discuss a motion control algorithm of the PRP for realizing the variable dynamics of the handling object.

For controlling the PRP, firstly, we define the coordinate systems as shown in Fig.3. ${}^G\Sigma$ is the global coordinate system, ${}^r\Sigma$ is the robot coordinate system attached to the PRP, and ${}^{ob}\Sigma$ is the object coordinate system attached to the handling object. We express a position and an orientation of the PRP with respect to the ${}^{ob}\Sigma$ as ${}^{ob}\boldsymbol{q} = \left[{}^{ob}x_r \; {}^{ob}y_r \; {}^{ob}\theta_r\right]^T$. The force/moment applied to the robot through the object by a human operator are ${}^{ob}\boldsymbol{F}_h = \left[{}^{ob}f_{h_x} \; {}^{ob}f_{h_y} \; {}^{ob}n_{h_z}\right]^T$, and the brake force/moment generated by the servo brake attached to each wheel of the PRP is ${}^{ob}\boldsymbol{F}_b = \left[{}^{ob}f_{b_x} \; {}^{ob}f_{b_y} \; {}^{ob}n_{b_z}\right]^T$.

Under the assumption that the PRP does not consider the apparent dynamics of the handling object with respect to the rotational direction because the PRP carries an object through the free joint, the motion equation of the PRP with respect to its position is expressed as follows;

$$(\boldsymbol{M}_r + \boldsymbol{M}_{ob})^{ob}\ddot{\boldsymbol{q}} + \boldsymbol{D}_r{}^{ob}\dot{\boldsymbol{q}} = {}^{ob}\boldsymbol{F}_h - {}^{ob}\boldsymbol{F}_b \tag{4}$$

where,

$$\boldsymbol{M}_r = \begin{bmatrix} m_{r_x} & 0 \\ 0 & m_{r_y} \end{bmatrix}, \boldsymbol{M}_{ob} = \begin{bmatrix} m_{ob_x} & 0 \\ 0 & m_{ob_y} \end{bmatrix}, \quad \boldsymbol{D} = \begin{bmatrix} d_x & 0 \\ 0 & d_y \end{bmatrix},$$
$${}^{ob}\boldsymbol{q} = \begin{bmatrix} {}^{ob}x_r \\ {}^{ob}y_r \end{bmatrix}, {}^{ob}\boldsymbol{F}_h = \begin{bmatrix} {}^{ob}f_{h_x} \\ {}^{ob}f_{h_y} \end{bmatrix}, {}^{ob}\boldsymbol{F}_b = \begin{bmatrix} {}^{ob}f_{b_x} \\ {}^{ob}f_{b_y} \end{bmatrix} \tag{5}$$

where $\boldsymbol{M}_r \in \boldsymbol{R}^{2\times2}$, $\boldsymbol{M}_{ob} \in \boldsymbol{R}^{2\times2}$, $\boldsymbol{D}_r \in \boldsymbol{R}^{2\times2}$ are actual inertia matrix of the PRP, actual inertia matrix of the handling object and actual damping coefficient matrix of the PRP respectively.

For realizing the variable motion characteristics of the handling object, we consider to design the motion control algorithm of the PRP as if it has the following dynamics.

$${}^{ob}\boldsymbol{M}_d{}^{ob}\ddot{\boldsymbol{q}} + {}^{ob}\boldsymbol{D}_d{}^{ob}\dot{\boldsymbol{q}} = {}^{ob}\boldsymbol{F}_h \tag{6}$$

where,

$${}^{ob}\boldsymbol{M}_d = \begin{bmatrix} {}^{ob}m_{d_x} & 0 \\ 0 & {}^{ob}m_{d_y} \end{bmatrix}, {}^{ob}\boldsymbol{D}_d = \begin{bmatrix} {}^{ob}d_{d_x} & 0 \\ 0 & {}^{ob}d_{d_y} \end{bmatrix}$$

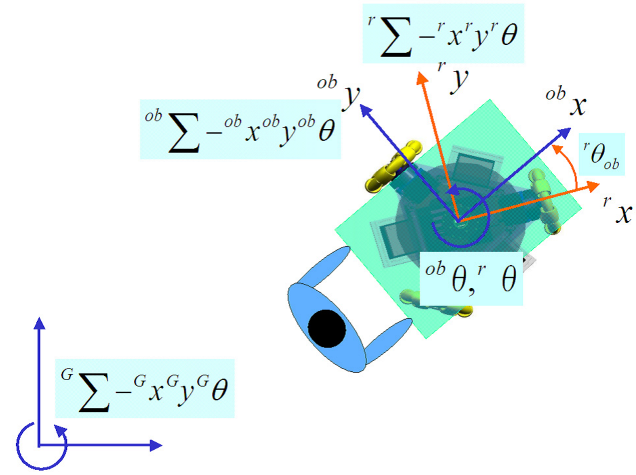


Fig. 3. Coordinate Systems of PRP with Free Joint

where ${}^{ob}\boldsymbol{M}_d \in \boldsymbol{R}^{2\times2}$ is the apparent inertia matrix of the handling object and ${}^{ob}\boldsymbol{D}_d \in \boldsymbol{R}^{2\times2}$ is the apparent damping coefficient matrix of the handling object respectively. If we can change the apparent dynamics of the handling object expressed by ${}^{ob}\boldsymbol{M}_d$ and ${}^{ob}\boldsymbol{D}_d$ appropriately, the maneuverability of the object could be changed.

For realizing above dynamics, we derive the required brake force moment for controlling the PRP from Eq.(4) and Eq.(6) as follows;

$${}^{ob}\boldsymbol{F}_b = \{{}^{ob}\boldsymbol{M}_d - (\boldsymbol{M}_r + \boldsymbol{M}_{ob})\}^{ob}\ddot{\boldsymbol{q}} + ({}^{ob}\boldsymbol{D}_d - \boldsymbol{D}_r)^{ob}\dot{\boldsymbol{q}} \tag{7}$$

When we derive the brake force/moment from Eq.(7), and specify the brake torque of the powder brakes based on the servo brake condition as shown in Eq.(3), the PRP can move as if it has the apparent dynamics expressed by ${}^{ob}\boldsymbol{M}_d$ and ${}^{ob}\boldsymbol{D}_d$ in Eq.(6). Therefore, we can vary the mobility characteristics of the handling object so that the maneuverability of the human operator would be improved. The methods for defining suitable apparent dynamics for the user are part of the research on human-robot cooperation. In this paper, we illustrate some example of the apparent dynamics of the handling object in some experiments described in section IV.

B. Actual Motion Control Method of PRP

The prototype developed in this research could not provide accurate acceleration feedback because it has only a low-resolution encoder for each wheel to calculate its acceleration. Therefore, to use the PRP, we assume that ${}^{ob}\boldsymbol{M}_d$ is equal to $(\boldsymbol{M}_r + \boldsymbol{M}_{ob})$, and modify Eq.(7) as the following equation.

$${}^{ob}\boldsymbol{F}_b = ({}^{ob}\boldsymbol{D}_d - \boldsymbol{D}_r)^{ob}\dot{\boldsymbol{q}} \tag{8}$$

However, the apparent inertia matrix could not be changed in this case, that is the apparent dynamics of the handling object is satisfied as follows;

$$(\boldsymbol{M}_r + \boldsymbol{M}_{ob})^{ob}\ddot{\boldsymbol{q}} + {}^{ob}\boldsymbol{D}_d{}^{ob}\dot{\boldsymbol{q}} = {}^{ob}\boldsymbol{F}_h \tag{9}$$

Note that, if we use high-resolution encoders or acceleration sensors to detect the correct acceleration of the PRP, we can change both the apparent inertia matrix and the apparent damping matrix of the handling object expressed in Eq.(6) under the relationship expressed in Eq.(3).

By satisfying the apparent dynamics of the handling object expressed in Eq.(9), we change the maneuverability of the object with respect to the damping confident. In general, we can consider two kinds of the apparent dynamics of the handling object: isotropic dynamics and anisotropic dynamics. In the isotropic dynamics, the damping parameters of the PRP along ${}^{ob}x$ and ${}^{ob}y$ directions are the same value so that the maneuverability of the handling object is not different in any directions. On the other hand, in the anisotropic dynamics, we specify the different damping parameters to each direction of the object coordinate system. This dynamics is suitable for the straight line motion of the object and is robust against the disturbance force applied from the perpendicular to the motion direction.

In this research, the robot carries the handling object through the free joint, because the required operational force of the object applied by the human operator is reduced [7]. However, in this case, the relative orientation between the robot and the handling object is changed in real time during the handling task. If we specify the isotropic motion characteristic of the handling object to the robot controller, we may not need to concern the relative orientation between the robot and the handling object, because the maneuverability of the handling object is not depend on the orientation of the PRP. However, if we consider the anisotropic motion characteristic of the handling object, the relative orientation between the robot and the handling object is required for the actual control of the robot, because the PRP has to change the apparent dynamics based on the orientation of the object.

In this research, we attach the potentiometer to the free joint part of the PRP for measuring the relative orientation between the robot and the handling object ${}^r\theta_{ob}$ and the orientation of the handling object with respect to the global coordinate system ${}^G\theta_{ob}$ is expressed from the orientation of the robot with respect to the robot coordinate system ${}^G\theta_r$ and the relative angle between the robot and the handling object ${}^r\theta_{ob}$ as follows;

$$ {}^G\theta_{ob} ={}^G \theta_r +{}^r \theta_{ob} \tag{10} $$

When we define the rotation matrix from the object coordinate system to the global coordinate system ${}^G\boldsymbol{R}_{ob}$, the required brake force with respect to the object coordinate system ${}^{ob}\boldsymbol{F}_b$ is expressed as the brake force with respect to the global coordinate ${}^G\boldsymbol{F}_b$ based on the following equation.

$$ {}^G\boldsymbol{F}_b ={}^G \boldsymbol{R}_{ob}{}^{ob}\boldsymbol{F}_b \tag{11} $$

where,

$$ {}^G\boldsymbol{R}_{ob} = \begin{bmatrix} \cos {}^G\theta_{ob} & -\sin {}^G\theta_{ob} \\ \sin {}^G\theta_{ob} & \cos {}^G\theta_{ob} \end{bmatrix} \tag{12} $$

We can express the relation between braking torque $\boldsymbol{\tau}_b = [t_{bw_1}, t_{bw_2}, t_{bw_3}]^T$ generated by wheels and resultant braking force ${}^G\boldsymbol{F}_b = \left[{}^G f_{b_x} \; {}^G f_{b_y} \; 0\right]^T$ applied to the robot as follow;

$$ \boldsymbol{\tau}_b = \boldsymbol{J}^T \; {}^G\boldsymbol{F}_b \tag{13} $$

This relation is exactly the same with systems with servo motors which has a linear mapping in the case that Jacobian matrix J is full rank because of the wheel arrangement of PRP. However what we need to consider here is that the servo brake applies a torque to the wheel according to the sign of the rotational direction of the wheel, which influences the feasible braking torque of the robot. The derivation of the feasible braking torque based on the servo brake condition is explained in [7].

IV. EXPERIMENTS FOR HANDLING OBJECT

In this paper, we experimented with the PRP for handling a single object to illustrate the validity of the proposed control algorithm realizing the variable motion characteristics of the handling object.

A. *Velocity Response of PRP*

In the first experiment, we moved the PRP on a slope, as shown in Fig.4. This simulates a user applying a constant force to the PRP, and provides velocity responses as experimental results. We firstly specified four damping parameters with respect to ${}^{ob}x$ direction (${}^{ob}d_{d_x} - d_x = 50, 100, 150, 200[Ns/m]$), while maintaining damping with respect to ${}^{ob}y$ direction, and move it on the slope along ${}^{ob}x$ direction based on the gravity force. One of the examples in this experiments shown in Fig.5(a) which is the path of the PRP. Next, We specified four damping parameters with respect to the ${}^{ob}y$ direction (${}^{ob}d_{d_y} - d_y = 50, 100, 150, 200[Ns/m]$), while maintaining damping with respect to ${}^{ob}x$ direction, and move it on the slope along ${}^{ob}y$ direction based on the gravity force. One of the path of the PRP in this experiment is shown in Fig.5(b).

The velocity responses of the first experiment detected by the encoder system of the PRP are shown in Fig.6, and the velocity responses of the second experiments are shown in Fig.7. These results show that the motion characteristics of the PRP can be changed arbitrarily along each direction so that we could specify many types of apparent dynamics of the handling object such as isotropic and anisotropic dynamics to improve the maneuverability of the human operator.

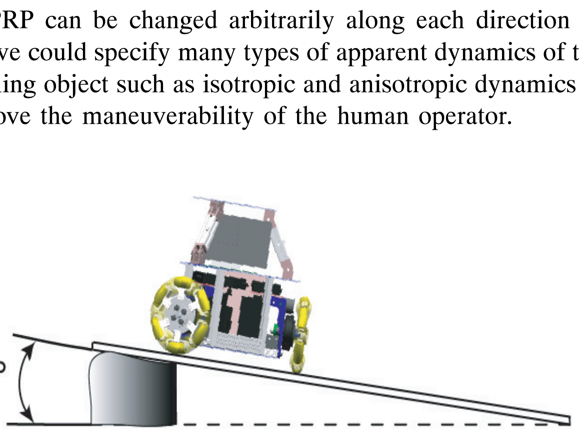
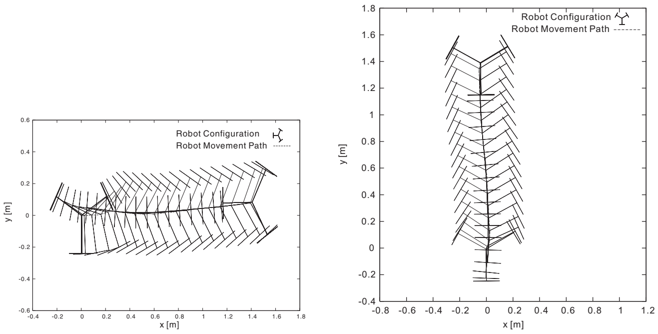


Fig. 4. Experimental Setup using Slope



(a) Experiment for ^{r}x Direction (b) Experiment for ^{r}y Direction

Fig. 5. Paths of PRP Moved by Gravity Force

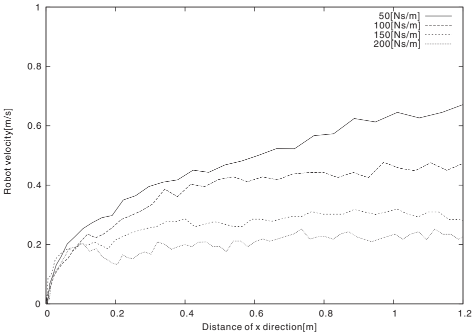


Fig. 6. Velocity Response in Experiment for ^{ob}x Direction

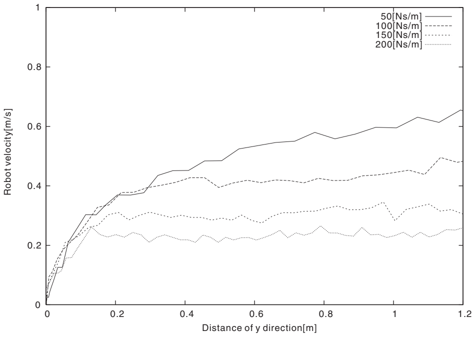


Fig. 7. Velocity Response in Experiment for ^{ob}y Direction

B. Experiments of Object Handling by Human Operator

In this experiment, we realize an anisotropic apparent motion characteristic of the handling object by changing the elements of the apparent damping coefficient matrix $^{ob}d_{d_x}$, $^{ob}d_{d_y}$ expressed in Eq.(9) respectively. In this experiment, we define the heading direction of the object along ^{ob}x axis of the object coordinate system so that the human operator can move the object along this direction. On the other hand, ^{ob}y axis is robust against the disturbance force applied to the object. For realizing this anisotropic motion characteristics of the object, we specify the damping parameters as $^{ob}d_{d_x} - d_x = 10[Ns/m]$ and $^{ob}d_{d_y} - d_y = 1000[Ns/m]$.

(a) 11[sec] (b) 17[sec]

(c) 22[sec] (d) 25[sec]

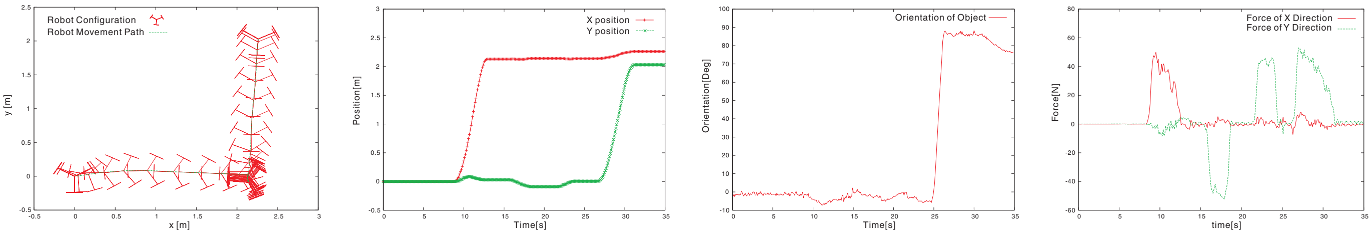
(e) 27[sec] (f) 29[sec]

Fig. 8. Experiment for Transporting an Object using Free Joint

During the experiment for handling the object, human operator moves it along its heading direction easily. If the human operator wants to change the direction of the transportation, he/she rotates the orientation of the object through the free joint easily and he/she could transport it to any destinations. Experimental results illustrate in Fig.8 and Fig.9. Fig.9(a) expresses the pass of the PRP, Fig.9(b) expresses the trajectories of the PRP along ^{G}x and ^{G}y direction with respect to the time, Fig.9(c) expresses the orientation of the object with respect to the time, and Fig.9(d) is force applied to the PRP with respect to the global coordinate system which is measured by the force/torque sensor attached to the PRP. Note that, the force/torque sensor is only used for evaluating the validity of the proposed control algorithm without using the control of the PRP.

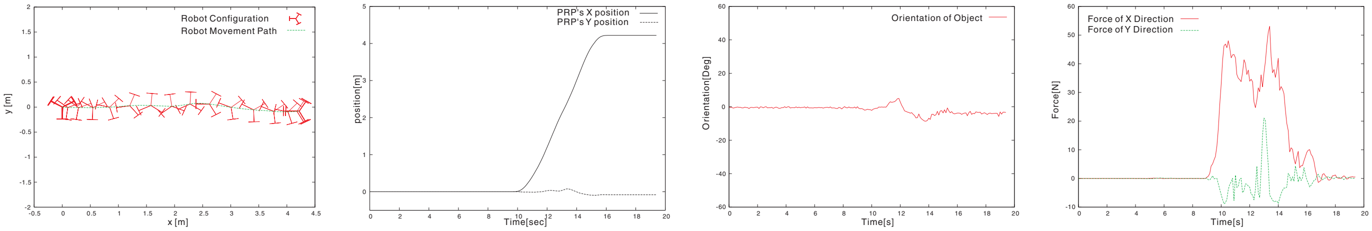
From Fig.8(a) and Fig.9(b),(d), the handling task was done based on the force applied along ^{G}x direction around $11[sec]$. Around $17[sec]$ and around $22[sec]$ as shown in Fig.8(b),(c), the PRP did not move in spite of applying the force (about $40[N]$) along ^{G}y direction as shown in Fig.9(b). On the other hand, after the human operator rotated the direction of the handling object using free joint as shown in Fig.8(d), he could move it along ^{G}y direction.

In next experiment, we applied the disturbance force to the object during the transportation. When the human operator transported it along heading direction of the object, another person applied the force intentionally to the perpendicular



(a) Path of PRP (b) Trajectory of PRP (c) Orientation of Object (d) Force Applied to PRP

Fig. 9. Experimental Results for Transporting an Object using Free Joint



(a) Path of PRP (b) Trajectory of PRP (c) Orientation of Object (d) Force Applied to PRP

Fig. 10. Experimental Results for Illustrating Validity of Anisotropic Dynamics

(a)11[sec] (b) 12[sec]

(c) 13[sec] (d) 14[sec]

Fig. 11. Experiment for Illustrating Validity of Anisotropic Dynamics

direction of the heading direction. Experimental results illustrate in Fig.10 and Fig.11. Fig.10(a) expresses the pass of the PRP, Fig.10(b) expresses the trajectories of the PRP along ${}^{G}x$ and ${}^{G}y$ direction with respect to the time, Fig.10(c) expresses the orientation of the object with respect to the time, and Fig.10(d) is force applied to the PRP with respect to the global coordinate system. From these experimental results, the transportation along ${}^{G}x$ direction was realized without being influenced by the disturbance force applied by another person around $13[sec]$ as shown in Fig.11(c).

V. CONCLUSIONS

In this paper, we proposed motion control algorithm of omni-directional passive object handling robot for realizing the variable motion characteristics of the object. Based on the orientation of the handling object, we designed anisotropic motion characteristics of the object by controlling of the servo brakes of passive mobile robot. Experimental results of the object handling illustrated the validity of the proposed method.

By using the proposed method, we could realize many kinds of motion characteristics of the handling object. The methods for defining suitable apparent dynamics for the user are part of the research on human-robot cooperation. In the future, we will introduce this research to the control of the PRP.

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