2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Control Passive Mobile Robots for Object Transportation
- Braking Torque Analysis and Motion Control -

ZhiDong Wang, Kenta Fukaya, Yasuhisa Hirata, and Kazuhiro Kosuge

Abstract— **In this paper, we propose a concept on realizing impedance-based motion control of passive type robots for transporting a single object in coordination with a human operator. In this research, we developed a prototype of passive type robot referred to as *P*assive *R*obot *P*orter or *PRP*, which consists of three omni-directional wheels with MR Brakes, and on-board computer system. We analyze the singularity of *PRP* braking torques, and control the brake torque of each wheel based on the brake force/moment constraint so that impedance characteristics is realized on *PRP* with human's pushing. This allows a *PRP* to track a 2D path which includes motion perpendicular to human's pushing direction without using servo motors, and multi-*PRP*s to work cooperatively on handling a single object with orientation control for avoiding collision with obstacles. Experimental results are shown to illustrate the validity of the proposed concept.**

I. Introduction

Beyond the conventional industrial applications, researches and developments on robotics recently are more focused on applications or areas related to our daily life, such as, entertainment, service, medical and welfare applications, etc. With these applications, human-robot cooperative systems on object handling and transportation are required. Studies in [1]∼[3] demonstrated various interesting and essential tasks on it. These studies address the dynamic interaction between human and robots, which is one of the most important factors on leading Robot Technology (RT) into our daily life.

As robots interact to our daily activities, several technical issues are becoming more important. One of the most important issues is safety pointed out by many researchers. In general, robotic systems consist of active actuating components such as motors. We are generally concerned about any problem on robot control which will lead to unexpected or undesirable motion of robots. This situation may let robots hit and hurt human being. Many researchers have been developing methods to examine this kind of collisions or predict the possibility of collisions by installing various sensors on the robot systems. These strategies are feasible but with limitation, especially when the type and number of sensors are not sufficient.

In this research, we focus on the development of a passive type robot system, which does not include any active component such as motor (Fig.1). This can realize a high level of safety without losing system's performance on object transportation. In this paper, we will address the system

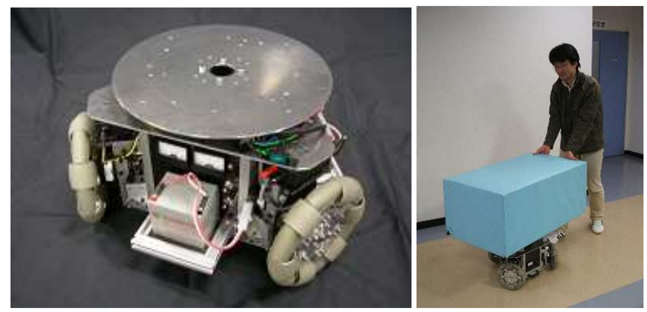


Fig.1 . *PRP* System for Object Transportation with Human

design of a passive robot, singularity analysis of the system and impedance-based motion control under braking torque constraints. Finally, experimental results on impedance-based motion control and cooperative object handling control are shown to illustrate the validity of the proposed system.

II. Passive Robotics

Conventional robot systems are developed by incorporating active actuators for both generating and controlling the motion of the system. Sometimes we have to design high gear ratio for small actuators. This lets the system lose its backdrivability. In other cases, we need to install big motors to keeping the backdrivability and to have enough power both. Either of the aforementioned systems will not be safe if actuators are out of control for unexpected reasons. Therefore, some safety measures should be carefully designed especially if the system is working in an environment with human.

Goswami's group [4] proposed the concept Passive Robotics, and the resulting system does not include any force driving component for motion generation. The motions are always due to the external forces applied to the system. In their system, some passive components such as mechanical springs and dampers are installed on the manipulator. By controlling the physical parameters of passive components, various motions are realized with the external forces on the end-effector. Unexpected motion due to out of control will not happen in a passive system since motion is a product of the applied force of the human operator. In this meaning, higher safety on motion control is achieved. In addition, some passive type actuators such as MR brake have good performance on torque-weight ratio. This is usually an advantage on developing simple and low power consuming robotic systems. From these points, the concept of Passive Robotics is unique and potential on achieving tasks with robot-human interaction.

Demonstrated by many researches, such as Davis and Book's work[5], passive actuators show its advantage on

Z.D. Wang is with the Department of Advanced Robotics, Chiba Institute of Technology, Narashino, Chiba, 275-0016, Japan. zhidong.wang@it-chiba.ac.jp

K. Fukaya, Y. Hirata and K. Kosuge are with Department of Bioengineering and Robotics, Tohoku University, Sendai, 980-8579, Japan. {fukaya, hirata, kosuge}@irs.mech.tohoku.ac.jp

manipulator control. An earlier work on developing object transportation system based on the concept of Passive Robotics is discussed in [6]. This system is designed by Peshkin and Colgate's group. The system consists of motors for steering three passive wheels. The robot and object are moved by the pushing force of the human operator, but trajectory of the system is controlled by a steering wheel. In our group, as well as active working helper system [7], we have developed a passive working helper [8][9] and it consists of two MR brakes. This system assists user to walk in environments with obstacles and it also provides proper dynamic characteristics to prevent the user from loosing his footing. However, the system is using normal wheels with non-holonomic constraints. Cobot also consist of active type actuator even it is for passive application. Recently, Ryu and Pathak's group also proposed a passive based control law for differentially driven mobile robot [11]. In this research, we focus on developing a robot system consisting of passive actuators and investigate the dynamic characteristics and constrains of the system. We will also realize a motion control and object handling with a good performance comparable to an active type system.

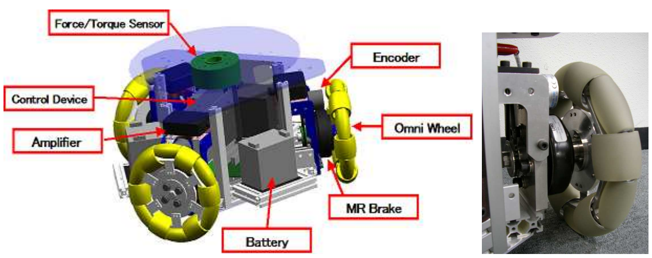


Fig.2 . Hardware Design of *PRP* and Omni Wheel with MR Brake

III. Passive type Robot Porter *PRP*

We have developed a passive type Robot Porter system based on the concept of the passive robotics and it is called *PRP*-robot. *PRP* consists of three omni-directional wheels with servo-brakes to perform safety object transportation task. The omni-directional wheel is equipped with several small rollers so that the wheel can generate driving force along its rotational direction, but can move freely in its wheel axis. Each omni-directional wheel is directly connected to a servo-brake, and the three wheels are arranged to have $2\pi/3$ angle between each pair of wheel axes. A force/torque sensor is installed on *PRP* for measuring the forces applied by the human operator. It is necessary to note that the force sensor is not indispensable to control of *PRP* if we do not need to have precise dynamic characteristics, such as, impedance characteristics of the system. Encoder is installed on each wheel used for odometry. A computer system is installed for controlling *PRP* and the system is powered by batteries.

The control performance of *PRP* system depends on the characteristics of the servo brakes installed. In the first prototype, we used MR Brake. The 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 a very reliable and linear braking torque, and relatively small power consuming compared with motors.

IV. Control of Passive Actuator

Passive actuators have some unique controlling characteristics. The output of active actuators such as servo motor will affect the control target independent of the target's motion. However, the output of a servo-brake will not affect the motion of the target if it is not moving and will not move. This is a very important feature in realizing safety actions. Also some constraints make the control of passive type robot systems to be different from controlling ordinary systems.

Let us consider how the output torque of an actuator is applied to a mobile robot in the case of active and passive actuator such as motor and servo-brake respectively.

(i) Motor Output Torque

It is well known that the torque applied to the wheel will be equal to the output torque of the motor as,

$$\tau_m = k_m I_m \tag{1}$$

I_m denotes the control input of a motor and k_m denotes the torque constant of the motor. Without losing generality, the gear ratio is assumed as 1.

(ii) Servo-Brake Output Torque

We consider the case that the *PRP* is moving by forces applied by the human operator or other system. $\dot{\phi}_w$ and f_{ew} denotes the angular velocity of and external force applied to the wheel respectively. I_b is input current to the brake and k_b is the torque coefficient of the servo brake. Let τ_w denote the resultant torque applied to the wheel from the brake. Then τ_w will be:

a) for $\dot{\phi}_w \neq 0$

$$\tau_w = -k_b I_b \mathrm{sgn}(\dot{\phi}_w) \tag{2}$$

b) for $\dot{\phi}_w = 0$

$$\tau_w = \begin{cases} -f_{ew} R_w & |f_{ew}| R_w \leq k_b I_b \\ -k_b I_b \mathrm{sgn}(f_{ew}) & |f_{ew}| R_w > k_b I_b \end{cases} \tag{3}$$

where, sgn(*) is the function to have sign of a parameter, and $k_b \geq 0$. Also as a brake, $I_b \geq 0$.

It is obvious that the characteristics of a brake-wheel system are complicated compared with a motor-wheel system. It is dependent on the wheel rotation. The sign of the output torque of the wheel is decided by the direction of the rotation of the wheel(Fig.3) and the magnitude of the

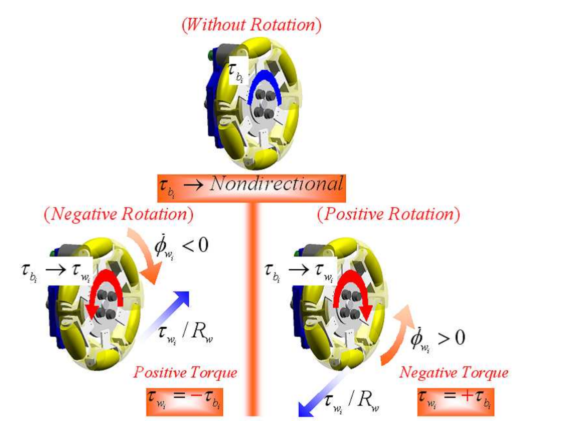


Fig.3 . Characteristic of Output Torque of Wheel with a Servo Brake

torque is proportional to the input current of the brake while the wheel is rotating. On the other hand, the torque will be expressed as a non-linear function to the external force applied on the wheel in the case that the wheel does not rotate. We call this the *Singular Point of Braking Torque* of a passive wheel. In object transportation, there are situations that a wheel does not rotate and they usually occur in a very short period. From the Eq.2, we can have the following condition between angular velocity of the wheel and braking torque of the brake-wheel system.

$$\tau_w \dot{\phi}_w \leq 0 \tag{4}$$

This condition is the servo-brake control constraint to the system and indicates that one cannot have arbitrary torque from a servo-brake. We need to consider feasible braking torque in the robot motion control based on this constraint.

V. Motion Control of *PRP*

A. Kinematics and Motion Type of PRP

The kinematics relation between the motion vector of *PRP*, $\dot{\boldsymbol{q}} = \left[\dot{x}, \dot{y}, \dot{\theta}\right]$, and angular velocity vector of wheels, $\boldsymbol{\Phi} = [\phi_{w_1}, \phi_{w_2}, \phi_{w_3}]$, can be express as:

$$\dot{\boldsymbol{q}} = \boldsymbol{J}\boldsymbol{\Phi} \tag{5}$$

where J,

$$\boldsymbol{J} = \begin{bmatrix} 0 & -\frac{R_w}{\sqrt{3}} & \frac{R_w}{\sqrt{3}} \\ -\frac{2R_w}{3} & \frac{R_w}{3} & \frac{R_w}{3} \\ -\frac{R_w}{3L} & -\frac{R_w}{3L} & -\frac{R_w}{3L} \end{bmatrix} \tag{6}$$

R_w denotes the radius of the wheel and L denotes the distance between center of the wheel and intersection point of three axes of wheels in the horizontal plane. Robot coordinates are shown in Fig.4. In addition, the Jacobian $\boldsymbol{J}$ is a full rank matrix. There is a unique mapping relationship between the robot motion and wheel angular velocities.

Since the brake torque of each wheel is dependent on the direction of the wheel rotation, we classify the motion of *PRP* into 8 different cases based on the signs of the angular velocities of the three wheels ($\mathrm{sgn}(\dot{\phi}_{w_i}), i \in 1, 2, 3$).

Table.I Motion Types and Conditions of PRP

	Sign of Angular Velocity of Wheel							
Wheel 1	+	+	+	+	-	-	-	-
Wheel 2	+	+	-	-	+	+	-	-
Wheel 3	+	-	+	-	+	-	+	-
Motion Type No.	1	2	3	4	5	6	7	8

In each motion type, signs of the angular velocities of the three wheels will not change. Therefore, the feasible braking torque on each wheel will follow the same relationship with the input current on the servo brake.

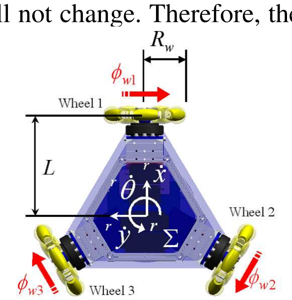


Fig.4 . Configuration and Robot Coordinates of *PRP* (Top View)

B. Braking Torque and Statics of PRP

We can express the relation between braking torque ($\boldsymbol{t}_w = [\tau_{w_1}, \tau_{w_2}, \tau_{w_3}]^T$) generated by wheels and resultant braking force and moment ${}^r\boldsymbol{F}_w = [{}^rf_x, {}^rf_y, {}^rn_z]^T$ as follow

$$\boldsymbol{t}_w = \boldsymbol{J}^T\ {}^r\boldsymbol{F}_w \tag{7}$$

This static relationship is exactly the same to a system with active actuators. Based on the wheel arrangement of *PRP*, J is full rank. However, we have to consider that the passive actuators will apply different or opposing output torques to the robot for different motion types. With the possible torques for all motion types, the braking torque set V will be the same as system with active actuators. This is shown in Fig.5-(a), as a closed cube in the configuration space of braking torque.

$$V = \{\sum_{i=1}^{3} \tau_{v_i}\boldsymbol{e}_i \ \mid\ |\tau_{b_i}| \leq \tau_{max}\} \tag{8}$$

However, it does not mean that all torques in this set will be feasible by setting proper control input since the robot motion only belongs to a particular motion type in each moment. The servo-brake control constraint in Eq.4 should be included in the analysis. Here, we discuss the feasible braking torque in each motion type. U_k denotes the set of feasible braking torque when *PRP* robot is in k-th motion type ($k = 1, 2, \cdots, 8$), and $A(U_k)$ denotes the resultant force and moment on the robot from the braking torque set U_k.

$$U_k = \{\sum_{i=1}^{3} \tau_{w_i}\boldsymbol{e}_i \ \mid\ |\tau_{w_i}| \leq \tau_{max},\ \tau_{w_i}\dot{\phi}_{w_i} \leq 0\} \tag{9}$$

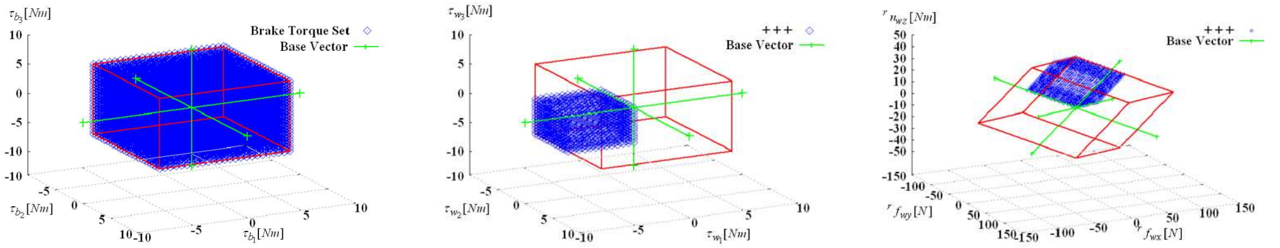
$$A(U_k) = \{\sum_{i=1}^{3} \tau_{w_i}\boldsymbol{v}_i \ \mid\ \tau_{w_i} \in U_k\} \tag{10}$$

where

$$\begin{aligned} \left[\ \boldsymbol{e}_1 \quad \boldsymbol{e}_2 \quad \boldsymbol{e}_3\ \right] &= diag(1, 1, 1) \\ \left[\ \boldsymbol{v}_1 \quad \boldsymbol{v}_2 \quad \boldsymbol{v}_3\ \right] &= \boldsymbol{J}^{T^{-1}}\left[\ \boldsymbol{e}_1 \quad \boldsymbol{e}_2 \quad \boldsymbol{e}_3\ \right] \\ k &\in 1 \sim 8\ (PRP\ Motion\ Condition\ Case\ Number) \end{aligned}$$

Since *PRP* has eight different motion types, eight sets of U_k exist as the subset of set V and correspondingly, eight $A(U_k)$ sets also exist. It is easy to know that $V = \sum_{k=1}^{8} U_k$. But we want to note that $U_j \cap U_k \neq 0 (j, k = 1, 2, \cdots, 8, j \neq k)$ and also $A(U_k)$ have the same propositions.

Fig.5-(b,c) show the set of U_k and $A(U_k)$ respectively when *PRP* is in *Case 1*. U_k is a subset of V just in one quadrant of the braking torque configuration space with six plane constraints. The three constraint planes connected to the origin of the coordinates are the braking torque constraints. The other three constraint planes are from maximum torque limitation of each servo-brake. Since the feasible resultant force and moment set $A(U_k)$ is the set projected from U_k, each constraint surface of $A(U_k)$ set has the same meaning. Based on the motion which belongs to one motion type in *Case 1∼8*, feasible resultant general force (${}^r\boldsymbol{F}_w$) and its corresponding braking torque $\boldsymbol{t}_w$ could be determined uniquely.



(a) (b) (c)

Fig.5 . (a) The Total Set of Braking Torque V (b) Wheel Braking Torque Set U_1 (c) Feasible Resultant Force and Moment Set $A(U_1)$

C. Singularity of PRP Braking Torque

Since the omni-directional wheel incorporated in this system rotates free on the axis direction of the wheel, $\boldsymbol{v}_{wi}$, the velocity of wheel i will have two independent components, velocity on driving direction, $\boldsymbol{v}_{wi\_drv}$, and velocity on passive direction, $\boldsymbol{v}_{wi\_pas}$. It is well known that motion of *PRP* will have an *Instantaneous Center of Rotation*, $\boldsymbol{x}_{ICOR}$ and velocity of any point on the robot will be perpendicular to the line connected to $\boldsymbol{x}_{ICOR}$ (Fig.6). According to the discussion in the previous session, the singular point of braking torque exists in the case that $\boldsymbol{v}_{wi\_drv} = 0$. In the moment, $\boldsymbol{v}_{wi} = \boldsymbol{v}_{wi\_pas}$. Singular point of braking torque is not unique in this kind of system. Here, let's denote l_{sig_wi} the set of points that the wheel i is braking singular where instantaneous center of rotation $\boldsymbol{x}_{ICOR}$ is located on. In *PRP* (Fig.6-(b)), l_{sig_wi} is a line parallel with the rotational direction of the wheel i, and passing through the intersecting point of the wheel and wheel axis.

From this geometric propriety, it is easy to identify the singular point of the braking torque, and to check the motion type of *PRP* when we control a *PRP*. Also from the geometric analysis, we can understand that there also exists points that two wheels are in singulars on braking torques (Fig.6-(c)). In this moment, only braking torque of one wheel can be controlled on the Eq.2. Other two wheels can not be control directly. Torques from those two wheels are governed by Eq.3. Above discussion on singularity on braking torque can be applied to all other type passive robots with different wheel configurations. This makes the method described later be feasible to other passive mobile platforms.

D. Local Controllability and Motion Control of PRP

During object transportation, the force and moment ${}^{r}\boldsymbol{F}_{w\_d}$ which should be generated by the robot are determined by the control law applied to the system such as motion control for path tracking and obstacle collision avoidance, impedance control, etc. For an active type robot, we just simply command the motors of the robot to generate torques for realizing this desired force and moment. However, to a passive type robot system, the feasible force and moment is always dependent on its current motion. We need to examine if the desired force and moment ${}^{r}\boldsymbol{F}_{w\_d}$ is in the feasible force and moment region in the current motion type, which is determined by the sign of the angular velocities wheels(Fig.7). In the case that it is in the feasible region $A(U_k)$, we can command the servo-brakes directly with desired braking torque $\boldsymbol{t}_{w\_d}$ obtained from inverse dynamics of the system. This is the same approach with an active type robot system.

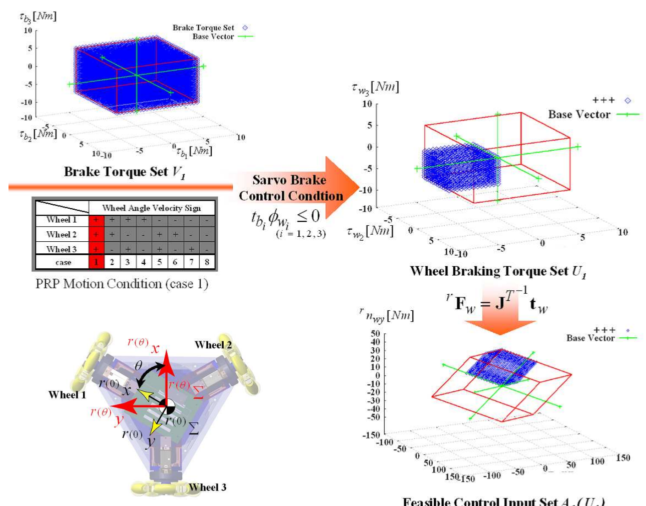


Fig.7 . Derivation of Feasible Resultant Force and Moment for Control

On the other hand, there are cases in which the desired force and moment ${}^{r}\boldsymbol{F}_{w\_d}$ is located outside the feasible set $A(U_k)$, and cannot be generated by the passive actuators in the current type of motion. One typical example is that a passive type robot cannot generate force to accelerate the object by itself whether it is moving or in halt mode.

Because U_k is always in one of the quadrants of the braking torque space, it is not locally controllable around the origin of force and moment space of *PRP*. However, if there is a proper offset of the force/moment applied to the system, we can have the local controllability around that force/moment. Actually, this proper offset of the force/moment leading default control force/moment into inside of the set U_k is a kind of resistant force/moment to the motion of passive robot *PRP*. Then, we can have the local controllability of *PRP* where the motion of *PRP* is decelerated if there is no any other external force applied to the system.

E. Impedance-based Motion Control

In this study, we consider that a human operator is always pushing the object transportation system (Fig.8). This is important to us because this could not only let the object transportation task be achieved without losing speed, but also guarantee local controllability of *PRP* system during object transportation, if we design the control algorithm properly. In [12], we demonstrated the path following control of *PRP*

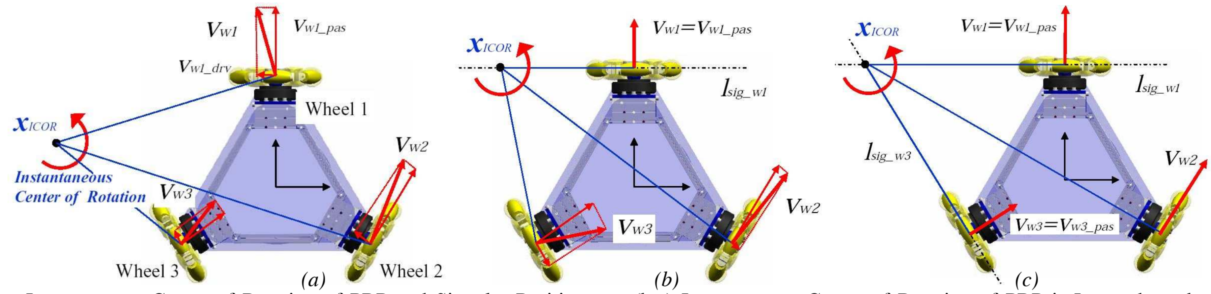


Fig.6 . Instantaneous Center of Rotation of PRP and Singular Position: (b,c) Instantaneous Center of Rotation of PRP is Located on the Singular Position: (a) Wheel 1 is singular on braking torque, (b) both Wheel 1 and Wheel 3 are singular on braking torques.

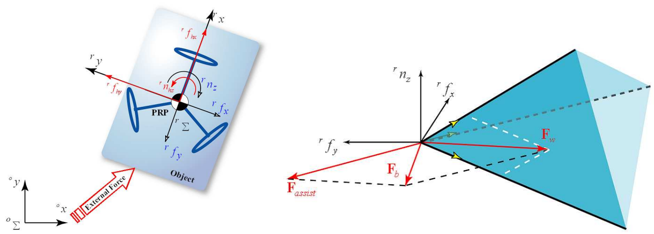


Fig.8 . (a)*PRP* with External Force and Moment during Object Transpiration, (b)Relationship of ${}^rF_{assist}$, ${}^rF_b$ and ${}^rF_w$

which includes the motion perpendicular to the pushing direction by the operator but that task did not need have detailed design of the interaction with human being.

Here, we are focusing on how to realize a desired apparent dynamics of *PRP*. This is more challenging than tracking a path since it needs to have detailed design of the interaction with human being or environment. We consider impedance based apparent dynamics because it not only is useful on considering safety issue while the system has directly interaction with human being or environment, but also contribute to realizing cooperative object handling with multiple *PRP*s.

The dynamics of the whole system can be represented as:

$$(\boldsymbol{M}_{PRP}+\boldsymbol{M}_{Obj})^r\ddot{\boldsymbol{q}}+\boldsymbol{D}^r\dot{\boldsymbol{q}}+\boldsymbol{F}_{kf}({}^r\boldsymbol{q})={}^r\boldsymbol{F}_{assist}+{}^r\boldsymbol{F}_w \tag{11}$$

where, $\boldsymbol{M}_{PRP}$ and $\boldsymbol{M}_{Obj}$ denote robot's and object's mass, $\boldsymbol{D}$ and $\boldsymbol{F}_{kf}$ denote damping coefficient (including the viscous friction of the motion) and coefficient of kinetic friction respectively. $\boldsymbol{F}_{assist}$ is the force applied by the human operator and $\boldsymbol{F}_w$ is the braking force and moment generated by wheels of *PRP*. With a non-zero $\boldsymbol{F}_{assist}$ which could maintain the motion of *PRP*, $\boldsymbol{F}_w$ will be a vector which is not near the origin. It will be located inside of the feasible force moment set $A(U_k)$, and the system will be locally controllable. Then, we can control the motion of *PRP* under certain boundary of the braking force and moment (Fig.7) for trajectory following and collision avoidance, as controlling active type robots.

We consider realizing the following apparent dynamics to the *PRP* system including the object on *PRP*.

$$\boldsymbol{M}\Delta\ddot{\boldsymbol{q}}_e+\boldsymbol{D}\Delta\dot{\boldsymbol{q}}_e+\boldsymbol{K}\Delta\boldsymbol{q}_e = \boldsymbol{F} \tag{12}$$

$$\Delta\boldsymbol{q}_e = \boldsymbol{q}_m-\boldsymbol{q}_d \tag{13}$$

where, $\boldsymbol{q}_m$ and $\boldsymbol{q}_d$ are desired position and orientation of *PRP* without and with effect of extended force $\boldsymbol{F}$ respectively. $\boldsymbol{M},\boldsymbol{D},\boldsymbol{K}$ are apparent inertial, damping and compliant coefficient matrix respectively. Then Eq.12 could be rewritten as:

$$\frac{d}{dt}\begin{bmatrix}\boldsymbol{q}_e\\ \dot{\boldsymbol{q}}_e\end{bmatrix}=\begin{bmatrix}0 & \boldsymbol{I}\\ -\boldsymbol{M}^{-1}\boldsymbol{K} & -\boldsymbol{M}^{-1}\boldsymbol{D}\end{bmatrix}\begin{bmatrix}\boldsymbol{q}_e\\ \dot{\boldsymbol{q}}_e\end{bmatrix}+\begin{bmatrix}0\\ \boldsymbol{M}^{-1}\end{bmatrix}\boldsymbol{F} \tag{14}$$

Here $\boldsymbol{F}$ is the resultant force of external force exclude the part of assistant force for guarantee that the braking torques are inside of the feasible force/moment set $A(U_k)$.

$$\boldsymbol{F}=\boldsymbol{F}_{ext}+(\boldsymbol{F}_{assist}-\boldsymbol{F}_w) \tag{15}$$

where $\boldsymbol{F}_{ext}$ is the external force applied by the other one or environment except the human operator. By realizing the impedance characteristics on each *PRP*, the cooperative object handling strategy we proposed for active type robots[1][3][10] can be applied to passive type system directly.

VI. Experiments

In this research, we demonstrated impedance-based motion control in object transportation of *PRP* with human operator. The human operator pushes the system along ${}^rx$. Also it is pushed by other one in the perpendicular to the original path during the transportation. In the experiment, the orientation of the object is controlled to keep a desired orientation (-90 degree) and a desired angular velocity of zero. Fig.9 $\sim$ Fig.11 show the results of the experiment. Fig.9 shows that *PRP* is pushed by other one during object transportation.

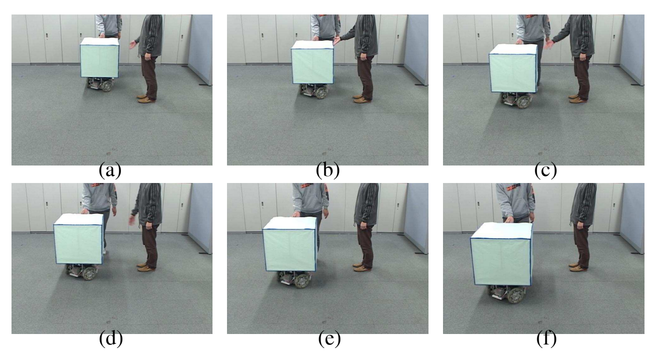


Fig.9 . Experiment of Impedance-based Motion Control

Fig.10 shows path of *PRP*, and Fig.11 shows the force applied to *PRM* in ${}^ry$ direction which is $\boldsymbol{F}_ext$ in Eq.15 and the position and orientation of *PRP*. The experiment results show that with only braking torque, *PRP* performs good impedance-based motion characteristics (Fig.11-(b)) in

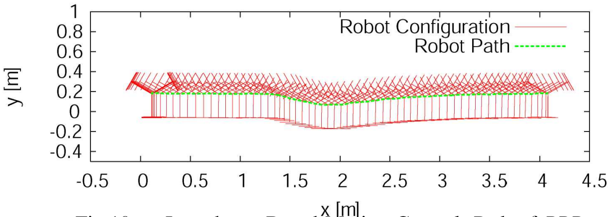
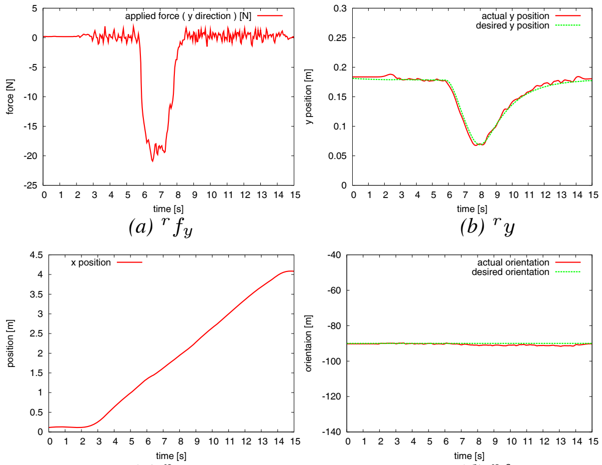
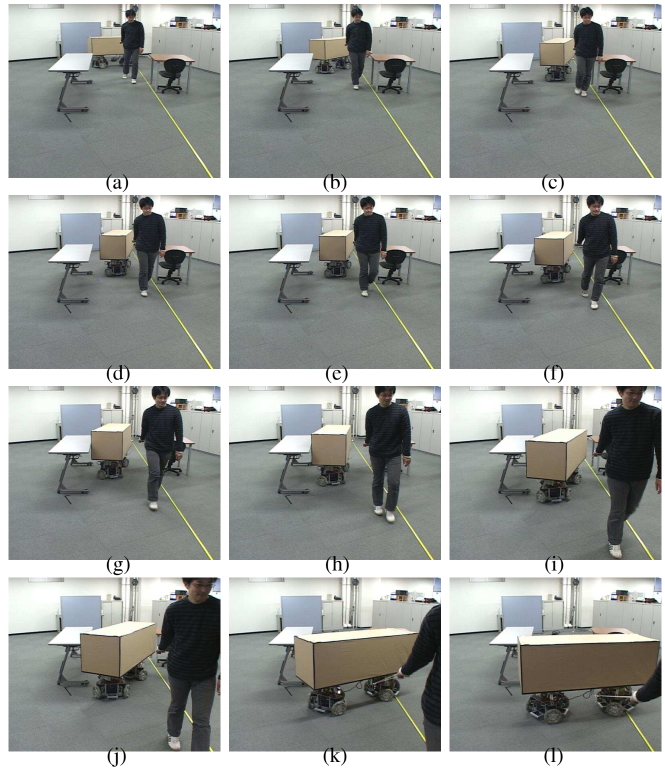


Fig.10 . Impedance Based Motion Control: Path of *PRP*



(a) ^rf_y (b) ^ry (c) ^rx (d) $^r\theta$

Fig.11 . Experiment Result of Impedance Based Motion Control: Force in y direction and Trajectory of Position and Orientation



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Fig.12 . Orientation Control for Passing an Object through a Narrow Place: Only the pulling force is applied to the center of the object-robot system. *PRP*s rotate the object to an orientation cooperatively when they are passing the narrow place, and more the object back to the initial orientation finally.

the direction perpendicular to the moving direction. When the human being pushes *PRP* ($5.5sec \sim 8.5sec$), *PRP* is moving to compliant the push. After the human being stops his push ($8.5sec$), *PRP* is moving back to its original path.

In Fig.12, we demonstrate that two *PRP* robots control the object orientation cooperatively so that the object can pass through a narrow place. During the demonstration, a human operator only pulls the *PRP*-object system by a wire and only pulling force is applied to the mass center of the object. The moment for rotating the object is generated by braking force of two *PRP* robots which incorporating the impedance based cooperation strategy we proposed. The object was rotated to an orientation (Fig.12-(c)) which can pass the narrow place and was rotated back to the initial orientation(Fig.12-(l)) which is perpendicular with the pulling direction.

VII. Conclusion

In this paper, we have presented the concept of object transportation with a passive type robot system *PRP*. We have also realized a impedance-based motion control for a robot system consisting of passive actuators, even the human operator pushes the robot system in only one direction. The analysis of feasible braking force/moment set, which depends on the motion of the system, and singularity of the system are provided. A basic strategy for controlling *PRP* with assistance force from human operator was proposed. Finally, we have demonstrated the concept and control strategy by prototype *PRP* robots and illustrated the validity of the proposed concept. How large assistance force we need to have is depending on two points. One is the magnitude of resultant force that we need to generate for handling the object. Another one is the relation between direction of assistance force and geometric configuration of passive wheels. This is the problem of manipulability of passive type systems with the push of the human operator. Some basic investigations on this issue have been done to our prototype *PRP* robot. Systematic analysis of manipulability and design of interaction force will be our future works.

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