Motion Control of Distributed Robot Helpers Transporting a Single Object in Cooperation with a Human

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Abstract: In this paper, we propose a concept of distributed robot helpers referred to as DR Helpers, and a decentralized control algorithm for them to transport a single object in cooperation with a human/humans. The proposed control algorithm could be applied to DR Helpers more than three, even if each DR Helper has a slippage between its wheels and the ground. The proposed decentralized control algorithm is experimentally applied to three DR Helpers for illustrating the validity of the proposed algorithm.

1. Introduction

Most of robots have been used as industrial robots in factories to replace humans doing tasks, which humans do not want to do or could not do. Most of these robots have been isolated from humans. If robots could do tasks together with a human/humans, robots could be applied to other fields, such as applications in a house, in a hospital, in a shopping center, in a construction site, for elderly care, etc. A robot could not be applied to these applications without any interactions with humans.

Much researches have been done for the human-robot cooperation by several researchers[1]-[4]etc. However, the working space of these cooperation systems is restricted, because the control algorithms were designed for a manipulator/manipulators. Mobility is the important function to cover a large working space in an environment.

Colgate and Peshkin have proposed a control algorithm of transporting an object by a mobile robot referred to as a Cobot in cooperation with a human [5]. However, this type human-robot cooperation is not suitable for transporting a large or a heavy object, because there is a limitation with respect to the size and the weight of an object handled by a single robot. The system has no actuator to generate the motion of the robot.

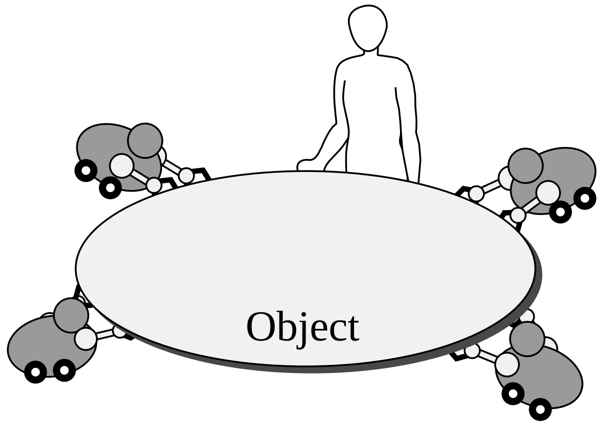


Figure 1. Handling an Object with Robot Helpers

To overcome these problems, we consider a human-robots cooperation system using multiple mobile robots as shown in Figure 1. Khatib has proposed the control system by multiple mobile manipulators in cooperation with a human [6]. However, this control system could not realize effective human-robots cooperation without integration of the human arm inertial properties and a description of the human grasp.

We have proposed a concept of a human-robots cooperation system referred to as distributed robot helpers and a decentralized control algorithm for them to transport an object together with a human/humans with unknown dynamics [7]. In this algorithm, each robot is controlled as if it has a dynamics of caster wheel as shown in Figure 2 and transports an object in cooperation with a human. However, this algorithm could not be applied to mobile robots more than three, when a slippage between the wheels of each robot and the ground could not be negligible. The motion of an object could be constrained completely, when each robot has a slippage between its wheels and the ground during a transportation of an object.

In this paper, we extend the caster-like dynamics proposed in [7] and propose a decentralized motion control algorithm for mobile robots more than three, even if each robot has a slippage between its wheels and the ground during a transportation of an object. The proposed control algorithm is experimentally applied to three Dr Helpers and experimental results illustrate the validity of the system.

2. Distributed Robot Helpers

We briefly explain the concept of distributed robot helpers referred to as Dr Helpers proposed in [7]. When we would like to move a large or a heavy object, which could not be handled by a human, we move it with other people or helpers. If a robot/robots could play a role of human helpers, we could move it without any help of humans. A robot helper is a robot, which plays a role of the human helpers as shown in Figure 1.

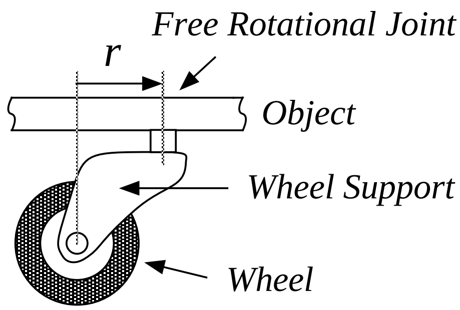


Figure 2. Real Caster

The robot helper is expected to do tasks in an ordinary environment with humans. Mobility is an important function to cover a working space in the environment. Multiple small robots are more appropriate for such a system than a large and heavy robot from a safety point of view. Because each small robot has less kinetic energy than the large and heavy one, when they are moving with the same speed, and less harmful to a human when it collides with a human/humans. The distributed robot helper is a small mobile robot, and helps humans to carry an object together with other robot helpers as shown in Figure 1.

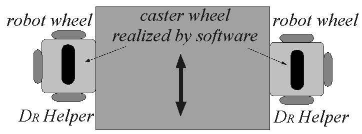
3. Motion of Object

In this section, we consider how the distributed robot helpers are controlled so that a human/humans can transport a single object in cooperation with them. We design a passivity-based control system to guarantee the stable realization of the human-robots interaction through a manipulated object, under the assumption that the passivity conditions for human/humans are satisfied.

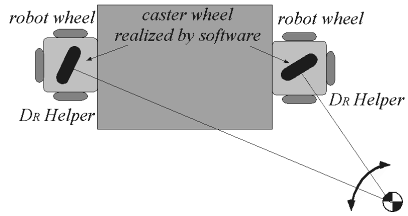
The passivity-based controller design is well known in the area of teleoperation [8]etc., and has been applied to DR Helpers transporting an object in cooperation with a human/humans [7]. In this algorithm, each DR Helper is controlled as if it has a dynamics of a caster wheel as shown in Figure 2. However, we could not apply the same control principle proposed in [7] to DR Helpers more than three, when each DR Helper has a slippage between its wheels and the ground during a transportation of an object.

When two DR Helpers handle an object, the motion of the object supported by them is characterized by two kinds of motion based on the heading direction of the caster wheel. One is the translational motion of the object along the heading direction of the caster wheel as shown in Figure 3(a), and the other is the rotational motion of the object around a point defined by an angle of the caster wheel as shown in Figure 3(b).

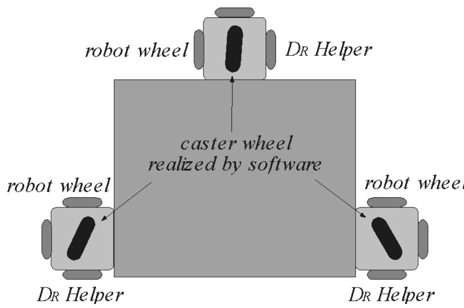
When DR Helpers more than three handle an object, the motion of the object supported by them is characterized by three kinds of motion based on the heading direction of caster wheel. One is the translational motion of the object as shown in Figure 3(a), another is the rotational motion of the object around



(a) Translational Motion



(b) Rotational Motion



(c) Constrained Motion

Figure 3. Motion of Object

a point as shown in Figure 3(b), and the other is the completely constrained motion as shown in Figure 3(c) because of the misalignment of the caster wheel.

Under the assumption that the caster wheel of each Dr Helper could rotate to the direction of the force applied by a human/humans using the adaptive dual caster action proposed in [7] and each Dr Helper does not have a slippage between its wheels and the ground, the motion of the object supported by multiple Dr Helpers is the translational one or the rotational one around a point, and each Dr Helper could transport a single object in cooperation with a human/humans.

However, if each Dr Helper has a slippage between its wheels and the ground during a transportation of an object, the motion of the object supported by multiple Dr Helpers is constrained completely because of the misalignment of the caster wheel. In this case, each Dr Helper could not move along the direction of the force applied by a human/humans, and a human could not transport the object in cooperation with multiple Dr Helpers.

To overcome this problem, we extend the caster-like dynamics proposed in [7]. In the algorithm proposed in [7], each Dr Helper is controlled as if it has a dynamics of a caster wheel. Therefore, each Dr Helper could not move along the direction of the caster wheel axis and the motion of an object could be constrained completely because of the misalignment of the caster wheel. In this paper, we consider that each robot is controlled as if it has a dynamics of a free rotational joint of the caster.

In this case, the motion of an object supported by multiple Dr Helpers is not constrained completely, because each Dr Helper could generate the velocity in all directions. Therefore, a human could transport a single object in cooperation with multiple Dr Helpers, even if each Dr Helper has a slippage between its wheels and the ground.

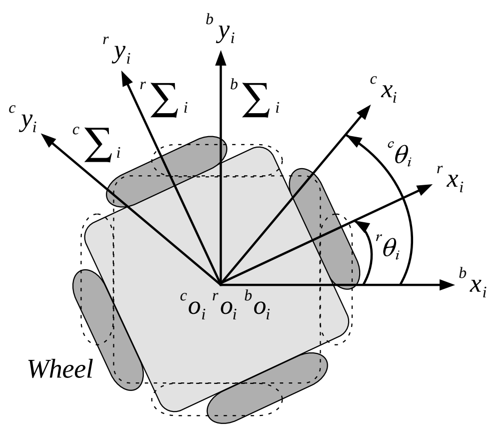
4. Velocity-based Caster-like Motion

To realize a dynamics of the free rotational joint, we define three coordinate systems of i-th Dr Helper as shown in Figure 4; a base coordinate system ${}^b\Sigma_i$, a robot coordinate system ${}^r\Sigma_i$ and a caster coordinate system ${}^c\Sigma_i$. The origins of these coordinate systems are located at the center of the force/torque sensor.

The base coordinate system is fixed to the mobile robot. The orientation of the coordinate system is not changed even if the orientation of the mobile robot changes. The mobile robot coordinate system is fixed to the mobile robot and moves together with the robot. The force/moment applied to the robot is measured in this coordinate system. Let ${}^r\theta_i$ be the rotational angle of the robot coordinate system with respect to the base coordinate system as shown in Figure 4.

The caster coordinate system rotates around its origin to mimic the free rotational motion of the caster support as shown in Fiuger 2. The direction of ${}^cx_i$-axis of the caster coordinate system is defined as the heading direction of the caster wheel. Let ${}^c\theta_i$ be the rotational angle of the caster coordinate system with respect to the base coordinate system as shown in Figure 4.

A velocity-controlled servomotor drives each wheel of the Dr Helper which realizes the omni-directional motion, and we assume that each wheel rotates with a specified angular velocity. We could generate the translational motion



Omni-directional Mobile Robot

Figure 4. Coordinate System of i-th Dr Helper (top view)

of the caster wheel based on the force applied to the robot as follows;

$$\begin{aligned} {}^{tran}D_i {}^c\dot{x}_i &= {}^c f_{xi} \\ &= ({}^r f_{xi} - {}^r f_{xi}^{in}) \cos({}^c\theta_i - {}^r\theta_i) + ({}^r f_{yi} - {}^r f_{yi}^{in}) \sin({}^c\theta_i - {}^r\theta_i) \end{aligned} \quad (1)$$

where ${}^{tran}D_i \in R$ is a positive damping coefficient and ${}^c\dot{x}_i \in R$ is the velocity of the robot along ${}^c x_i$-axis of the caster coordinate system. ${}^r f_{xi},\ {}^r f_{yi} \in R$ are the forces applied to the robot with respect to the $i-th$ robot coordinate system and ${}^r f_{xi}^{in},\ {}^r f_{yi}^{in} \in R$ are the specified internal forces applied to the object by the robot with respect to the $i-th$ robot coordinate system.

To mimic the motion of the wheel support as shown in Figure 2, we obtain the angular velocity of the caster coordinate system ${}^c\dot{\theta}_i$ using the following equation.

$$\begin{aligned} {}^{cast}D_i {}^c\dot{\theta}_i &= \frac{1}{r_i} {}^c f_{yi} \\ &= \frac{1}{r_i}\{-({}^r f_{xi} - {}^r f_{xi}^{in}) \sin({}^c\theta_i - {}^r\theta_i) + ({}^r f_{yi} - {}^r f_{yi}^{in}) \cos({}^c\theta_i - {}^r\theta_i)\} \end{aligned} \quad (2)$$

where ${}^{cast}D_i \in R$ is a positive damping coefficient, r_i is the caster offset as shown in Figure 2, and ${}^c f_{yi}$ is the force applied to the robot along ${}^c y_i$-axis of the caster coordinate system. To realize the caster-like motion around the free rotational joint, we generate the motion of the robot based on the angular velocity of the caster coordinate system using the following equation and make the caster coordinate system rotate around its origin based on ${}^c\dot{\theta}_i$.

$${}^c\dot{y}_i = r_i {}^c\dot{\theta}_i \quad (3)$$

where ${}^c\dot{y}_i \in R$ is the velocity of the robot along ${}^c y_i$-axis of the caster coordinate system.

When the robot holds the object rigidity, the kinematic relation between the robot and the object is kept unchanged. Each robot has to generate the motion of the free rotational joint. For this purpose, the rotational motion of each robot is controlled so as to have the following dynamics based on a moment ${}^r n_i \in R$ applied to the robot.

$${}^{rot}D_i {}^r\dot{\theta}_i = {}^r n_i \quad (4)$$

where ${}^{rot}D_i \in R$ is a positive damping coefficient and ${}^r\dot{\theta}_i \in R$ is the real angular velocity of the robot. It should be noted that the relative angle between ${}^r\theta_i$ and ${}^c\theta_i$ is not changed.

The adaptive dual caster action proposed in [7] is also implemented in this system, so that a human could manipulate the object easily together with the Dr Helpers. The adaptive dual caster action adjusts the position of the caster offset and changes the apparent dynamics of an object supported by multiple Dr Helpers according to the tasks.

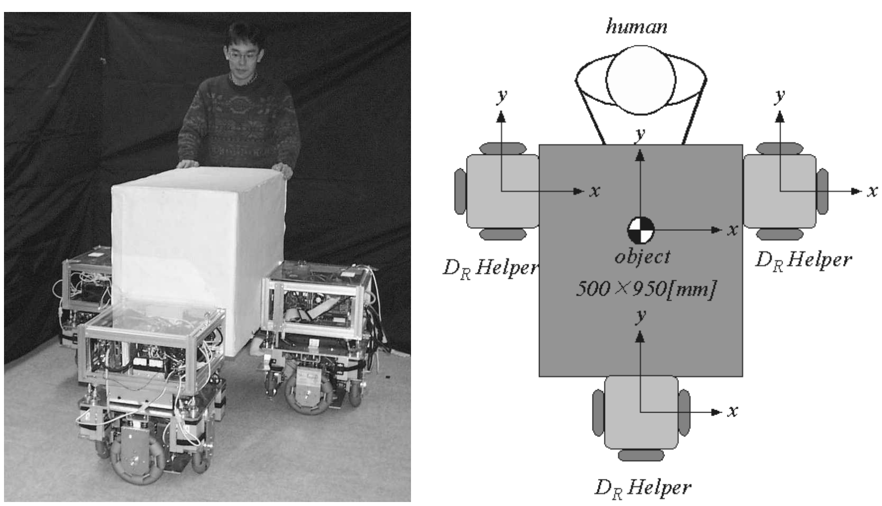
5. Experiments

We did experiments of transporting a single object using three DR Helpers in cooperation with a human as shown in Figure 5 to illustrate the validity of the proposed algorithm. We did two types of experiments to compare the conventional algorithm proposed in [7] with the proposed algorithm explained in this paper. The control algorithms were implemented using VxWorks. The sampling rate was 1024[Hz].

In each experiment, we applied the force to the object along y-axis as shown in Figure 5(b) and transported the object along y-axis in cooperation with the DR Helpers. It should be noted that each robot is controlled using the same control parameters in each experiment. Experimental results are shown in Figure 6. These figures show the motion of a DR Helper and the force/moment applied to the DR Helper during the transportation of the object.

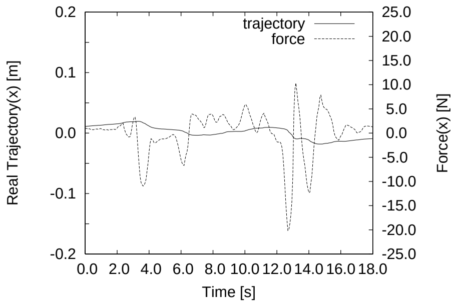
In the experiment using the conventional algorithm as shown in Figure 6(I), the force applied to the robot by a human along y-axis of the object coordinate system is larger than the force in the experiment using the proposed algorithm, and the force/moment applied to the robot had the vibratory part. These results means that a constrained motion of the object as shown in Figure 3(c) was occurred slightly during the transportation of the object because of a slippage between the wheels of each robot and the ground.

As shown in Figure 6(II), a human could transport a single object easily in cooperation with multiple DR Helpers using the proposed control algorithm, even if each robot has a slippage between its wheels and the ground. An example of tasks by three DR Helpers is shown in Figure 7. In this experiment, a human transported a single object in cooperation with DR Helpers successfully.

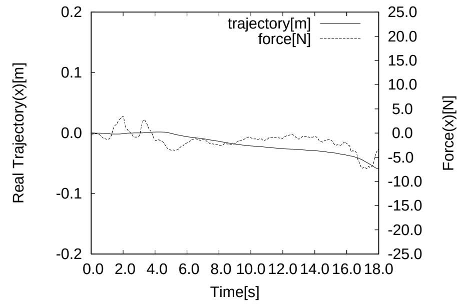


(a) (b)

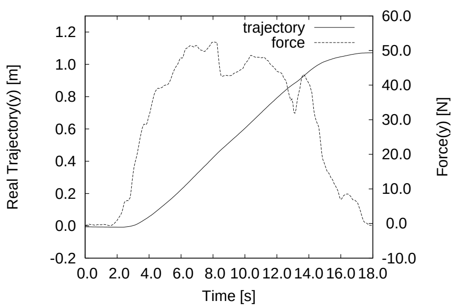
Figure 5. Experimental System



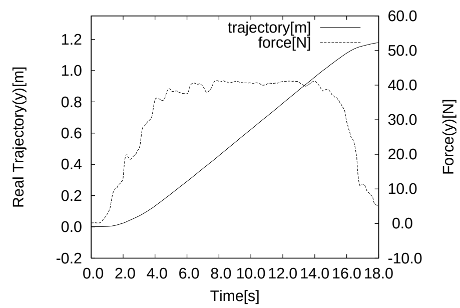
(a) x axis



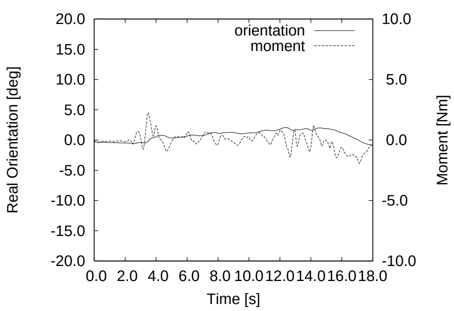
(a) x axis



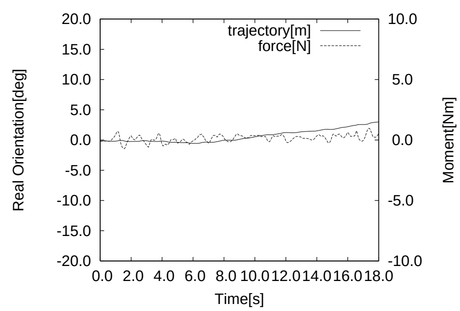
(b)y axis



(b) y axis



(c) rotation



(c) rotation

(I) Conventional Algorithm

(II) Proposed Algorithm

Figure 6. Experimental Results

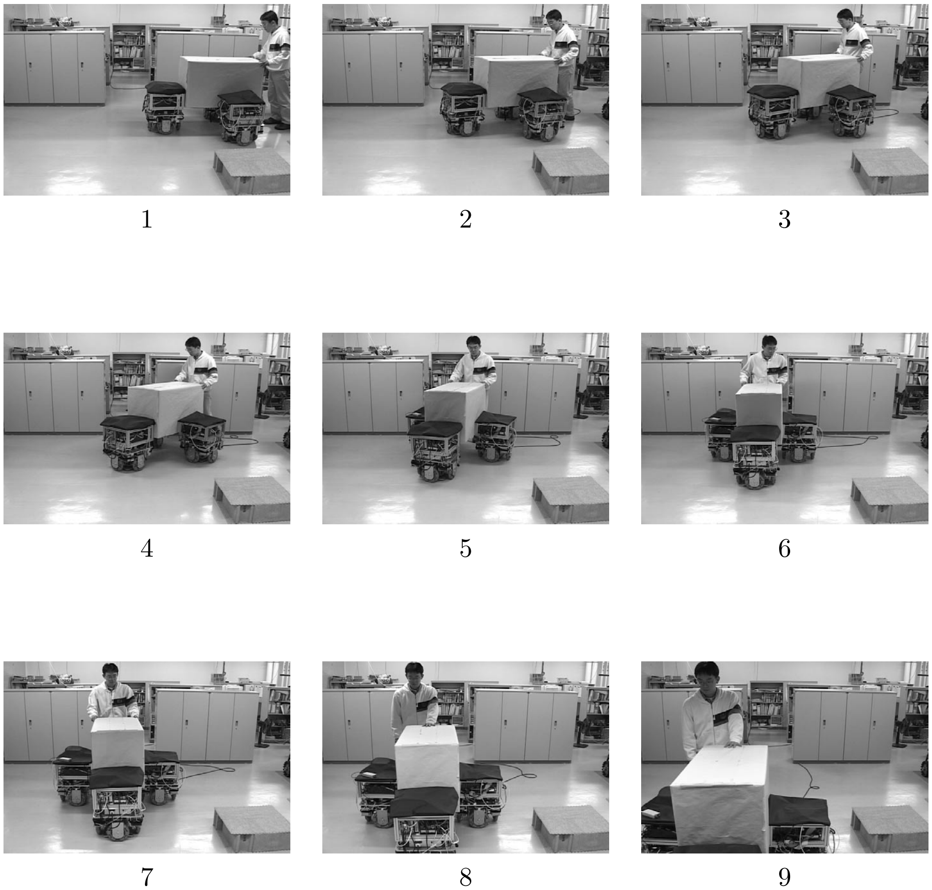


Figure 7. Task by DR Helpers

6. Conclusions

In this paper, we proposed a concept of distributed robot helpers referred to as DR Helpers, and a decentralized control algorithm for them to transport a single object in cooperation with a human/humans. The proposed control algorithm could be applied to DR Helpers more that three, even if each DR Helper has a slippage between its wheels and the ground. The proposed decentralized control algorithm is experimentally applied to three DR Helpers for illustrating the validity of its algorithm.

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