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# Map-based Control of Distributed Robot Helpers for Transporting an Object in Cooperation with a Human

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## Abstract

*In this paper, we propose a decentralized motion control algorithm of multiple mobile robots transporting a single object in cooperation with a human based on a path generated from an environment. Each mobile robot is controlled as if it has a wheel with a free rotational joint and moves along the path based on the intentional force applied by a human. The proposed decentralized control algorithm is experimentally applied to the omni-directional mobile robots referred to as DR Helpers. Experimental results illustrate the validity of the proposed control algorithm.*

## 1 Introduction

With the development of robot technologies, robots have been applied to many fields as industrial robots. Most of these Robots, however, have been used as programmable machines for the execution of a preprogrammed task isolated from humans. Robots are expected to execute various tasks in our daily life, 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.

Many control algorithms have been proposed for the control problem of a robot system handling an object in cooperation with a human/humans [1, 2, 3, 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 Cobot in cooperation with a human [5].

Figure 1: Handling an Object with Robot Helpers

This type human-robot cooperation system is realized by the single robot, which has no actuator to generate the velocity of the motion of its wheel. Therefore, there is a limitation with respect to the size and the weight of the object handled by this system.

To overcome these problems, we consider a human-robots cooperation system using multiple mobile robots as shown in Figure 1. Khatib have 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 the 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 [7]. The distributed robot helpers referred to as DR Helpers are multiple autonomous mobile robots, which have been developed for enabling a human to move a heavy or a large object by without any human assistant as shown in Figure 1.

In the algorithm proposed in [7], each Dr Helper is controlled as if it has a caster-like dynamics and communicates with a human by a intentional force/moment, that is, a human applies the intentional force/moment to an object supported by multiple Dr Helpers and transports it to the destination together with the robots. This algorithm is designed based on the passivity-based control system to guarantee the stable realization of human-robots interaction through a manipulated object.

However, a human could not manipulate a large object easily, if each Dr Helper is controlled passively along all directions using the algorithm proposed in [7], because the human could not apply a moment precisely to a grasping point of the human to adjust the orientation of the object [8]. In addition, the human also have to apply the intentional force/moment to the object precisely to transport it to the destination without colliding obstacles.

To overcome these problems, in this paper, we consider that each Dr Helper has a map information of an environment under the assumption that this system is used in the known environment such as an office, a hospital and a home, etc. If each Dr Helper knows the information of its environment, it could generate a path form its environment and move along its path based on the intentional force applied by a human.

In this system, the human could transport an object easily together with multiple Dr Helpers without colliding known obstacles. In addition, the human do not have to apply a moment to the object to change the orientation of it, because the object supported by Dr Helpers could change the orientation automatically based on the path.

Since the velocity of the motion of the object along the path is generated based on the intentional force applied by a human, this system is more appropriate than a system in which multiple mobile robots transport an object along the path autonomously from a safety point of view. The human could change the velocity of the motion of the object without using the additional sensor based on a condition of an environment, which change in real time.

In the following part of this paper, we propose the decentralized motion control algorithm of multiple mobile robots to transport an object in cooperation with a human based on a path generated from an environment. We also consider how to generate the path from an environment. The control algorithm is experimentally implemented in two omni-directional mobile robots referred to as Dr Helpers and the experimental results illustrate the validity of the proposed control algorithm.

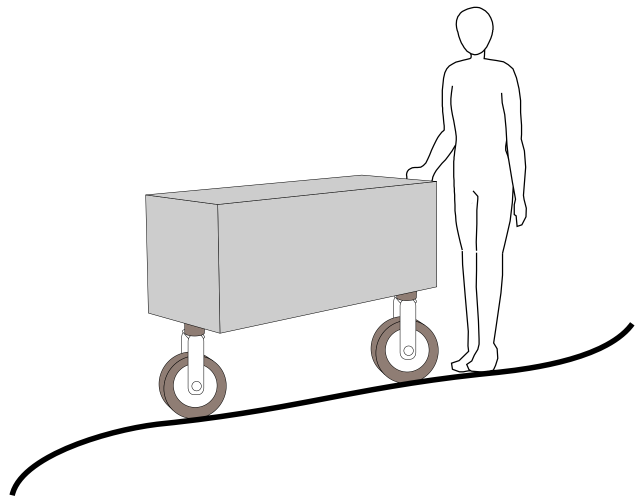

Figure 2: Transportation along Path

## 2 Motion Control System

### 2.1 Transportation Using Multiple Wheels with Free Rotational Joint

In this section, we consider how the Dr Helpers are controlled to transport a single object in cooperation with a human based on a path generated from an environment. Under the assumption that each Dr Helper has the same path and moves along its path, we will design a controller for each Dr Helper, which tailors the motion of the object as if it was supported by multiple wheels through a free rotational joint as shown in Figure 2.

To realize this system, each Dr Helper supports the weight of the object and is controlled as if it has a wheel with a free rotational joint as shown in Figure 3. Under the assumption that the wheel with the free rotational joint realized by each Dr Helper always moves along a path generated from an environment, a human could transport the object to the destination along the path by applying only intentional force to the object without applying a moment to it.

### 2.2 Velocity-based Motion Control

Let us consider the motion of a wheel with a free rotational joint as shown in Figure 3 to implement it to each Dr Helper. The motion of the wheel with the free rotational joint is characterized by two kinds of motion around the free rotational joint. One is a translational motion along the heading direction of the

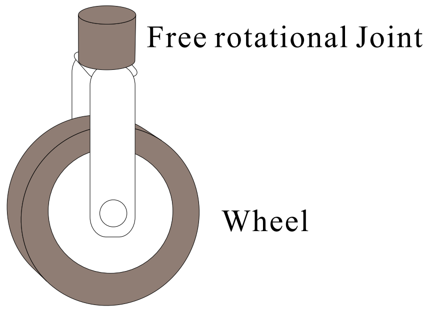


Figure 3: Wheel with Free Rotational Joint

wheel and the other is a free rotational motion around the free rotational joint.

Each wheel of the omni-directional mobile base of each Dr Helper is driven by a velocity-controlled servo motor. We assume that each wheel rotates with a specified angular velocity. We design a kind of damping control scheme to generate the motion of the robot based on the force/moment applied to the robot. Note that this type of controller is passive to guarantee the stable realization of the human-robots interaction, under the assumption that the passivity condition for the human is satisfied [9].

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

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 free joint coordinate system rotates around its origin to mimic the motion of the wheel with the free rotational joint. The direction of ${}^f x_i$-axis of the free joint coordinate system is defined as the heading direction of the wheel with the free rotational joint realized by each Dr Helper. Let ${}^f\theta_i$ be the rotational angle of the free joint coordinate system with respect to the base coordinate system as shown in Figure 4.

We could generate the translational motion of the wheel with the free rotational joint based on the force ${}^f f_{xi}$ applied to the robot along ${}^f x_i$-axis of the free joint coordinate system as follows;

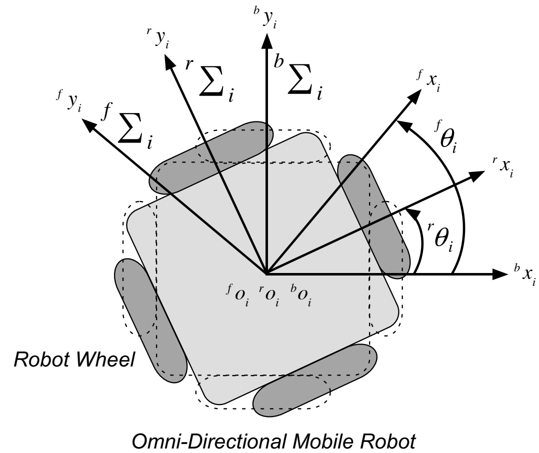


Figure 4: Coordinate System

$$ {}^{tran}D_i {}^f\dot{x}_i \quad = \quad {}^f f_{xi} \tag{1} $$

where ${}^{tran}D_i \in R$ is a positive damping coefficient and ${}^f\dot{x}_i \in R$ is the velocity of the robot along ${}^f x_i$-axis of the free joint coordinate system. It should be noted that the translational motion of the wheel with the free rotational joint is always realized along the path generated from an environment, that is, the rotational angle of the free joint coordinate system ${}^f\theta_i$ is equally to the tangential angle of its path with respect to the base coordinate system.

When the robot holds the object, 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 ${}^r n_i$ applied to the robot.

$$ {}^{rot}D_i {}^r\dot{\theta}_i = {}^r n_i \tag{2} $$

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 ${}^f\theta_i$ is independent of ${}^r\theta_i$.

## 3 Path Planning

In this section, we consider how to generate a path from an environment to transport an object along its path by multiple Dr Helpers in cooperation with a human. We utilize the method based on the unsteady diffusion equation strategy proposed in [10] to path planning. In this algorithm, collision free path from a start point to a goal point is generated very rapidly by on-line simulation of a diffusion process.

The diffusion process is modeled by an unsteady of dynamic diffusion equation as follows;

$$\frac{\partial C}{\partial t} = D\nabla^2 C - gC \tag{3}$$

where $C$ denotes the concentration distribution function over time and Cartesian space with $x = [x, y, \ldots]^T$. $D$ and $g > 0$ are the diffusion constant and the substance disintegration rate respectively.

To generate a path for mobile robots, the following discussion will treat two-dimensional diffusion. Let $C_{t,x,y}$ be a discrete-time regular sampling of $C$ on a uniform rectangular grid. By application of standard finite difference methods, the following time and space discredited model of eq.(3) could be obtained for a grid point as follows;

$$C_{t+1,x,y} = \{\frac{D\tau}{h^2}(C_{t,x+1,y} + C_{t,x-1,y} + C_{t,x,y+1} + C_{t,x,y-1}) - \tau g C_{t,x,y}\} + C_{t,x,y} \tag{4}$$

where $\tau$ is the time step size and $h$ is the grid width.

We derive the grid point with maximum concentration in the set of immediate neighbors of the current point based on eq.(4) and the boundary function expressed in table 1. Then, we continue with the same procedure from a start point until a goal point. The shortest path of an environment is given by the sequence of grid points as shown in Figure 5.

However, if we specify the gird width $h$ widely to generate a map of an environment, the path proves to be comparatively rough for the motion of mobile robot. In this paper, we generate a smoother path by the method based on Riesenfeld Spline function as follows;

$$x(t) = \sum_{i=0}^{N-1} x_i B_{i,K}(t), \quad y(t) = \sum_{i=0}^{N-1} y_i B_{i,K}(t) \tag{5}$$

where $B_{i,K}(t)$ is B-spline function of $K-1$ order. $N$ is the number of grid point derived by eq.(4). $x_i$, $y_i$ are the position of the $i$-th grid point respectively. We

Table 1: Boundary Function

| Grid Point | Concentration $C_{t,x,y}$ |
|---|---|
| Start Point $P_s$ | $C_{t,P_s} = 0$ |
| Goal Point $P_g$ | $C_{t,P_g} = 5$ |
| Walls and Obstacles $P_w$ | $C_{t,P_w} = -1$ |
| Others $P_o$ | $C_{0,P_o} = 0$ |

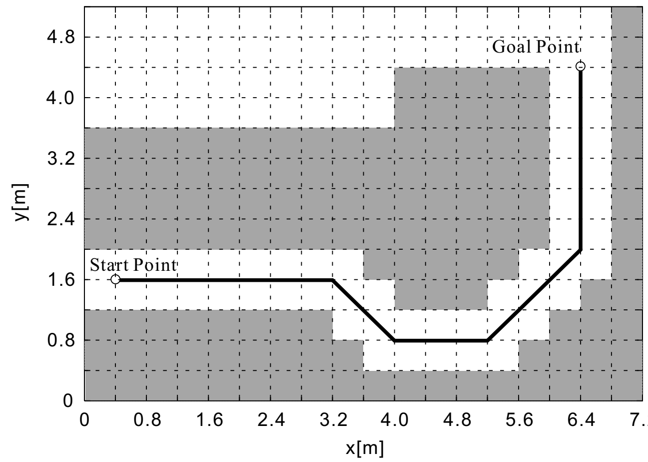


Figure 5: Generated Map using Diffusion Equation

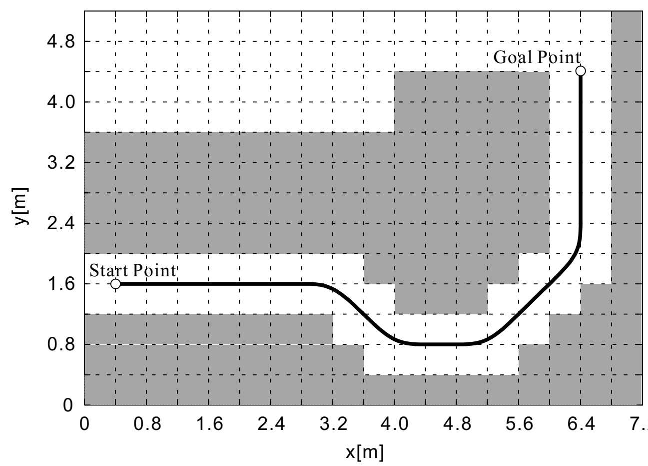


Figure 6: Generated Path using Riesenfeld Spline

could generate the smoother path of the environment using $x(t)$, $y(t)$ derived by eq.(5) as shown in Figure 6.

## 4 Experiments

The control algorithm was implemented in the distributed robot helpers referred to as DR Helpers as shown in Figure 7. Each DR Helper consists of an omni-directional mobile base, a body force sensor [11] and a forklift system. The omni-directional mobile base has the ZEN mechanism proposed in [12]. The control algorithm was implemented using VxWorks. The sampling rate was 1024[Hz].

We did the experiments of transporting a single object using two DR Helpers in cooperation with a human as shown in Figure 8. In this experiment, we gave the map of the environment as shown in Fiugre

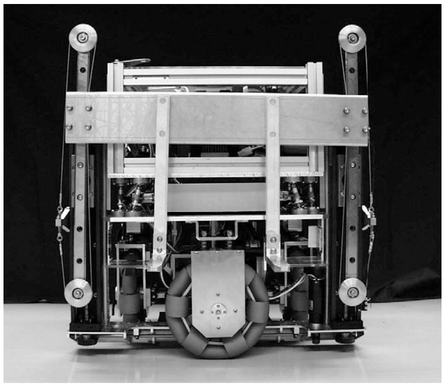

Figure 7: Dr Helper

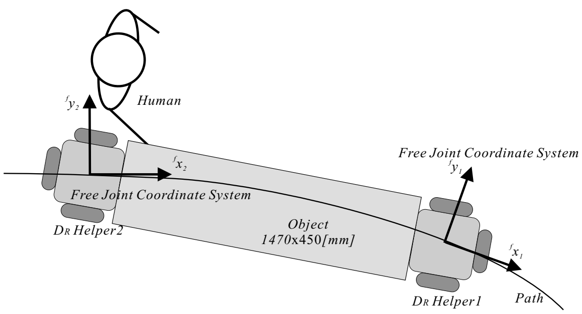


Figure 8: Experimental System

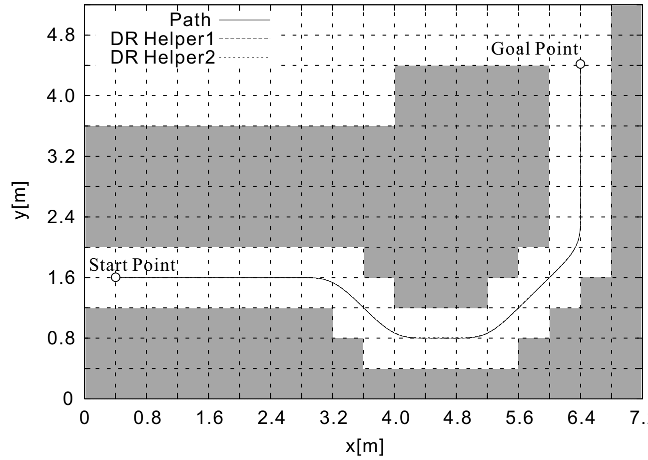


Figure 9: Experimental Results

5 to each Dr Helper and each Dr Helper generated the path from the map using the algorithm proposed in this paper as shown in Figure 6. Then, a human applied the intentional force to an object as shown in Figure 8 and transported it from the start point to the goal point in cooperation with Dr Helpers.

The experimental results are shown in Figure 9 and Figure 10. Figure 9 shows the path generated from the map of its environment and the motion of each Dr Helper detected by its dead reckoning system. As shown in Figure 9, the motion of each Dr Helper is almost coincide with the path generated from the environment as shown in Figure 6.

Figure 10 shows an example of the experiments using two Dr Helpers, which have the map information of the environment as shown in Figure 5. As shown in Figure 9 and Figure 10, the human could transport the object along the path successfully in cooperation with multiple Dr Helpers.

## 5 Conclusions

In this paper, we proposed a decentralized control algorithm of multiple mobile robots transporting a single object in cooperation with a human along a path generated from an environment. Each mobile robot is controlled as if it has a wheel with a free rotational joint and moves along the path. The proposed decentralized control algorithm was experimentally applied to the omni-directional mobile robots referred to as Dr Helpers. Experimental results illustrated the validity of the proposed control algorithm.


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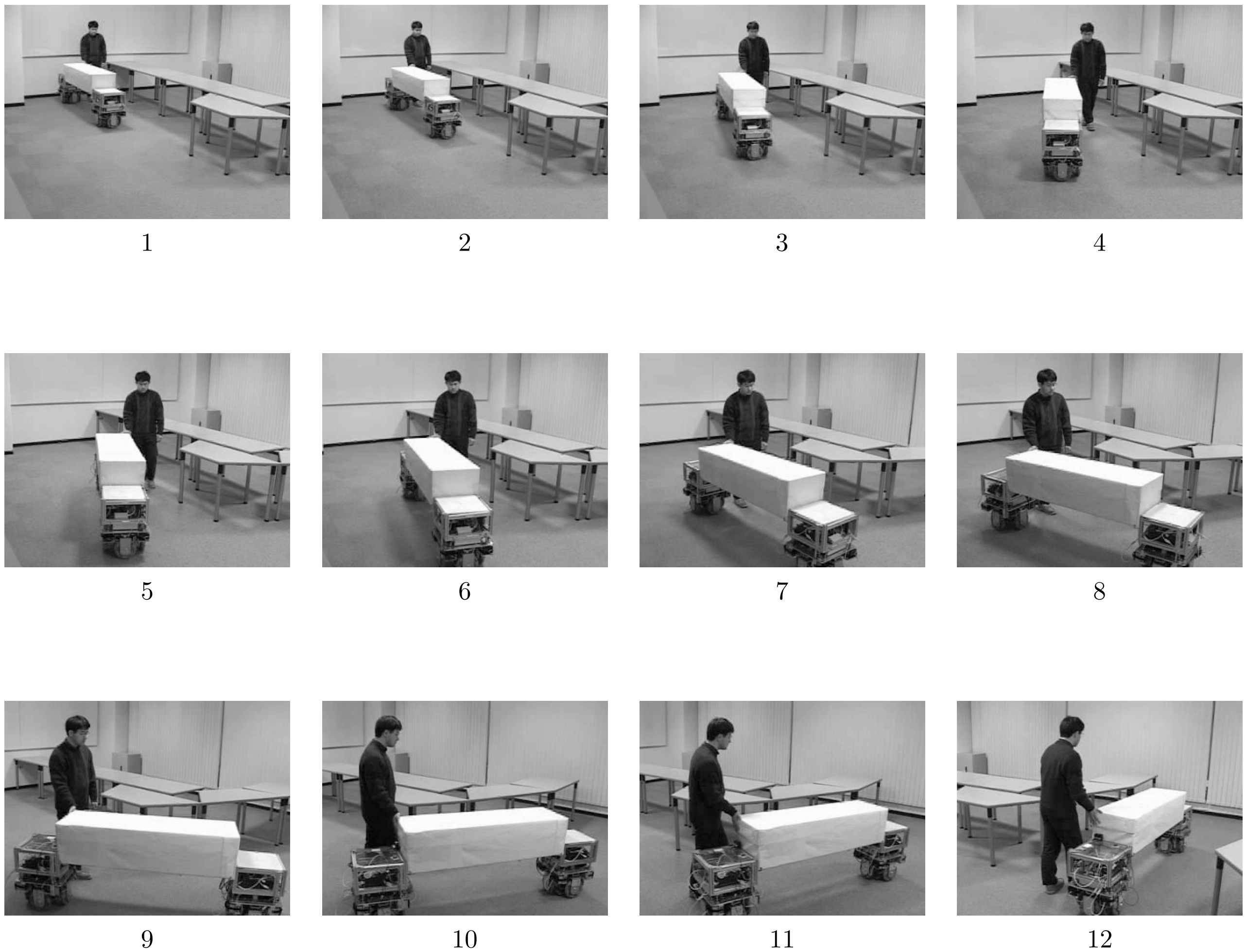


Figure 10: Example of Experiments


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