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Variable Motion Characteristics Control of an Object by Multiple Passive Mobile Robots in Cooperation with a Human

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***Abstract*— In this paper, we introduce a passive mobile robot called PRP (Passive Robot Porter), which has passive dynamics with respect to an applied force and its appropriate motion is controlled based on the servo brakes. This paper especially focuses on a motion control algorithm of multiple passive mobile robots for handling a single object in cooperation with a human. By controlling each passive mobile robot in the decentralized way, we realize several kinds of motion characteristics of the object to improve the maneuverability for the human operator. By changing the apparent dynamics of the representative point of the object and its position, we realize an anisotropic apparent motion characteristic of the handling object and the obstacle avoidance function as examples. The proposed motion control algorithms are implemented to two PRPs actually, and experimental results illustrate the validity of the proposed algorithms.**

I. Introduction

As societies age and experience a shortage of people for nursing care, robots are expected to be used in the living environment based on the physical interaction between robots and humans. For practical use of robots with physical interaction, we need to consider safety of their users. However, if we cannot appropriately control the servo motors which are used by most of robots for controlling their motion, they move unintentionally and might be dangerous for humans.

From the view point of safety, Goswami et al. proposed the concept of passive robotics [1], in which a system moves passively based on external force/moment without using servo motors, and Peshkin et al. developed an object handling system called Cobot [2], in which its steering angle is only controlled by the servo motor. These passive systems are intrinsically safe because they cannot move unintentionally. Thus, passive robotics will prove useful in many types of intelligent systems through physical interaction between the systems and humans.

We have also developed passive intelligent walker called RT Walker to support the walking of the handicapped people including the elderly [3]. It differs from other passive robots in that they control servo brakes appropriately without using any servo motors. The servo brakes can navigate the RT Walker and its maneuverability can change based on environmental information or the difficulties and conditions faced by the user.

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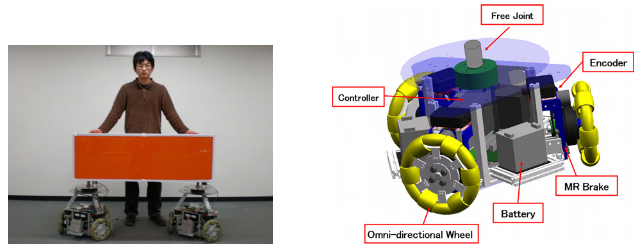


(a) Object Handling with Two PRPs (b) Component of PRP

Fig. 1. Passive Mobile Robot Called PRP

We have extended the brake control technologies of the RT Walker to the control of the omni-directional-type object handling robot called PRP (Passive Robot Porter) [4]. In [4], we analyze the conditions of the servo brake control and derive the feasible region of the control input theoretically for realizing the desired motion of the PRP such as collision avoidance motion.

In the conventional researches on the passive mobile robot including the RT Walker and the PRP, the researchers have considered the control of the single mobile robot which is the natural extension from the research on active-type robot with servo motors. On the other hand, in this paper, we consider the multiple mobile robots coordination for handling a large or a long object in cooperation with a human. Similar to the coordination by multiple robots with servo motors proposed by many researchers, e.g. [5], [6], the coordination using multiple passive robots also has advantages for manipulating a large object.

Different from the collaboration using robots with servo motors, the collaboration of passive robots is challenging, because the passive robot cannot generate the arbitrarily motion we expected and only prevents its motion generated by the external force applied. In this paper, we consider the motion control algorithm of multiple passive mobile robots with servo brakes for handling a large or a long object in cooperation with a human.

In the following part of this paper, first, we introduce the omni-directional type passive mobile robot called PRP and fundamental motion control algorithm. Next, we propose motion control algorithm of multiple PRPs for changing the motion characteristics of the handling object to improve the maneuverability of the user. In addition, by extending the proposed algorithm for changing the motion characteristics of the handling object, we propose a simple collision avoidance function for handling a large or a long object, which changes the orientation of the handling object based on the environment information without using communication among robots.

II. Omni-directional Passive Mobile Robot

A. Hardware of PRP (Passive Robot Porter)

We have developed passive robot porter based on the concept of the passive robotics [4] called PRP as shown in Fig.1. The PRP consists of three omni-directional wheels with servo brakes. The omni-directional wheel consists of several small free rollers so that the wheel can move in all directions. Each omni-directional wheel is directly connected to a servo brake. Three encoders are also installed on three wheels for odometry. We used MR Brake (Magneto-Rheological fluid Brake: Load Corp., MRB-2107-3, Maximum on-state Torque: 5.6[Nm]) as the servo brake. It provides high responsibility and good linearity on controlling the braking torque of wheels.

In addition, the PRP carries an object through the free joint. By using the free joint, 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 of the human operator for handling the object could be reduced [7]. The reduction of the required force of the human operator is necessarily for a passive robot.

B. Control Condition of Servo Brake

The PRP moves based on only the external force/moment applied to it, because it does not have any actuators such as servo motors. 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 the magnitude of the torque is proportional to the input current of the brake. We have the following condition between the angular velocity of the wheel and the braking torque of a brake-wheel system.

$$t_{bw}\dot{\phi}_w \leq 0 \tag{1}$$

where t_{bw} is the brake torque generated by the servo brake and $\dot{\phi}_w$ is the angular velocity of the wheel with servo brakes. This condition is the servo brake control constraint 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 [4].

C. Fundamental Motion Control Algorithm of Single PRP

Firstly, we define the coordinate systems for controlling the PRP. ${}^g\Sigma$ is the global coordinate system and ${}^r\Sigma$ is the robot coordinate system attached to the PRP as shown in Fig.2. We express a position and an orientation of the PRP with respect to the ${}^r\Sigma$ as ${}^r\boldsymbol{q}_r = [{}^r x_r \ {}^r y_r \ {}^r\theta_r]^T$. The force/moment applied to the robot by a human operator is ${}^r\boldsymbol{F}_h = [{}^r f_{h_x} \ {}^r f_{h_y} \ {}^r n_{h_z}]^T$, and the brake force/moment generated by the servo brake attached to each wheel of the PRP is ${}^r\boldsymbol{F}_b = [{}^r f_{b_x} \ {}^r f_{b_y} \ {}^r n_{b_z}]^T$.

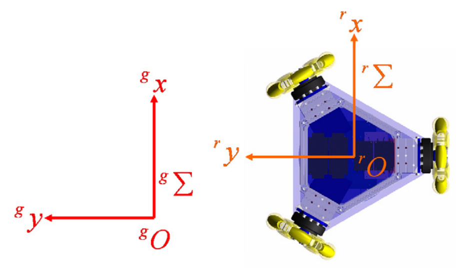


Fig. 2. Coordinate Systems of Single PRP

Under the assumption that the PRP does not consider the apparent dynamics of PRP's rotation 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;

$${}^r\boldsymbol{M}_r {}^r\ddot{\boldsymbol{q}}_r + {}^r\boldsymbol{D}_r {}^r\dot{\boldsymbol{q}}_r = {}^r\boldsymbol{F}_h - {}^r\boldsymbol{F}_b \tag{2}$$

where,

$${}^r\boldsymbol{M}_r = \begin{bmatrix} {}^r m_{r_x} & 0 \\ 0 & {}^r m_{r_y} \end{bmatrix}, {}^r\boldsymbol{D}_r = \begin{bmatrix} {}^r d_{r_x} & 0 \\ 0 & {}^r d_{r_y} \end{bmatrix},$$
$${}^r\boldsymbol{q}_r = \begin{bmatrix} {}^r x_r \\ {}^r y_r \end{bmatrix}, {}^r\boldsymbol{F}_h = \begin{bmatrix} {}^r f_{h_x} \\ {}^r f_{h_y} \end{bmatrix}, {}^r\boldsymbol{F}_b = \begin{bmatrix} {}^r f_{b_x} \\ {}^r f_{b_y} \end{bmatrix} \tag{3}$$

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

For controlling the dynamics of a PRP, we consider to design the motion control algorithm of the PRP as if it has the following dynamics.

$${}^r\boldsymbol{M}_r {}^r\ddot{\boldsymbol{q}}_r + {}^r\boldsymbol{D}_d {}^r\dot{\boldsymbol{q}}_r = {}^r\boldsymbol{F}_h \tag{4}$$

where,

$${}^r\boldsymbol{D}_d = \begin{bmatrix} {}^r d_{d_x} & 0 \\ 0 & {}^r d_{d_y} \end{bmatrix} \tag{5}$$

${}^r\boldsymbol{D}_d \in \boldsymbol{R}^{2\times2}$ is the apparent damping coefficient matrix of the PRP. If we can change the apparent damping coefficient matrix of the PRP expressed by ${}^r\boldsymbol{D}_d$ appropriately, the maneuverability of the PRP could be changed.

For realizing above dynamics, we derive the required brake force for controlling the PRP from eq.(2) and eq.(4) as follows;

$${}^r\boldsymbol{F}_b = ({}^r\boldsymbol{D}_d - {}^r\boldsymbol{D}_r){}^r\dot{\boldsymbol{q}}_r \tag{6}$$

When we derive the brake force/moment from eq.(6) and specify the brake torques of the wheels based on the servo brake condition as shown in eq.(1), the PRP can move as if it has the apparent dynamics expressed in eq.(4).

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 ${}^r\boldsymbol{F}_b = [{}^r f_{b_x} \ {}^r f_{b_y} \ 0]^T$ applied to the robot as follow;

$$\boldsymbol{\tau}_b = \boldsymbol{J}^T \ {}^r\boldsymbol{F}_b \tag{7}$$

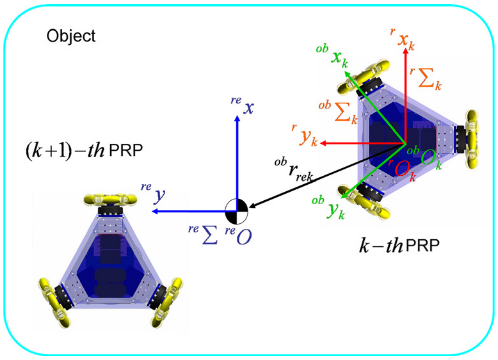


Fig. 3. Relationship between PRP and Representative Point of Object

This relation is exactly the same as a 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 the 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 was explained in [7].

III. Motion Control of Multiple Passive Mobile Robots for Handling an Object

If we can change the motion characteristics of the handling object supported by multiple PRPs arbitrarily, the maneuverability of the human operator for handling the object would be improved. In this section, we discuss a motion control algorithm of multiple PRPs for realizing the variable dynamics of the handling object carried by them and we realize simple collision avoidance function by changing the motion characteristics of the handling object according to the environment information.

A. Coordinated Control of Multiple Passive Robots for Realizing Variable Motion Characteristics of an Object

In this research, the PRPs carry the object through the free joint to reduce the required force of the human operator [7]. When we control the motion characteristics of the handling object supported by multiple PRPs, each PRP need to know the relative angle between the orientation of the robot and the object, because the relative angle always changes through the free joint. In this research, we attach a encoder to the free joint for measuring the relative angle between the robot and the handling object $^{ob}\theta_r$. Note that we define the object coordinate system $^{ob}\Sigma_k$ as shown in Fig.3 to express the motion dynamics of the handling object with respect to $k-th$ robot.

When we define the rotation matrix from the robot coordinate system to the object coordinate system $^{ob}\boldsymbol{R}_r$, the required brake force and the motion of the PRP with respect to the object coordinate system are expressed as the following equations.

$$^{ob}\boldsymbol{F}_b = {}^{ob}\boldsymbol{R}_r{}^{r}\boldsymbol{F}_b, \quad {}^{ob}\boldsymbol{q}_r = {}^{ob}\boldsymbol{R}_r{}^{r}\boldsymbol{q}_r \tag{8}$$

where,

$$^{ob}\boldsymbol{R}_r = \begin{bmatrix} \cos {}^{ob}\theta_r & -\sin {}^{ob}\theta_r \\ \sin {}^{ob}\theta_r & \cos {}^{ob}\theta_r \end{bmatrix} \tag{9}$$

From these relationships, we can rewrite the apparent dynamics of $k-th$ PRP expressed in eq.(4) as follows:

$$^{ob}\boldsymbol{M}_k{}^{ob}\ddot{\boldsymbol{q}}_{rk} + {}^{ob}\boldsymbol{D}_{dk}{}^{ob}\dot{\boldsymbol{q}}_{rk} = {}^{ob}\boldsymbol{F}_{hk} \tag{10}$$

where $^{ob}\boldsymbol{M}_k \in \boldsymbol{R}^{2\times 2}$ is the actual inertial matrix of the handling object including the inertia of the PRP and $^{ob}\boldsymbol{D}_{dk} \in \boldsymbol{R}^{2\times 2}$ is the apparent damping coefficient matrix of the handling object with respect to the object coordinate system.

When we define the representative point of the object in the arbitrarily position on the object and the coordinate system $^{re}\Sigma$ is attached to it, we can derive the apparent dynamics of the object around its representative point. Under the assumption that n robots carry the object through the free joint, the angular velocity and the angular acceleration of the orientation of the object $^{re}\dot{\theta}_{ob}$, $^{re}\ddot{\theta}_{ob}$ with respect to the $^{re}\Sigma$ are expressed by using the angular velocity and the angular acceleration of the orientation of the object $^{ob}\dot{\theta}_{obk}$, $^{ob}\ddot{\theta}_{obk}$ with respect to the object coordinate system of $k-th$ robot as follows;

$$^{re}\dot{\theta}_{ob} = {}^{ob}\dot{\theta}_{obk}, \quad {}^{re}\ddot{\theta}_{ob} = {}^{ob}\ddot{\theta}_{obk} \tag{11}$$

In addition, the relationships of the velocity and the acceleration between the representative point and the $k-th$ robot are expressed as follows;

$$^{re}\dot{\boldsymbol{q}}_{ob} = {}^{ob}\dot{\boldsymbol{q}}_{rk} + {}^{ob}\dot{\theta}_{obk}\ \mathbf{P}_k^T, \tag{12}$$

$$^{re}\ddot{\boldsymbol{q}}_{ob} = {}^{ob}\ddot{\boldsymbol{q}}_{rk} + {}^{ob}\ddot{\theta}_{obk}\ \mathbf{P}_k^T \tag{13}$$

where $^{re}\dot{\boldsymbol{q}}_{ob}$, $^{re}\ddot{\boldsymbol{q}}_{ob}$ are the velocity and the acceleration of the object around the representative point, and we assumed that $\mathbf{P}_k$ is a matrix defined by the element of the translation vector $^{ob}r_{rek} = (r_{xk}, r_{yk})^T$ as follows;

$$\mathbf{P}_k = \begin{bmatrix} -r_{yk} & r_{xk} \end{bmatrix} \tag{14}$$

From these relationships, we can derive the apparent dynamics of the object around its representative point as follows;

$$\begin{bmatrix} \sum {}^{ob}\boldsymbol{M}_k & \sum -{}^{ob}\boldsymbol{M}_k\mathbf{P}_k^T \\ \sum -\mathbf{P}_k{}^{ob}\boldsymbol{M}_k & \sum \mathbf{P}_k{}^{ob}\boldsymbol{M}_k\mathbf{P}_k^T \end{bmatrix} \begin{bmatrix} {}^{re}\ddot{\boldsymbol{q}}_{ob} \\ {}^{re}\ddot{\theta}_{ob} \end{bmatrix} + \begin{bmatrix} \sum {}^{ob}\boldsymbol{D}_k & \sum -{}^{ob}\boldsymbol{D}_k\mathbf{P}_k^T \\ \sum -\mathbf{P}_k{}^{ob}\boldsymbol{D}_k & \sum \mathbf{P}_k{}^{ob}\boldsymbol{D}_k\mathbf{P}_k^T \end{bmatrix} \begin{bmatrix} {}^{re}\dot{\boldsymbol{q}}_{ob} \\ {}^{re}\dot{\theta}_{ob} \end{bmatrix} = \begin{bmatrix} {}^{re}\boldsymbol{F}_h \\ {}^{re}N_h \end{bmatrix} \tag{15}$$

where, $^{re}\boldsymbol{F}_h$ and $^{re}N_h$ are external force and moment applied to the object by the human operator and all of the PRPs;

$$^{re}\boldsymbol{F}_h = \sum_{k=1}^{n} {}^{re}\boldsymbol{F}_{hk} = \sum_{k=1}^{n} {}^{ob}\boldsymbol{F}_{hk} \tag{16}$$

$$^{re}N_h = \sum_{k=1}^{n} {}^{re}N_{hk} = \sum_{k=1}^{n}(-{}^{ob}r_{re} \times {}^{ob}\boldsymbol{F}_{hk}) \tag{17}$$

As shown in eq.(15), the behavior of the object is very complicated. We could not use such dynamics expressed in eq.(15) as the apparent dynamics of the handling object for improving the maneuverability. The conventional researches point out that the simple dynamics is suitable for handling a large or a long object in cooperation with a human [8], [9].

To realize the simple dynamics of the object, we consider geometrical constraints so that the apparent dynamics of the handling object is specified to the center of the gravity as satisfying the following equations.

$$\sum_{k=1}^{n} {}^{ob}\boldsymbol{M}_k \mathbf{P}_k'^T = 0 \tag{18}$$

$$\sum_{k=1}^{n} {}^{ob}\boldsymbol{D}_{dk} \mathbf{P}_k'^T = 0 \tag{19}$$

where,

$$\mathbf{P}_k' = \begin{bmatrix} r_{yk} & r_{xk} \end{bmatrix} \tag{20}$$

Then, the resultant impedance of the object expressed in eq.(15), is rewritten as follows;

$$\begin{bmatrix} \sum {}^{ob}\boldsymbol{M}_k & 0 \\ 0 & \sum \mathbf{P}_k {}^{ob}\boldsymbol{M}_k \mathbf{P}_k^T \end{bmatrix} \begin{bmatrix} {}^{re}\ddot{\boldsymbol{q}}_{ob} \\ {}^{re}\ddot{\theta}_{ob} \end{bmatrix} + \begin{bmatrix} \sum {}^{ob}\boldsymbol{D}_k & 0 \\ 0 & \sum \mathbf{P}_k {}^{ob}\boldsymbol{D}_k \mathbf{P}_k^T \end{bmatrix} \begin{bmatrix} {}^{re}\dot{\boldsymbol{q}}_{ob} \\ {}^{re}\dot{\theta}_{ob} \end{bmatrix} = \begin{bmatrix} {}^{re}\boldsymbol{F}_h \\ {}^{re}N_h \end{bmatrix} \tag{21}$$

When we specify the apparent dynamics of the object around the center of the gravity of the object based on this equation and the human operator applies an intentional force/moment to it, we realize simple dynamics of the object around it for improving the maneuverability of the human operator.

B. Orientation Control of Handling Object based on Position of Representative Point

Though the human operator generally applies an intentional force/moment to the representative point for handling the object, if we change the position of the representative point of the object from the point to which human operator applied the intentional force, the maneuverability of the handling object can be changed.

As one of the examples for changing the maneuverability based on the moving of the representative point, in this paper, we pay special attention to the collision avoidance motion of the handling object. If each robot detects the position of the obstacles and changes the orientation of the object based on the collaboration of the multiple mobile robots, human operator could transport the object by only applying an intentional force to it without applying the intentional moment. It would be very helpful for handling of a large or a long object.

In this research, we propose a collision avoidance method by extending the method for changing the apparent dynamics of the handling object proposed in the previous section. We assume that each robot has a sensor for measuring

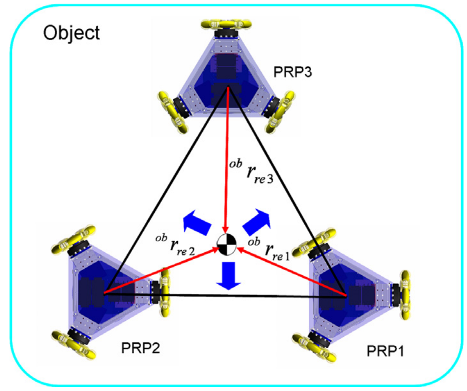


Fig. 4. Geometrics Constraints among Robots and Representative Point

the distance between the robot and the obstacle such as a laser range finder or an ultrasonic sensor. When a robot detects an obstacle and need to avoid a collision with it, the damping parameters of the robot as shown in eq.(10) along the direction of the obstacle is increased with keeping the geometric constraints among robots and the representative point of the object expressed in eq.(18) and eq.(19).

In the previous section, the representative point of the object is located at the center of the gravity so that the geometrical constraint expressed in eq.(18), eq.(19) is satisfied. However, if we can change the damping parameters of each robot based on eq.(19), we can control the position of the representative point of the object as shown in Fig.4 with respect to the damping coefficient. The geometrical constraints expressed in eq.(19) says that the representative point could be located at the inside among n mobile robots as shown in Fig.4.

In this case, the apparent dynamics of the object around the representative point is expressed as follows;

$$\begin{bmatrix} \sum {}^{ob}\boldsymbol{M}_k & \sum -{}^{ob}\boldsymbol{M}_k \mathbf{P}_k^T \\ \sum -\mathbf{P}_k {}^{ob}\boldsymbol{M}_k & \sum \mathbf{P}_k {}^{ob}\boldsymbol{M}_k \mathbf{P}_k^T \end{bmatrix} \begin{bmatrix} {}^{re}\ddot{\boldsymbol{q}}_{ob} \\ {}^{re}\ddot{\theta}_{ob} \end{bmatrix} + \begin{bmatrix} \sum {}^{ob}\boldsymbol{D}_k & 0 \\ 0 & \sum \mathbf{P}_k {}^{ob}\boldsymbol{D}_k \mathbf{P}_k^T \end{bmatrix} \begin{bmatrix} {}^{re}\dot{\boldsymbol{q}}_{ob} \\ {}^{re}\dot{\theta}_{ob} \end{bmatrix} = \begin{bmatrix} {}^{re}\boldsymbol{F}_h \\ {}^{re}N_h \end{bmatrix} \tag{22}$$

From this equation, the motion characteristics of the object around the representative point is complicated when the robot is accelerated. However, if we assume that the human operator applies only intentional force to the center of the gravity of the object, the apparent dynamics of the object around its center of the gravity has the following one and the angular velocity around this point is generated based on only intentional force of the human operator without applying the moment to the object.

$$\sum {}^{ob}\boldsymbol{M}_k {}^{re}\ddot{\boldsymbol{q}}_{ob} + \sum {}^{ob}\boldsymbol{D}_k {}^{re}\dot{\boldsymbol{q}}_{ob} - \sum {}^{ob}\boldsymbol{D}_k \mathbf{P}_k^T {}^{re}\dot{\theta}_{ob} = {}^{re}\boldsymbol{F}_h \tag{23}$$

As one of examples, when we utilize two PRPs, we can change the position of the representative point along the line

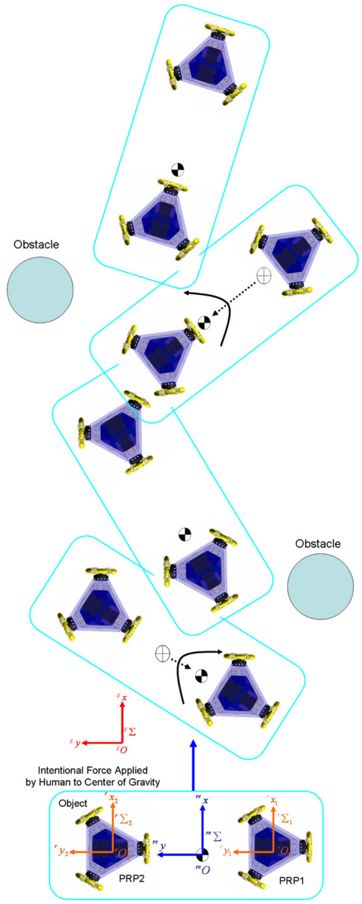


Fig. 5. Two Robots Coordination for Collision Avoidance

between both robots as shown in Fig.5 by satisfying the geometric constraints. When a human operator applies the intentional force to the center of the gravity of the object which is the middle of the object in this case and a PRP detects the obstacle along the heading direction of the PRP, the PRP changes the damping parameters along ${}^{ob}x$ direction and the representative point is moved close to the PRP as shown in Fig.5. As the result, the object rotates based on the applied force and collision avoidance motion is realized. In the same way, if other robot detects the other obstacle and change the damping parameters, the representative point is moved to another side and collision avoidance function is realized again as shown in Fig.5.

By using this method, we can realize simple collision avoidance motion of the object by applying only intentional force to it without using the explicit communication between robots. Of course, we should consider the appropriate damping parameters for controlling the orientation of the object according to environment information, handling tasks information and operational motion characteristics of the human operator as future works.

IV. Experiments for Handling Object

In this paper, we experimented with two PRPs for handling a single object to illustrate the validity of the proposed control algorithm realizing the variable motion characteristics of the handling object and the collision avoidance function.

A. Experiments for Handling of Object with Anisotropic Motion Characteristic

In this experiment, we realize an anisotropic apparent motion characteristics 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.(10) respectively. In this experiment, we define the heading direction of the object along ${}^{re}x$ axis of the object coordinate system so that the human operator can move the object along this direction. On the other hand, ${}^{re}y$ 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 ${}^{ob}d_{d_x} = 10[Ns/m]$ and ${}^{ob}d_{d_y} = 2000[Ns/m]$.

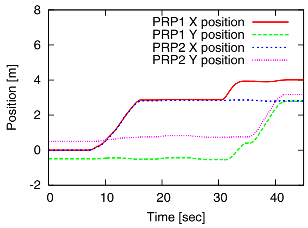
Experimental results are illustrated in Fig.6. Fig.6(a) expresses the trajectory of each PRP along ${}^{g}x$ and ${}^{g}y$ direction with respect to the time, Fig.6(b) expresses the path and the orientation of each PRP on xy-plane, Fig.6(c),(d) are force applied to the PRP with respect to the global 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.

From Fig.6(a),(b), the handling task was done based on the force applied along ${}^{g}x$ direction around $7[sec]$. Around $20[sec]$ and around $25[sec]$ as shown in Fig.6(a),(c),(d), the PRP did not move in spite of applying the force (about $50[N]$) applied along ${}^{g}y$ direction. On the other hand, after the human operator rotated the direction of the handling object as shown in Fig.6(b), he could move it along ${}^{g}y$ direction.

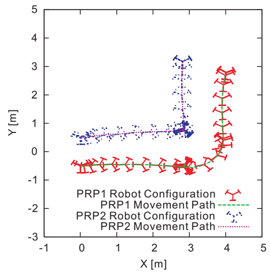
B. Experiments of Object Handling for Collision Avoidance

Next, we experimented with two PRPs for realizing a simple collision avoidance function. In this experiment, we pull the object supported by two PRPs by using a rope, so that the human operator cannot apply any moment to the object. The experimental set up is similar to Fig.5 and we specify the positions of two obstacles to each PRP in advance. In this experiment, when each PRP close to the obstacle, the damping parameters of the PRP were changed from ${}^{ob}d_{d_x} = 50[Ns/m]$ and ${}^{ob}d_{d_y} = 10[Ns/m]$ to ${}^{ob}d_{d_x} = 250[Ns/m]$ and ${}^{ob}d_{d_y} = 10[Ns/m]$ and the position of the representative point moved. Those damping parameters were specified experimentally. As the result, the orientation of the object was changed based on the applied force by the human operator.

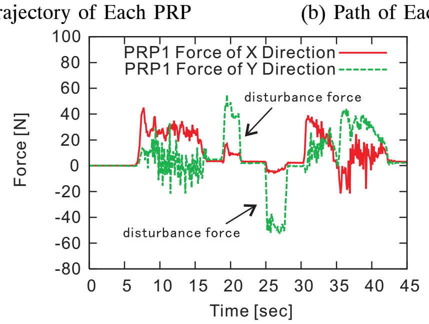
Experimental results are illustrated in Fig.7 and Fig.8. Fig.7(a) expresses the trajectory of each PRP along ${}^{g}x$ and ${}^{g}y$ direction with respect to the time, Fig.7(b) expresses the orientation of the object calculated by each PRP. Fig.7(c) expresses the path of each PRP on xy-plane. From Fig.7 and Fig.8, you can see that the human operator transports the object by applying the force to it and collision avoidance motion is realized by changing the orientation of it.



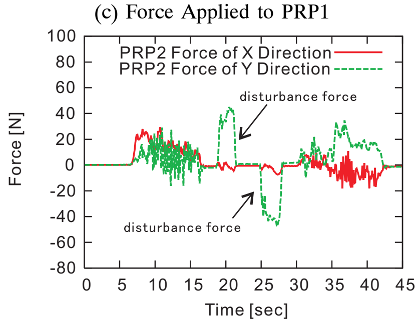
(a) Trajectory of Each PRP



(b) Path of Each PRP

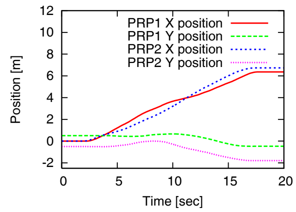


(c) Force Applied to PRP1

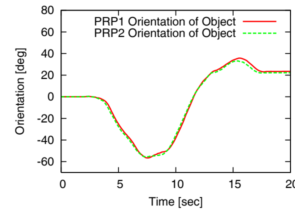


(d) Force Applied to PRP2

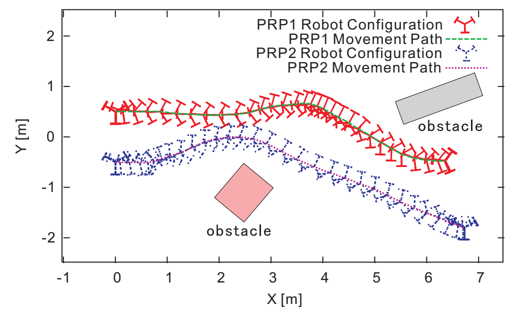
Fig. 6. Experimental Results for Variable Motion Characteristic of Object



(a) Trajectory of Each PRP



(b) Orientation of Object

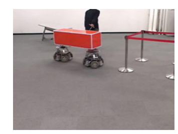


(c) Path of Each PRP

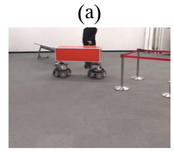
Fig. 7. Experimental Results for Collision Avoidance

(a)

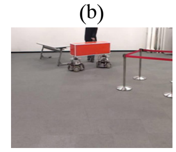
(b)



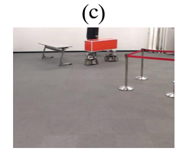
(c)



(d)



(e)



(f)

Fig. 8. Experiment for Collision Avoidance

V. Conclusions

In this paper, we proposed motion control algorithms of multiple passive mobile robots for handling a single object in cooperation with a human. By controlling each mobile robot in the decentralized way, we realized several kinds of motion characteristics of the object to improve the maneuverability of the human operator. By focusing on the apparent dynamics of representative point of the object and its position, we realized an anisotropic apparent motion characteristics of the handling object and the simple obstacle avoidance function as examples. The proposed motion control algorithms are implemented to two PRPs actually, and experimental results illustrated the validity of the proposed algorithms. As future works, we should consider how to design the appropriate dynamics of the object including the position of the representative point according to the environment information, task information and/or operational characteristics of the human operator.

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