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Structural Design for Omni-Directional Mobile Base of Passive-type Mobile Robot

Yasuhisa Hirata*, Hamin Song*, Zhidong Wang** and Kazuhiro Kosuge*
** Department of Bioengineering and Robotics, Tohoku University,*
6-6-01, Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
*** Department of Advanced Robotics, Chiba Institute of Technology,*
2-17-1,Tsudanuma, Narashino, Chiba 275-0016, Japan
{hirata, song, kosuge}@irs.mech.tohoku.ac.jp, zhidong.wang@it-chiba.ac.jp

***Abstract*— We have developed a passive-type mobile robot based on the concept of the passive robotics. Different from the active-type robot with servo motors, the developed passive-type robot is controlled by using the servo brakes, in which its driving force is applied by a human operator. Therefore, the original motion characteristics of the robot with respect to the human handling force are very important for its maneuverability and it is changed by the structural design of the robot such as the arrangement of the wheels. In this paper, we investigate the original motion characteristics of the passive-type omni-directional mobile robot and discuss the equilibrium orientation of the robot and the required handling force of the human operator. Finally, we consider the appropriate arrangement of the wheels of the robot for realizing the human support system such as object handling system and the walking support system.**

Index Terms*— Passive Robotics, Passive-type Mobile Robot, Original Motion Characteristics, Structural Design

I. Introduction

With the development of robot technologies, intelligent robot systems are expected to utilize in many fields such as home, office, hospital and so on, where are the environments with humans. Especially, some of these robot systems have to support the human being based on the physical interaction between the robot systems and the human being. By considering the physical interaction, we could realize the several assistive tasks for human such as the walking assist, sit to stand assist, object handling and so on.

To realize these tasks, many researchers have been developed several kinds of intelligent robot systems. Most of the conventional intelligent robot systems have servo motors and they are controlled based on the sensory information such as the force/torque sensor, ultrasonic sensor and laser range finder. Therefore, the high performances for intelligent robot systems are realized based on the many functions such as power assist, collision avoidance, navigation, variable motion characteristics, and so on.

However, if we cannot control the servo motors of the intelligent systems appropriately, they would move unintentionally and be a dangerous system for human being. Especially, in Japan, the legislation has to be formulated for using them in a living environment with humans practically. In addition, such system with servo motors must be heavy and its structure must be complicated, because it has servo motors, reduction gears, sensors, controller, batteries, and so on. The battery problem is also very severe for its long time working, because the servo motors need much electricity to work. Without solving these problems we could not use the intelligent robot systems with servo motors practically in the real world environment with humans.

On the other hand, some researchers have considered the passive-type robot systems from the safety point of view for using them in the real world environment with humans. Goswami et al. have proposed a concept of the passive robotics [1], in which the system moves passively based on the external force/moment without using the actuators, and have dealt with the passive wrist, whose components are springs, hydraulic cylinders, dampers, and so on. The passive wrist computes a particular motion in response to every applied force and changes the physical parameters of the components for realizing the desired motion.

This passive robotics concept is extended to the mobile robot systems for realizing the object handling and the walking assist. Peshkin et al. have developed a handling system of an object referred to as Cobot [2] based on passive robotics, which consists of the caster and the servo motor for steering its caster. In the fields of research on intelligent walker system, Wasson et al. [3] and A. J. Rentschler et al. [4] have proposed passive-type intelligent walkers. In the most of them, the servo motor was attached to the steering wheel similar to Cobot system in order to control only the steering angle based on the information of an environment for navigating the user.

We have also proposed passive-type intelligent walker referred to as RT Walker [5] and passive-type object handling system referred to as PRP (Passive-type Robot Porter) [6]. Different from the other passive-type walkers or object handling system such as Cobot, RT Walker and PRP control the servo brakes attached to the wheels appropriately to realize the several functions without using any servo motors. These passive-type mobile robot systems are intrinsically safe, since they do not move unintentionally. The concept of the passive robotics will be very useful for many types of the intelligent systems based on the physical interaction between the human and the system from the safety point of view.

However, though the driving force of the passive-type mobile robot system is the force/moment applied by the human operator, the operation of the robot system would be out of control if the required external force and moment for moving the robot become large. In addition, the motion characteristics of the robot with respect to the human handling force are very important for its maneuverability and it is changed by the arrangement of the wheels of them. In this paper, we investigate the original motion characteristics of the omni-directional passive-type mobile robot and discuss the equilibrium orientation of the robot and the required handling force of the human operator.

In the following part of this paper, we introduce a developed passive-type mobile robot system referred to as PRP (Pasive-type Robot Porter) briefly. Next, we consider the moment applied to the center of mass of the robot based on the friction force of the wheels, and discus the equilibrium orientation of the robot. Finally, we consider the required handling force of the human being to move the robot with keeping the same velocities, and investigate the appropriate arrangement of the wheels of the robot for supporting the human being.

II. Passive type Robot Porter -PRP-

We have developed a passive-type robot porter referred to as PRP as shown in Fig.1 based on the concept of the passive robotics [6]. PRP consists of three omni-directional wheels with servo brakes (MR Brakes), some sensors such as force/torque sensor and encoder, a controller, and batteries as shown in Fig.2. The omni-directional wheel equips several small rollers so that the wheel can move in all directions. Each omni-directional wheel is directly connected to a servo-brake, and three wheels are arranged to have $2\pi/3$ between each pair of wheel axes. 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 investigate 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 PRP depends on the characteristics of servo brakes. In the first prototype of PRP, we used MR 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.

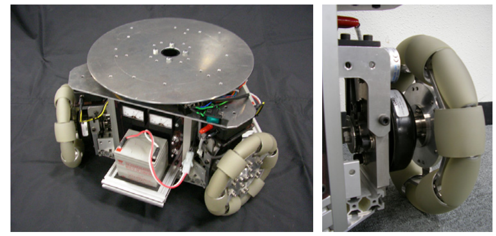


Fig. 1. Passive-type Robot Porter -PRP-

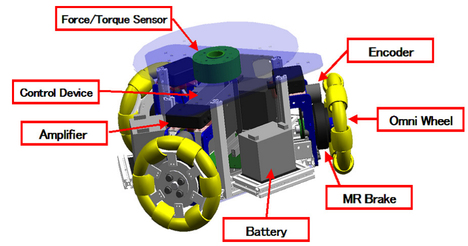


Fig. 2. Components of PRP

By controlling the brake system, we could realize the several kinds of functions such as variable motion characteristics, path following, collision avoidance, gravity compensation and so on, which are the similar functions for the active-type mobile robot system with servo motors. However, in this paper, we do not consider about the control of the brake system. Before considering the brake control, the original motion characteristics of the robot which is depend on the structural design such as the arrangement of the wheels are very important. If the original motion characteristics of the robot are complicated with respect to the force/moment applied by the human, we could not realized the several functions and could not improve the maneuverability of human operator, even if we design the brake control algorithm. Because the brake systems do not generate the driving force and only restrict the external force/moment applied by the human different from the control of the servo motors.

III. Original Motion Characteristics of Passive-type Mobile Robot

In this section, we discuss the original motion characteristics of the passive-type mobile robot with omni-directional mobile base. For the simplicity of the discussion, in this research, we restrict our attention to the passive-type omni-directional mobile robot with three wheels like PRP. In addition, we assume that the rotational axis of each omni-direction wheel is intersected with each other at a point and the center of mass of the robot is on the point. In this case, a moment around the point is generated based on the friction forces existed between the wheels and the ground during the motion of the robot.

A. Moment Generated around Center of Mass of Robot Based on Friction of Wheels

For investigating the motion of the passive-type mobile robot with three omni-directional wheels with respect to their friction forces, we experimented with PRP for moving it. In this experiment, PRP grasps the object thorough the free joint and a human push the object along ${}^{O}x$ axis of the object coordinate systems ${}^{O}\Sigma$ attached to the object for transporting it as shown in Fig.3. In this case, the friction force is applied to each wheel and a moment generates from the different friction forces of the wheels around the center of mass of the robot. As the results, a rotational motion of the robot around the center of mass is generated. In this experiment, since PRP grasps the object thorough the free joint, the human could not applies the intentional moment to the robot so that he/she could not control the orientation of the robot system.

Thorough these experiments, we fund that the orientation of the robot usually converse to some orientations because of the friction force of the wheels. This means that the motion characteristics of the robot with respect to the intentional force applied by the human are depend on the arrangement of the wheels and this arrangement influences the maneuverability of the robot system. In this section, we discuss the friction force applied to the wheels and the motion characteristics of the robot with respect to the intentional force applied by the human.

Firstly, we consider a moment generated around the center of mass of the robot based on the friction force of the wheels for investigating the original motion characteristics of the robot. For analyzing the motion of the robot, we define the coordinate systems as shown in Fig.3. ${}^{G}\Sigma$ is the global coordinate system fixed on the ground and ${}^{r}\Sigma$ is the robot coordinate system attached to the point of the center of mass of the robot and its orientation is the same with the orientation of the robot.

In addition, we express the arrangement of the wheels of the robot by using α as shown in Fig,4. By changing the α, we could design the several kinds of mobile base of the robot such as the slender-type mobile base and the wide-type mobile base. In the case of PRP, $\alpha = 120$ and the arrangement of the wheels is symmetry each other.

In this research, we assume that the robot moves to keep the velocity along ${}^{G}x$ axis of the global coordinate system and its damping coefficient of the omni-directional wheels are quall each other and the friction of the small free rollers of the wheels for realizing the omni-directional motion of the robot is ignored. When we consider the rolling friction of the wheels, we can derive a moment generated around the center of mass of the robot with respect to the orientation of the robot.

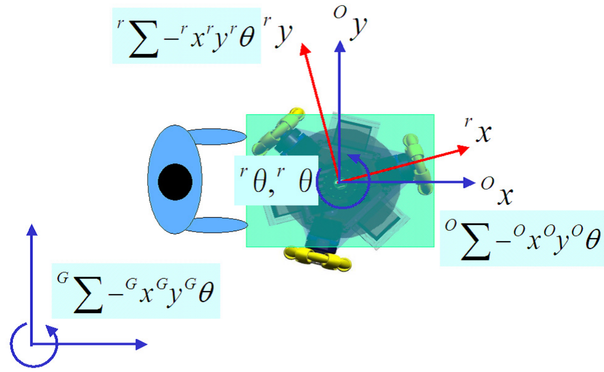
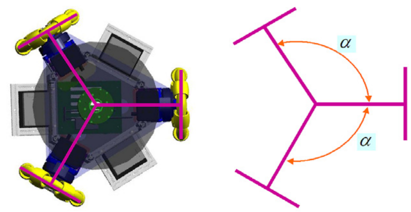


Fig. 3. Coordinate Systems of PRP



(a)PRP Model (b)PRP Simple Model

Fig. 4. PRP Model

Here, we derive the relationship between the velocity of the robot with respect to the global coordinate system ${}^{G}\dot{\boldsymbol{q}} = \left[{}^{G}\dot{x}_r, {}^{G}\dot{y}_r, {}^{G}\dot{\theta}_r\right]^T$ and the velocity of the robot with respect to the robot coordinate system ${}^{r}\dot{\boldsymbol{q}} = \left[{}^{r}\dot{x}_r, {}^{r}\dot{y}_r, {}^{r}\dot{\theta}_r\right]^T$ as follows;

$$ {}^{r}\dot{\boldsymbol{q}} = {}^{r}\boldsymbol{R}_G {}^{G}\dot{\boldsymbol{q}} \tag{1} $$

where,

$$ {}^{r}\boldsymbol{R}_G = \begin{bmatrix} \cos {}^{G}\theta_r & \sin {}^{G}\theta_r & 0 \\ -\sin {}^{G}\theta_r & \cos {}^{G}\theta_r & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

where ${}^{r}\boldsymbol{R}_G$ is the rotational matrix of the velocity of robot from the global coordinate system to the robot coordinate system. When we define the angular velocity of each wheel $\dot{\boldsymbol{\Phi}} = \left[\dot{\phi}_{w1}, \dot{\phi}_{w2}, \dot{\phi}_{w3}\right]^T$ and the Jacobian $\boldsymbol{J}$, the relationship between the angular velocity of the wheel and the velocity of robot is expressed as follows;

$$ {}^{r}\dot{\boldsymbol{q}} = \boldsymbol{J}\dot{\boldsymbol{\Phi}} \tag{2} $$

From eq.(1) and eq.(2), the velocity of robot with respect to the global coordinate system is expressed as the following relationship by using the angular velocity of the wheels $\dot{\boldsymbol{\Phi}}$.

$$ \dot{\boldsymbol{\Phi}} = \boldsymbol{J}^{-1\,r}\boldsymbol{R}_G {}^{G}\dot{\boldsymbol{q}} \tag{3} $$

On the other hand, we can derive the friction force between a wheel and the ground ${}^{w}F_{f_i}$ by using the following equation, when each wheel rotates based on the angular velocity $\dot{\phi}_{wi}$.

$$ {}^{w}F_{f_i} = -\frac{B}{r}\dot{\phi}_{wi} - f\frac{N}{r}\mathrm{sgn}(\dot{\phi}_{wi})(i \in 1,2,3) \quad (4) $$

where,

$$ \mathrm{sgn}(\dot{\phi}_{w1}) = \begin{cases} 1 & 0 <^{G} \theta_r < 180 \\ -1 & 180 <^{G} \theta_r < 360 \\ 0 & {}^{G}\theta_r = 0, 180 \end{cases} $$

$$ \mathrm{sgn}(\dot{\phi}_{w2}) = \begin{cases} 1 & \alpha <^{G} \theta_r < \alpha + 180 \\ -1 & 0 <^{G} \theta_r < \alpha, \alpha + 180 <^{G} \theta_r < 360 \\ 0 & {}^{G}\theta_r = \alpha, \alpha + 180 \end{cases} $$

$$ \mathrm{sgn}(\dot{\phi}_{w3}) = \begin{cases} 1 & 0 <^{G} \theta_r < 180 - \alpha, \\ & 360 - \alpha <^{G} \theta_r < 360 \\ -1 & 180 - \alpha <^{G} \theta_r < 360 - \alpha \\ 0 & {}^{G}\theta_r = 180 - \alpha, 360 - \alpha \end{cases} $$

Here, B is the damping coefficient of the wheel, r is the radius of the wheel, f is the rolling friction of the wheel and N is the normal force applied to the wheel.

In addition, when we define the distance between the center of mass of the robot and the each wheel as l and the vector of the friction force of the wheels expressed in eq.(4), ${}^{w}\boldsymbol{F}_f = [{}^{w}F_{f_1}, {}^{w}F_{f_2}, {}^{w}F_{f_3}]^T$ is transformed to the friction force of the wheel with respect to the global coordinate system ${}^{G}\boldsymbol{F}_f = \left[{}^{G}F_{fx}, {}^{G}F_{fy}, {}^{G}N_{fz}\right]^T$, ${}^{G}\boldsymbol{F}_f$ is expressed as following equation.

$$ {}^{G}\boldsymbol{F}_f = {}^{G}\boldsymbol{R}_w {}^{w}\boldsymbol{F}_f \quad (5) $$

where,

$$ {}^{G}\boldsymbol{R}_w = \begin{bmatrix} \sin{}^{G}\theta_r & \sin({}^{G}\theta_r - \alpha) & \sin({}^{G}\theta_r + \alpha) \\ -\cos{}^{G}\theta_r & -\cos({}^{G}\theta_r - \alpha) & -\cos({}^{G}\theta_r + \alpha) \\ -l & -l & -l \end{bmatrix} $$

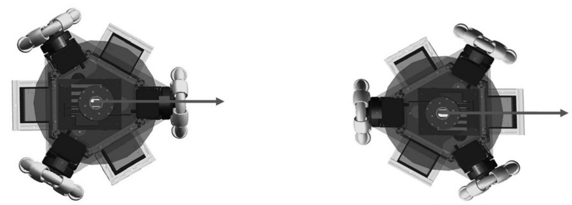
From this equation, the moment generated around the center of mass of PRP ${}^{G}N_{fz}$ is expressed as follows;

$$ {}^{G}N_{f_z} = -l\sum_{i=1}^{3} {}^{w}F_{f_i} \quad (6) $$

From these equations expressed in (3) - (6), we can derive the moment generated by the friction force of the wheels as following equation under the assumption that robot moves along ${}^{G}x$ axis of the global coordinate system with keeping the same velocity.

$$ {}^{G}N_{f_z} = \frac{l}{r^2}B\,{}^{G}\dot{x}_r\{\sin{}^{G}\theta_r + \sin({}^{G}\theta_r - \alpha) + \sin({}^{G}\theta_r + \alpha)\} + f\frac{l}{r}N\{\mathrm{sgn}(\dot{\phi}_{w1}) + \mathrm{sgn}(\dot{\phi}_{w2}) + \mathrm{sgn}(\dot{\phi}_{w3})\} \quad (7) $$

The first term of the right side of eq.(7) depends on the damping coefficient of the wheel and the second term of the right side of eq.(7) depends on the rolling friction of the wheel.



(a) Stable Equilibrium Orientation (b) Unstable Equilibrium Orientation

Fig. 5. Equilibrium Orientation of PRP

B. Equilibrium Orientation of PRP

In this section, especially, we consider the original motion characteristics of PRP. Since three wheels of robot are arranged to have $2\pi/3$ between each pair of wheel axes ($\alpha = 120$), the damping coefficient of eq.(7) is eliminated by the relationship of the trigonometric function and is expressed as follows;

$$ {}^{G}N_{f_z} = f\frac{l}{r}N(\mathrm{sgn}(\dot{\phi}_{w1}) + \mathrm{sgn}(\dot{\phi}_{w2}) + \mathrm{sgn}(\dot{\phi}_{w3})) \quad (8) $$

From this equation, the motion of PRP is influenced by the rolling friction of wheels.

When the value of eq.(8) is equal to zero, PRP could move with keeping its orientation without using any control of the actuators. These orientations are the equilibrium ones. There are two kinds of equilibrium orientations in PRP. One is the stable equilibrium orientation and the other is the unstable equilibrium orientation as shown in Fig.5.

In the stable equilibrium orientation of PRP, the moment around the center of mass of PRP is expressed by the following equations with respect to the sign of the deviation from the stable equilibrium orientation $\Delta\theta$.

(i) for $\Delta\theta = 0$

$$ {}^{G}N_{f_z} = 0 \quad (9) $$

(ii) for $\Delta\theta > 0$

$$ {}^{G}N_{f_z} = -f\frac{l}{r}N \quad (10) $$

(iii) for $\Delta\theta < 0$

$$ {}^{G}N_{f_z} = f\frac{l}{r}N \quad (11) $$

Since f, l, r, N are positive values, ${}^{G}N_{f_z}$ is generated for reducing the deviation of orientation $\Delta\theta$ and the orientation of PRP converge to 60[deg], 180[deg] or 300[deg], which are the stable equilibrium orientations of PRP.

On the other hand, in the unstable equilibrium orientation of PRP, the sign of the moment derived by eq.(8) becomes the same sign of the deviation of the orientation $\Delta\theta$ as follows;

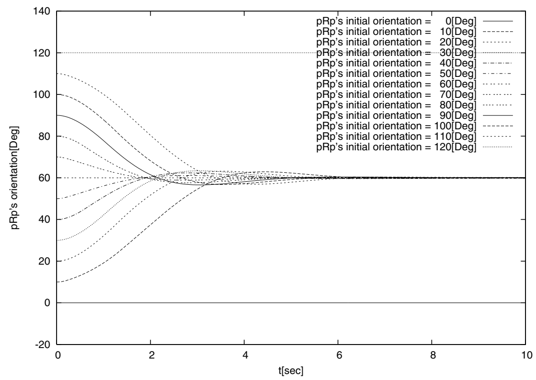


Fig. 6. Simulation Result Showing Change of Orientation of PRP

(i) for $\Delta\theta = 0$

$$^{G}N_{f_z} = 0 \tag{12}$$

(ii) for $\Delta\theta > 0$

$$^{G}N_{f_z} = f\frac{l}{r}N \tag{13}$$

(iii) for $\Delta\theta < 0$

$$^{G}N_{f_z} = -f\frac{l}{r}N \tag{14}$$

In this case, the orientation of PRP diverge from an equilibrium one and these orientations (0[deg], 120[deg] or 240[deg]) are called as unstable equilibrium ones.

For illustrating the validity of the analysis of the equilibrium orientations of PRP, we did simulation for moving PRP based on the constantan force. In this simulation, PRP grasp the object through the free joint and a force is applied to the object along ^{G}x axis of the object coordinate systems as shown in Fig.3. By changing the initial orientation of PRP every 10[deg] from 0[deg] to 120[deg], we investigate the changes of the orientation of PRP. The simulation result is shown in Fig.6.

From this result, you can see that the equilibrium orientations of PRP are 0[deg], 60[deg] and 120[deg], in which the orientation of PRP did not change. When we move PRP from the orientations except 0[deg], 60[deg] and 120[deg], the orientations are converge to 60[deg]. From this result, the stable equilibrium orientations of PRP is 60[deg] and the unstable equilibrium orientation is 0[deg] and [120] which are explained above theoretically.

IV. Required Force of Human for Moving Robot

In this section, we consider the force of human operator required to move the robot with keeping the same velocity. First, we derive the friction force applied along ^{G}x axis of the global coordinate system $^{G}F_{fx}$ by using similar way explained in eq.(1) - eq.(4) as follows;

$$\begin{aligned} ^{G}F_{fx} = & -\frac{B}{r^2}{}^{G}\dot{x}_r\{\sin^2{}^{G}\theta_r + \sin^2({}^{G}\theta_r - \alpha) \\ & + \sin^2({}^{G}\theta_r + \alpha)\} - f\frac{N}{r}\{\sin{}^{G}\theta_r \mathrm{sgn}(\dot{\phi}_{w1}) \\ & + \sin({}^{G}\theta_r - \alpha)\mathrm{sgn}(\dot{\phi}_{w2})\sin({}^{G}\theta_r + \alpha)\mathrm{sgn}(\dot{\phi}_{w3})\} \end{aligned} \tag{15}$$

where,

$$\mathrm{sgn}(\dot{\phi}_{w1}) = \begin{cases} 1 & 0 <^{G} \theta_r < 180 \\ -1 & 180 <^{G} \theta_r < 360 \\ 0 & ^{G}\theta_r = 0, 180 \end{cases}$$

$$\mathrm{sgn}(\dot{\phi}_{w2}) = \begin{cases} 1 & \alpha <^{G} \theta_r < \alpha + 180 \\ -1 & 0 <^{G} \theta_r < \alpha, \alpha + 180 <^{G} \theta_r < 360 \\ 0 & ^{G}\theta_r = \alpha, \alpha + 180 \end{cases}$$

$$\mathrm{sgn}(\dot{\phi}_{w3}) = \begin{cases} 1 & 0 <^{G} \theta_r < 180 - \alpha, \\ & 360 - \alpha <^{G} \theta_r < 360 \\ -1 & 180 - \alpha <^{G} \theta_r < 360 - \alpha \\ 0 & ^{G}\theta_r = 180 - \alpha, 360 - \alpha \end{cases}$$

From eq.(15), we can derive the required intentional force of human being $^{G}F_h$ to move the robot along ^{G}x axis with keeping the same velocity as follows;

$$^{G}F_h = -{}^{G}F_{fx} \tag{16}$$

V. Relationship between Arrangement of Wheels and Motion Characteristics of Robot

In the stable equilibrium orientation of robot, generally, the maneuverability of the robot is good, because unnecessary rotational motion would not occur unless the disturbance force/moment is applied to the robot. On the other hand, in the unstable equilibrium orientation of robot, the maneuverability of the robot decrees because the robot rotates based on the friction of the wheels as soon as its orientation is changed from the unstable equilibrium one.

In addition to the equilibrium orientation of the robot, the required force of human being should be decreased for moving the robot system, because it is passive system controlled by the servo brake and its driving force is the handling force/moment applied by the human. If the required force is large, the several kinds of functions of the robot could not be realized.

In this section, we discuss the structural design for the mobile base of the passive-type mobile robot. Especially, the arrangement of the wheels influences the motion characteristics of the robot. In the arrangement of the wheels like PRP, α is equal to 120 [deg] and the relationship between the orientation of the robot and the required force of human is shown in Fig.7

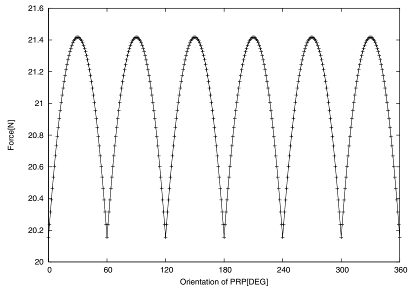
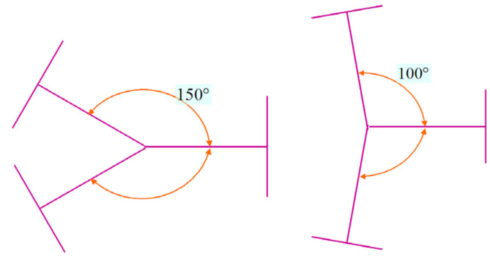
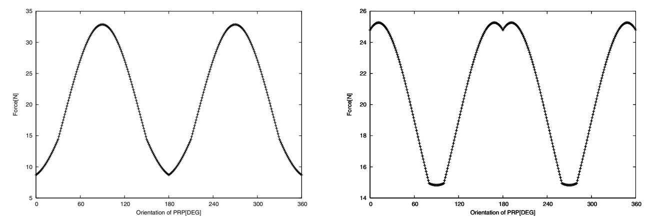


Fig. 7. Relation of PRP's Orientation and Handling Force



(a) Slender-type (b) Wide-type

Fig. 8. Structural Design of Mobile Robot



(a) Slender-type (b) Wide-type

Fig. 9. Handling Force Required to Move Mobile Robot

In Fig.7, the stable equilibrium orientations of the robot are 60[deg], 180[deg] and 300[deg], and the unstable ones are 0[deg], 120[deg] and 240[deg] as explained in previous section. When we investigate the difference of the required force of human between the stable and unstable equilibrium orientations of the robot, we can see that the difference is only 1.2[N]. This value is extremely small, when we consider the tasks such as the object handling. Therefore, such arrangement of the wheel is suitable for the tasks which are not concerned the change of the orientation of the robot.

Next, we consider two kinds of arrangements of the wheels which are asymmetry different from PRP. One is the slender-type arrangement $\alpha = 150$ as shown in Fig.8(a) and the other is the wide-type one $\alpha = 100$ as shown in Fig.8(b). In the slender-type arrangement of the wheels, the stable equilibrium orientations of the robot is $\theta = 180$ and the unstable one is $\theta = 0$. The required force of the human is smallest in the equilibrium orientations of the robot as shown in Fig.9(a). In addition, the difference of the required force between minimum and the maximum forces is about 25[N] which is large value as shown in Fig.9(a). Therefore, such structural design is suitable for the tasks or systems such as the intelligent walker, in which the motion direction is decided in advance and its heading direction is not almost changed.

On the other hand, in the wide-type arrangement of the wheel, the stable equilibrium orientations of the robot is $\theta = 180$ and the unstable one is $\theta = 0$. However, in this arrangement, the smallest operational force for human is different orientations ($\theta = 90, \theta = 270$) from the equilibrium orientations of the robot as shown in Fig.9(b). Therefore, though the human could move the robot easily by using the small amount of the force in $\theta = 90$ and $\theta = 270$, the moment is always generated around the center of mass because these orientations are not equilibrium ones. This situation would decrees the maneuverability of the robot system.

VI. Conclusions

We have developed a passive-type mobile robot based on the concept of the passive robotics. Different from the active-type robot with servo motors, the passive-type robot is controlled by using the servo brakes, in which its driving force is applied by a human operator. Therefore, the original motion characteristics of the robot with respect to the human handling force are very important for its maneuverability and it is changed by the arrangement of the wheels. In this paper, we investigated the original motion characteristics of the omni-directional mobile robot and discussed the stable equilibrium orientation of the robot and the required handling force of the human operator. Finally, we investigate the appropriate arrangement of the wheels of the robot and show that symmetrical-type like PRP and the slender-type structural design of mobile base could apply to the robot system for developing the human support system with good maneuverability.

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