Development of Passive Walking Assist System

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1. Introduction

As societies age and experience a shortage of people for nursing care, handicapped people, including the elderly and blind, find it increasingly necessary to be self-supporting. However, many such people suffer from injuries, poor eyesight, or a general lack of muscular strength, and need the support of other people in daily activities. In the living environment, the ability to walk is one of the most important and fundamental functions for humans, and enables them to realize high-quality lives.

This article focuses on a walker-type support system, which works on the basis of the physical interaction between the system and the user. Walkers are widely used by the handicapped because they are simple and easy to use. Many robotics researchers have considered improving their functionality by adding wheels with actuators and controlling them based on robot technology (RT), such as motion control technology, sensing technology, vision technology, and computational intelligence.

Fujie et al. developed a power-assisted walker for physical support during walking [1]. We developed a motion control algorithm for an intelligent walker with an omni-directional mobile base, in which the system is moved based on the user's intentional force/moments [2]. Manuel et al. proposed a non-holonomic navigation system for a walking-aid robot named Care-O-bot II [3]. Savaniti et al. developed a motorized rollator [4]. Yu et al. proposed the PAMM system to provide mobility assistance and user health status monitoring [5]. Kotani et al. proposed the HITOMI system, which helps the blind navigate outdoors [6].

Many intelligent walkers based on RT consist of servo motors mounted on a mobile base and sensors such as force/torque and ultrasonic sensors. Information from many types of sensors controls the servo motors. By appropriately controlling the servo motors, these intelligent walkers provide many functions, such as variable motion, obstacle avoidance, and navigation; thus, they provide a maneuverable system that supports walking.

On the other hand, simple walkers without servo motors consisting of a frame, wheels or casters, and handbrakes, are well known and commercially available. People can use these walkers intuitively, because they move these systems passively using intentional force/moment. However, unlike active intelligent walkers that employ servo motors, it is impossible to change the apparent dynamics of these systems; they are completely passive and cannot adapt to differing user difficulties. In addition, these systems cannot move properly in an environment with obstacles or slopes, because they offer no environment-based control over their motion.

In this article, we consider a passive intelligent walker, which is not only simple and safe but also offers many functions similar to those found in active walkers. We develop a passive intelligent walker called the RT Walker that uses servo brakes and incorporates passive robotics. First, we explain the concept of passive robotics, and introduce the passive intelligent walker. Then, we propose motion control algorithms that allow the walker to adapt to user characteristics and move based on information about its environment, and evaluate the validity of these motion control algorithms through several experiments.

2. Passive Robotics

For practical use of intelligent systems in the real world, we need to consider two main points: achieving high performance and user safety. Most conventional intelligent 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 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, active intelligent 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.

Goswami et al. proposed the concept of passive robotics [7], 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 [8] consisting of a caster and a servo motor for steering the caster based on passive robotics.

Wasson et al. [9] and MacNamara et al. [10] proposed passive intelligent walkers. 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. The RT Walker proposed in this article also has passive dynamics with respect to the force/moment applied. It differs from other passive walkers in that it controls servo brakes appropriately without using any servo motors. 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.

3. RT Walker

Conventional passive intelligent walkers consist of a frame for supporting the user's weight, a steering wheel, manual or automatic brakes, and sensors for detecting environmental information. A steering-wheel actuator is used for navigation in the environment. Brake systems such as hand brakes or automatic brakes limit the speed of the walker and prevent the user from falling. These functions, in particular, are important and essential for the safety of users.

In this research, we pay special attention to the braking system, and propose a new passive intelligent walker (RT Walker), which uses servo brake control. It differs from conventional passive intelligent walkers in that it does not have servo motors for steering. However, 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.

The developed RT Walker is shown in Fig. 1. This prototype consists of a support frame, two passive casters, two wheels with servo brakes (referred to as powder brakes), a laser range finder, tilt angle sensors, and a controller. The part of the rear wheel with the powder brake is shown in Fig. 2; the brake torque is transferred directly to the axle. The brakes change the torque almost in proportion to the input current.

RT Walker is lightweight because its structure is relatively simple compared to active intelligent walkers, and it needs little electricity to operate the servo brakes. The driving force of the RT Walker is the actual force/moment applied by the user, and therefore, he/she can move it passively without using the force/torque sensor. By changing the torque of the two rear wheels appropriately and independently, we can control the motion of the RT Walker, which receives environmental information from its laser range finder and tilt angle sensors. Based on this information, the RT Walker can realize the collision avoidance, gravity compensation, and other functions.

The servo brake and laser range finder are relatively expensive; however, they are high-performance components intended for industrial fields. In the welfare fields, human-assistance devices do not require high precision motions and the part costs could be reduced if they are designed for the human support systems. Therefore, from the viewpoint of safety and cost effectiveness, the RT Walker will be used in the near future.

Fig. 1. Passive Intelligent Walker
-RT Walker-

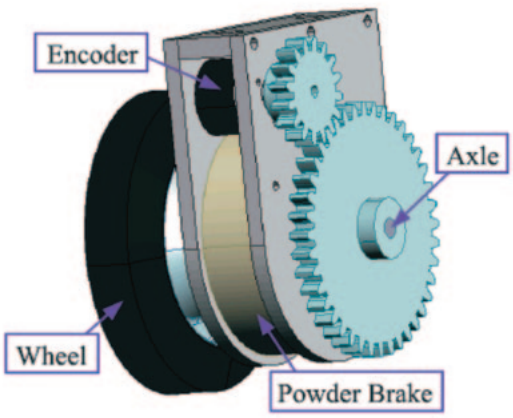


Fig. 2. Real Wheel with Servo Brake

4. Human Adaptive Motion Control

If we can change the apparent dynamics of the RT Walker based on the many kinds of difficulties the users face, we can improve its maneuverability and make it suitable as a rehabilitation system by increasing the load using the brake control. A fall-prevention function could be realized by changing the apparent dynamics of the RT Walker in real time based on the user's situation. The fall-prevention function is very important for walker users.

When we derive the brake force/moment for realizing an apparent dynamics expressed by inertia and damping matrices of the RT Walker and specify the brake torque of the powder brakes, we can vary the mobility characteristics of the RT Walker according to the difficulties faced by the users or their conditions. However, the prototype developed in this research could not provide accurate acceleration feedback because it has only a lower resolution encoder for each wheel to calculate its acceleration. Therefore, to use the RT Walker, we change only damping parameter. Note that, if we use high-resolution encoders or acceleration sensors to detect the correct acceleration of the RT Walker, we can change both the apparent inertia matrix and the apparent damping matrix of the RT Walker.

For illustrating the validity of the human adaptive motion control, we experimented with the RT Walker, in which the human adaptive motion control algorithm is implemented. In the first experiment, we moved the RT Walker on a slope, as shown in Fig. 3. We specified three damping parameters with respect to the walker's heading direction (100, 150, 200[Ns/m]), while maintaining damping with respect to rotational direction. This simulates a user applying a constant force to the walker, and provides velocity responses as experimental results.

Under the assumption that the original inertia, original damping, and the tilt angle of the slope were known, when we specify the desired damping, we can derive the velocity response of the RT Walker, as shown in Fig.3. We can also calculate the actual damping from the velocity responses based on the experiments, which compare the desired damping with the actual damping as shown in Fig. 4.

The velocity responses detected by the encoder system of the RT Walker are shown in Fig. 4, and the actual damping parameters calculated from Fig. 4 are shown in Table 1. These results show that the actual damping is close to the desired damping, and the motion characteristics of the RT Walker can be changed arbitrarily. Note that the theoretical velocity responses differ from the actual velocity responses before reaching a steady state. This may be caused by static or Coulomb friction, which are not considered in this experiment.

Next, we performed experiments with the RT Walker by changing the damping parameter with respect to the rotational direction, while keeping the damping parameter along the heading direction. In this experiment, we set the walker on a slope at an angle with respect to the gravity direction along the slope, and then moved it based on the gravitational force. When we specify five damping parameters with respect to the rotational direction (-40, -20, 0, 20, 40[Nms/rad]), the RT Walker was moved as shown in Fig.5, which is the path of the middle of the rear wheel axis, and Fig. 6, which is the angular velocity of the RT Walker. From Fig. 5 and Fig. 6, we can see that with a large damping parameter, the RT Walker moved straight compared to the motion with a small damping parameter and the motion characteristics could be changed with respect to the rotational direction as well as the heading direction.

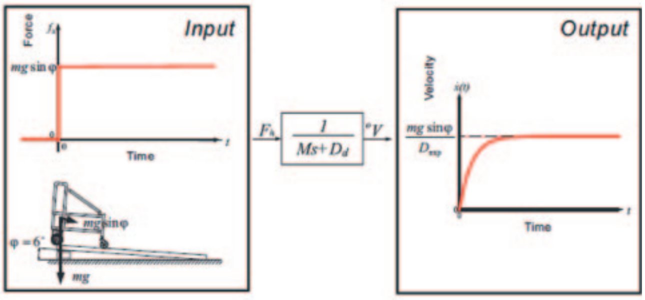


Fig. 3. Experiment Using Slope for Variable Motion Characteristics Function

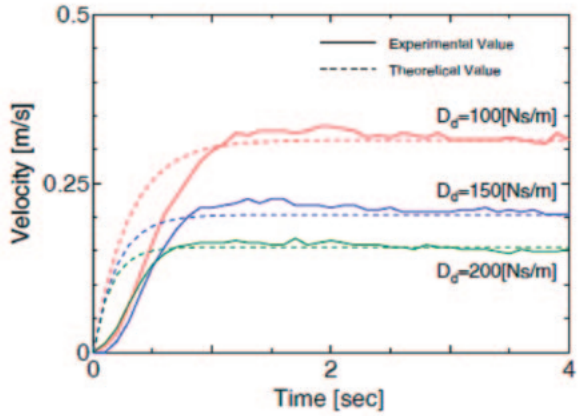


Fig. 4. Velocity Responses of RT Walker

Table 1. Damping Coefficients Calculated by Experiments

Desired Damping Coefficient $D_d[Ns/m]$	Actual Damping Coefficient $D_{exp}[Ns/m]$
100	94.89
150	146.29
200	203.95

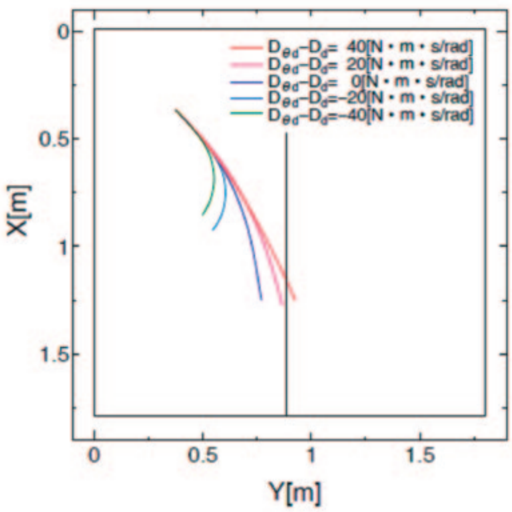


Fig. 5. Rotational Motion of RT Walker

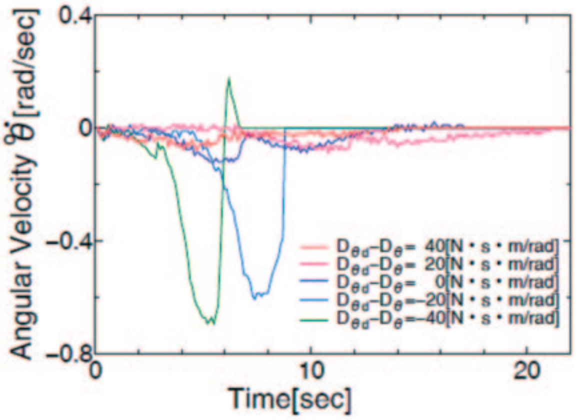


Fig. 6. Angular Velocity of RT Walker

5. Environmentally Adaptive Motion Control

When we use intelligent walkers in living environments, we must consider motion control algorithms based on information about the environment. In particular, in environments with differences in the street level, stairs, or many obstacles or slopes, using walkers safely and smoothly requires environmentally-adaptive motion control.

5.1. Navigation function

In this section we consider a navigation function so that many people including blind people could also use these walkers as navigation system for guiding the user to a destination. To realize the transportation of a large or long object by multiple mobile robots based on the intentional force applied by a human, we have proposed a map-based motion control algorithm in [11]. In this algorithm, the motion of the object supported by multiple mobile robots is generated based on the intentional force/moment applied by a human and the virtual force/moment derived by the information of an environment.

In this article, we extend this map-based control algorithm for multiple mobile robots, and propose a new control algorithm for controlling the brake torques of RT Walker based on the information of an environment. In this algorithm, we apply the virtual force/moment generated from the environmental information, and control the brake torques based on this virtual force/moment. To generate the virtual force/moment from the environmental information, we utilize the method referred to as artificial potential field proposed by Khatib in [12].

For illustrating the navigation function based on the virtual force/moment, we experimented with the RT Walker in an environment. From this environment, we generate an artificial potential field as shown in Fig. 7. In this experiment, five ordinary people used the RT Walker in the environment. Each person wore a blindfold to prevent the feedback of human being from eyes.

Experimental result is shown in Fig. 8. This result shows the path of five ordinary people detected by the encoder system of the RT Walker. You can see that five people moved without colliding with the wall along the environment. However, some people mentioned that the maneuverability of RT Walker was not so good, when the RT Walker closed to the wall. To overcome this problem, we have to consider the maneuverability of the RT Walker by changing the apparent dynamics of the RT Walker, the function of artificial potential field and so on, as the future works.

We also experimented with a path leading from a start point to a destination. In this experiment, we generated an S-line path for the RT Walker using the artificial potential field, which can generate the potential with a steep gradient. In this experiment, five university students with blindfolds operated the RT Walker. The results are shown in Fig. 9, and the differences between the desired and actual paths were almost zero; path following was successfully achieved.

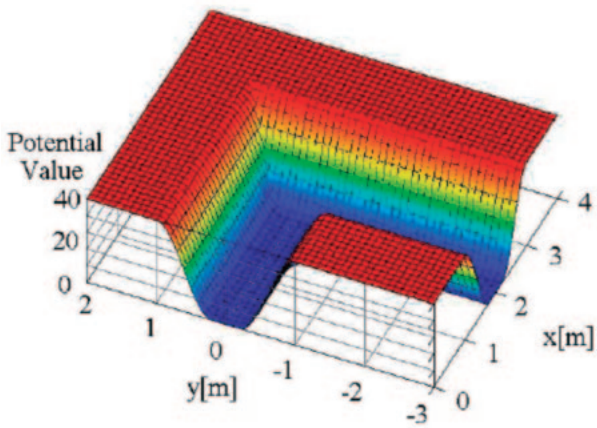


Fig. 7. Potential Field of Environment

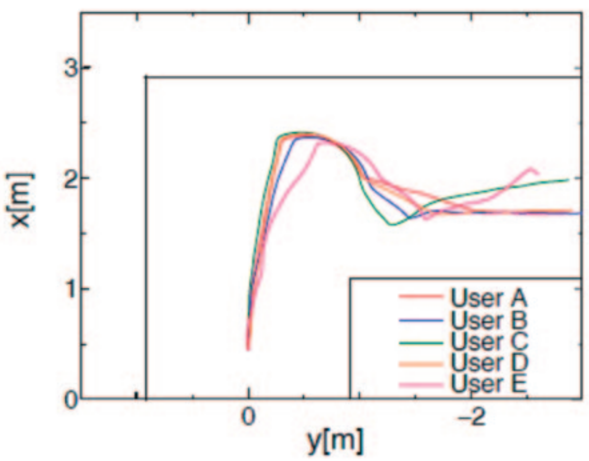


Fig. 8. Experimental Results of Collision Avoidance Function

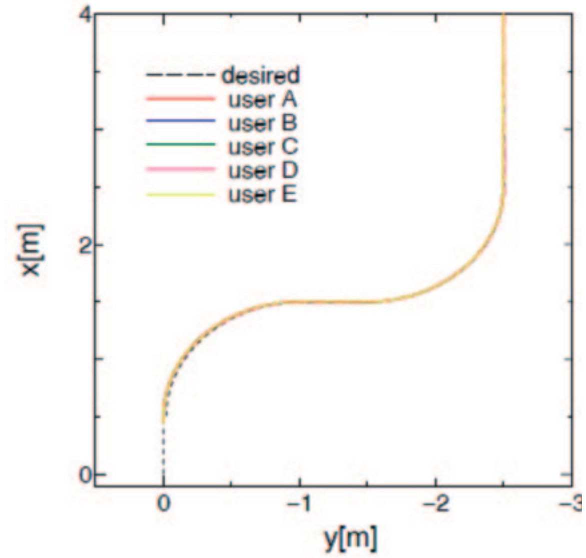


Fig. 9. Experimental Results of Path Following

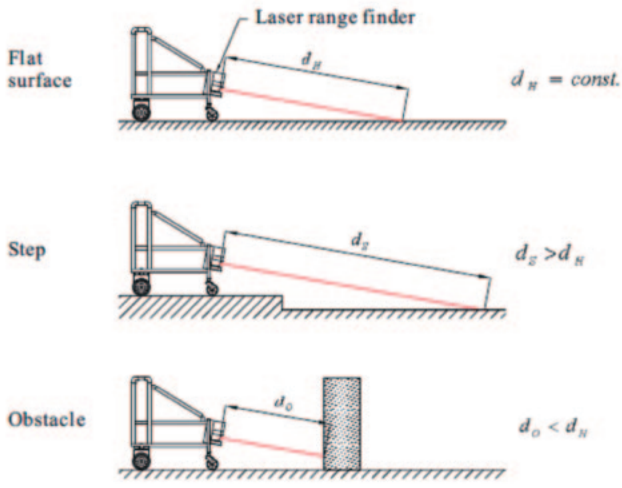


Fig. 10. Examples of Obstacle/Step Detection using Laser Range Finder

5.2. Obstacle/Step avoidance function

If we know position of an obstacle or a step, the RT Walker could avoid them based on the same control method explained in the previous section. Next, we introduce a measurement method of obstacle/step to generate the artificial potential field in the environment. In this research, we use the walker's laser range finder, which is attached at an angle to the horizontal plane, as shown in Fig. 10. Attaching the laser range finder at an angle to the horizontal plane allows detecting the positions of both the obstacles and the steps based on the measured distance.

If the distance is constant d_H, which is derived in advance based on the attached angle and height of the laser range finder from the ground level, it means that the walker is on flat ground. If the measured distance is larger than d_H, the RT Walker detects steps. When the measured distance is smaller than the constant distance d_H, the RT Walker detects obstacles.

In this case, the virtual force/moment is derived from the measured length to realize obstacle avoidance. When the RT Walker detects a level difference, it generates map information based on the boundary position of the level difference, as shown in Fig. 11. Here, the length from the step does not change after detecting the edge of the step. By deriving the virtual force/moment based on the map, as shown in Fig. 11, the user avoids a misstep.

For illustrating the validity of the obstacle/step avoidance function, we experimented with collision avoidance, preventing falling due to steps. In this experiment, a human pushed the RT Walker just enough to move it. This allowed us to determine the validity of the proposed control algorithm easily and intuitively. The experiments are shown in Fig. 12, and the paths of the representative point, to which the virtual force/moment is applied, and the center of the walker's axle are shown in Fig. 13. These results show that the RT Walker detects a wall and a step, and avoids them using only brake control.

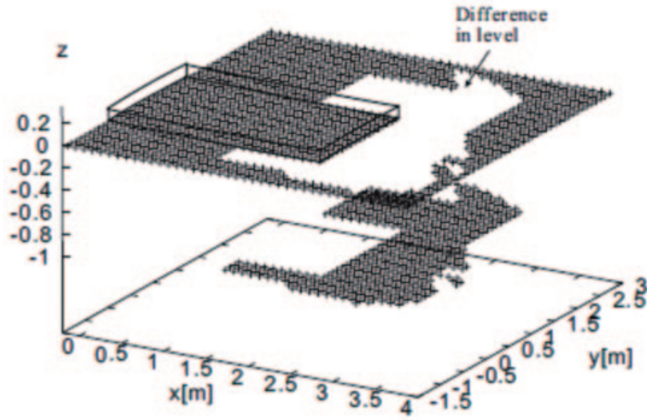


Fig. 11. Global Map of Steps


(a) Collision Avoidance Motion

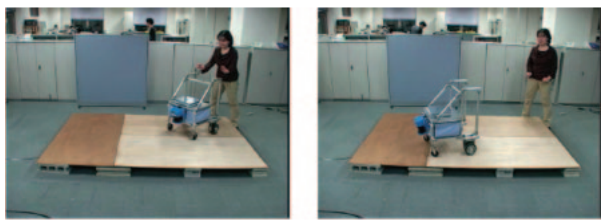
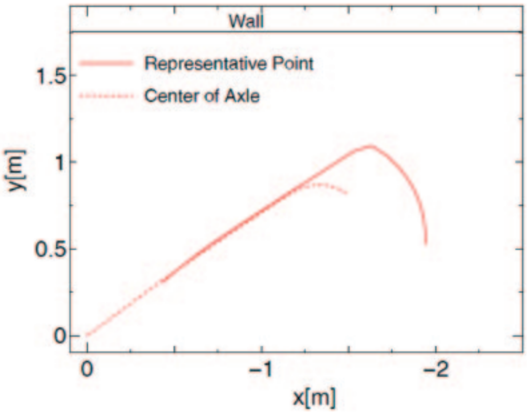
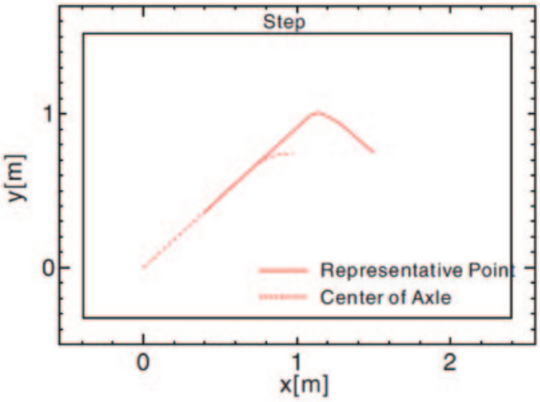

(b) Step Avoidance Motion

Fig. 12. Collision/Step Avoidance Functions



(a) Collision Avoidance Motion



(b) Step Avoidance Motion

Fig. 13. Experimental Results of Collision/Step Avoidance Functions

6. Adaptive Caster Action

When some robotics researchers consider an obstacle avoidance of robots, in general, they design a function of the artificial potential field, in which the value of the potential reaches to infinity, when robot closes to the obstacles. However, in the case of walking support systems, users may close to a place such as a door, a shelf, an elevator, a wall putted on the poster, and so on. Therefore, in this research, we propose a motion control based on the caster-like dynamics called adaptive caster action so that RT Walker could close to the many places based on the human intention.

The concept of the motion control of the robot based on the caster-like dynamics have been proposed in [13] for realizing the coordinative transportation of an object by using multiple mobile robots. In the algorithm proposed in [13], each mobile robot is controlled as if it has a caster-like dynamics as shown in Fig.14, and transports a single object together with other robots based on an intentional force/moment applied by a human. When the human applies the force/moment to the object, the wheel of each virtual caster rotates around the free rotational joint to the direction of the force applied by the human, so that the human could handle a single object together with multiple mobile robots. The caster-like dynamics is also robust against the inevitable positioning error of each robot, even if each robot has a slippage between the wheels of each mobile robot and the ground.

Intelligent walker realizes the physical interaction between the user and walker based on the force/moment applied by the user similar to the case of cooperative transportation of an object by a human and robots. In addition, the robustness with respect to the slippage between wheels of walker and the ground is required. In this article, we extend the caster-like dynamics proposed in [13] and propose the control algorithm of the RT Walker based on its caster-like dynamics for supporting the people who have walking difficulties.

In this section, we consider how the apparent dynamics of RT Walker are changed based on the condition of users or information of an environment. To realize the walker with good maneuverability, we propose Adaptive Caster Action in this article, which is a control algorithm based on the caster-like dynamics. To realize the caster-like dynamics for the RT Walker, first, we consider a motion of a real caster as shown in Fig. 14.

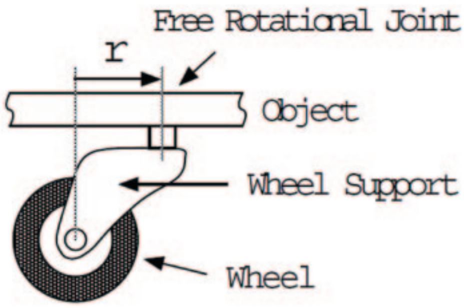


Fig. 14. Real Caster

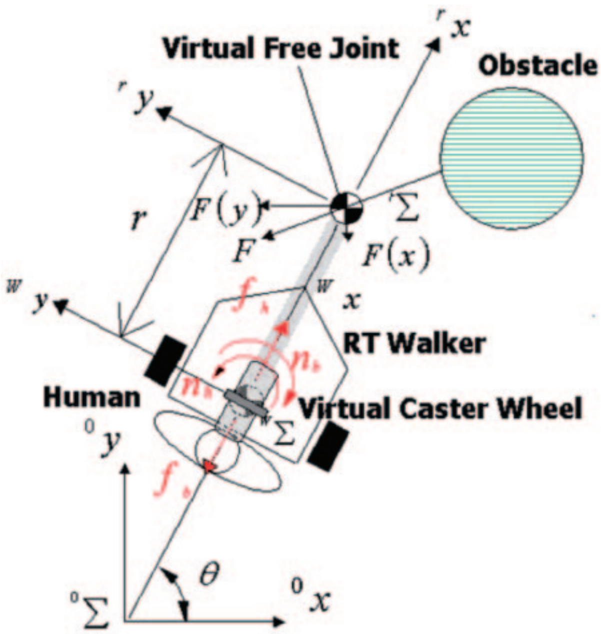


Fig. 15. Collision/Step Avoidance Functions Using Adaptive Caster Action

The real caster consists of a wheel, a free rotational joint and a wheel support, which connects the wheel and the free rotational joint as shown in Fig. 14. The motion of the caster is characterized by three kinds of motion. One is the translational motion of the wheel along the heading direction of its wheel, second one is the rotational motion of the wheel around a point where the wheel contacts with a ground, and third one is the rotational motion of the free rotational joint around its own.

In this article, we control the middle point of the axis of the rear wheels of the RT Walker so as to have virtual caster wheel, and the virtual free joint is designed in the forward of RT Walker along its heading direction as shown in Fig. 15. It should be noted that we do not consider the rotational motion of the free rotational joint of the real caster around its own for implementing the virtual caster, because it does not effect to the motion of RT Walker actually.

In this section, we consider the maneuverability of the RT Walker and propose a control algorithm referred to as Adaptive Caster Action for utilizing it effectively. The apparent dynamics of the RT Walker is determined by control parameters such as inertia and damping properties, or offset of virtual caster. Especially, the apparent dynamics is strongly affected by the caster offset. Adaptive Caster Action adjusts the caster offset based on the condition of users or information of environments

When the offset is large, the angular acceleration and the angular velocity of the virtual caster wheel are small. The larger offset will stabilize the straight line motion of the RT Walker against disturbance force perpendicular to the motion direction, but it will make the motion direction change difficult. On the contrary, when the offset is small, the virtual caster wheel rotates to the direction of the intentional force easily, so that the RT Walker could rotate to the intentional direction of user.

Let us consider an example of Adaptive Caster Action based on the velocity of the RT Walker along its heading direction. When a user moves in narrow space by using the RT Walker, its velocity would be low and its easy rotation would be effective. In this case, the smaller caster offset is selected. On the other hand, when the user walks a long distance by using the RT Walker, its velocity would be high and the straight line motion of the RT Walker would be useful during the walking. In this case, the large caster offset is selected, so that the straight line motion is stabilized and the user could use the RT Walker stably, even if the user applies the disturbance force to the RT Walker by stumbling. To select the caster offset automatically based on these situations, we change the caster offset according to the velocity of the heading direction of the RT Walker.

To apply the adaptive caster action to the environment-adaptive motion control, the virtual forces is applied to the virtual free joint of the virtual caster based on the information of an environment. By deriving the virtual forces based on the distance between obstacles/steps and the system appropriately and generate the brakes torques by using its virtual force/moment, a user could avoid the collision with obstacles or prevent missing his/her steps in a difference in level similar to the obstacle/step avoidance function explained in previous section.

When we utilize the Adaptive Caster Action, the position of the free joint is changed based on the velocity of the RT Walker as shown in Fig. 16. When the velocity of the RT Walker is high, the larger offset is selected. In this case, the RT Walker is influenced by the virtual forces and the avoiding motions with respect to the collision with obstacles and the falling down from the steps could be realized.

On the other hand, when the velocity of the RT Walker is low, the smaller offset is selected. In this case, the RT Walker would not be influenced by the virtual forces compared with the larger caster offset, so that the RT Walker could close to a door, a elevator, a shelf and so on. Even if the RT Walker collides with the obstacles with low speed, the dangerousness would also be reduced. It should be noted that the falling down from the step is dangerous situations compared with the collision with obstacles. If the RT Walker detects the steps, the control parameters of Adaptive Caster Action should be changed to prevent the falling accident.

Here, we implemented Adaptive Caster Action in RT Walker and did several experiments to illustrate the validity of the proposed control algorithm. In this experiment, we moved the RT Walker to the wall by pushing based on the different kinds of force as shown in Fig. 17, so that RT walker closes to the wall in the different kinds of velocity. Motion paths of the RT Walker with high speed and low speed are shown in Fig. 18(a), and caster offset during experiments are shown in Fig. 18(b).

From these experiments, you can see that the RT Walker generates the collision avoiding motion based on the larger caster offset, when its velocity is high. On the other hand, RT Walker can close to the wall, when its velocity is low based on the smaller caster offset. By using Adaptive Caster Action, we could change the apparent dynamics of the RT Walker based on its velocity, so that we could use it with good maneuverability in the real world environment.

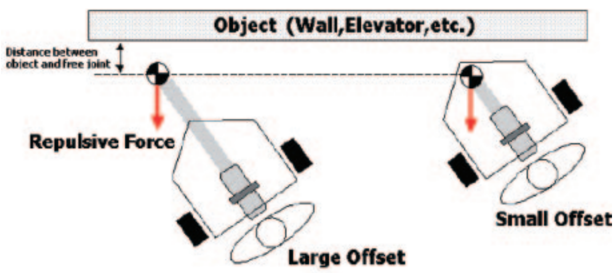
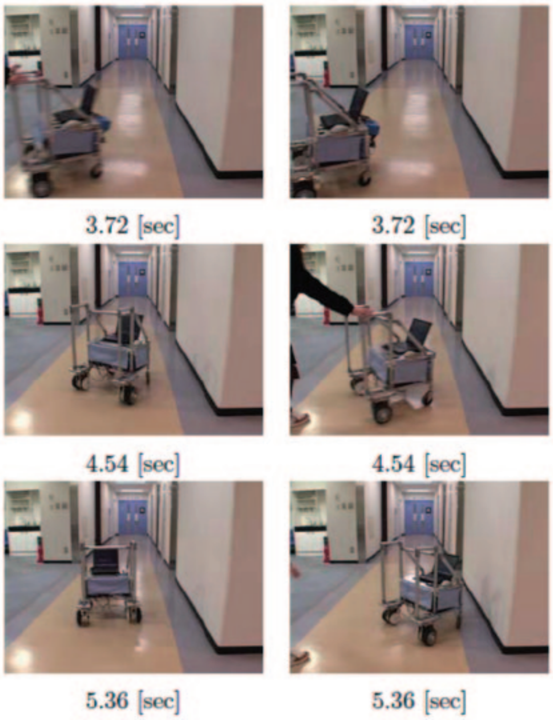


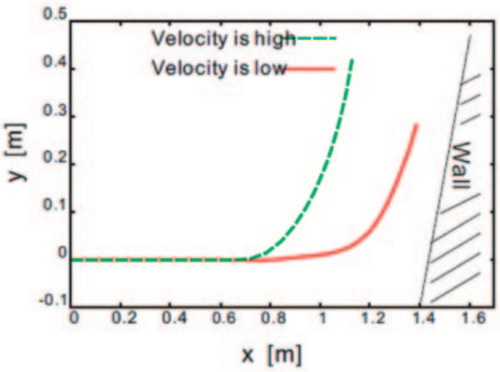
Fig. 16. Environment-adaptive Motion Based on

Adaptive Caster Action

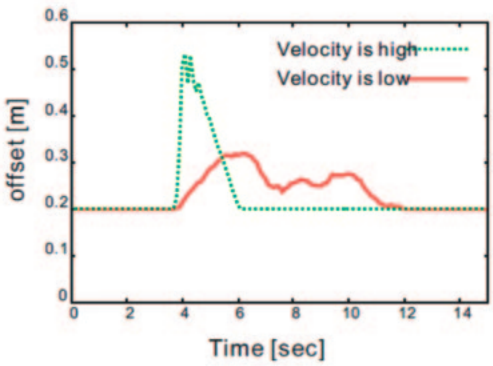


(a) High Speed Motion (b) Low Speed Motion

Fig. 17. Experiments Using Adaptive Caster Action



(a) Motion Path of RT Walker



(c) Virtual Caste Offset

Fig. 18. Experimental Results of Adaptive Caster Action

7. Gravity Compensation Function

In this section, we consider gravity compensation. If we compensate for gravity using the servo brakes, the walker will not move on a slope, unless the user applies intentional force/moment. Thus, the user could use the RT Walker as if it is always on a horizontal plane. Gravity compensation of the RT Walker is an important user safety function. To realize gravity compensation, we must derive the brake torque based on the pitch angle and roll angle as shown in Fig. 19. To obtain these angles, the RT Walker has two tilt angle sensors.

Next, we experimented with gravity compensation. The RT Walker was placed on a plate, as shown in Fig. 20(a). A fork lift tilted the plate. The walker's pitch and roll angles measured by the tilt angle sensors are shown in Fig. 20(b). The velocities of the RT Walker, detected by the encoders on the wheels, are shown in Fig. 20(c). These results showed that the RT Walker adjusted its brake force based on the angle changes compensating for changes in the force of gravity.

We also tested the RT Walker in a real-world environment, as shown in Fig. 21. Although the user did not touch the walker, which was either on a downhill or uphill road, it did not move because of the force of gravity. That is, it only moved when the user intentionally applied force to it, just as if it was always on a horizontal road. Note that the RT Walker cannot pull the user against gravity when walking uphill, which makes it different from active walkers. This is the disadvantage of the passive walker. However, when walking uphill, the user's load is less, because the passive walker is relatively lightweight and is not pulled downward by gravity.

8. Experiments in Real World Environment

In a final experiment, we used the RT Walker in a real-world environment with stairs, obstacles, and a down slope. A user wore a blindfold to prevent visual feedback, as shown in Fig. 22. From this experiment, you can see that the user can safely use the RT Walker, and can depend on it for navigation even in a complicated environment.

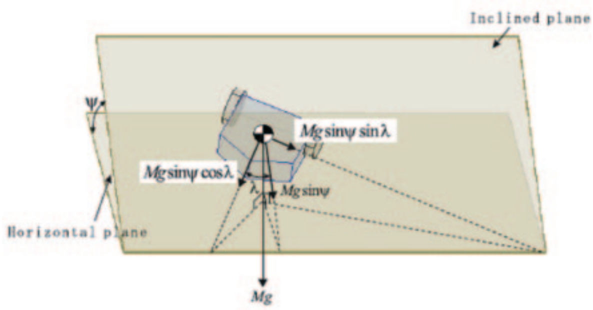
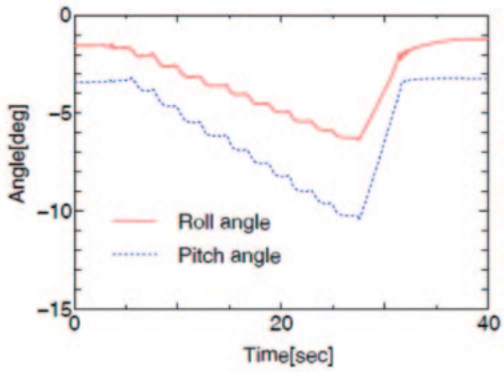
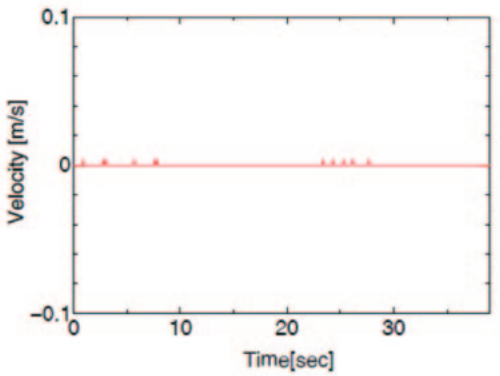


Fig. 19. Roll/Pitch Angles of RT Walker on Slope

(a) Experiments Using Fork Lift



(b) Roll/Pitch Angles



(c) Velocity of RT Walker

Fig. 20. Experimental Results of Gravity Compensation Function

(a) Experiments Going Downhill

(b) Experiments Going Uphill

Fig. 21. Gravity Compensation Function

Fig. 22. Experiment in Real World

9. Concussion

In this article, we proposed a new intelligent walker, based on passive robotics, to help the elderly, handicapped, or blind people who have difficulty walking. We developed a prototype walker, the RT Walker, which employs servo brakes. We also proposed motion control algorithms, which change the apparent dynamics of the passive intelligent walker, to adapt to the difficulties of the user and the environment.

In future work, we will consider the human adaptive and environmentally-adaptive motion control algorithms in more detail to improve the maneuverability of the RT Walker. In addition, we will evaluate the validity of the RT Walker through comments from many people, including the elderly, handicapped, blind people, physical therapists, and medical doctors. We will improve the mechanisms and control algorithms of the RT Walker.

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