Leader-Follower type Motion Control Algorithm of Multiple Mobile Robots with Dual Manipulators for Handling a Single Object in Coordination

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Leader-Follower type Motion Control Algorithm of Multiple Mobile Robots with Dual Manipulators for Handling a Single Object in Coordination

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Abstract

In this paper, we propose a leader-follower type motion control algorithm of multiple mobile robots with dual manipulators handling a single object in coordination. In this algorithm, the representative point of each robot is controlled as if it has a caster-like dynamics in 3-D space, and each robot handles a single object in coordination with other robots without using the geometric relations among the robots based on the leader-follower type motion control algorithm. The proposed control algorithm is experimentally applied to two mobile robots with dual manipulators, and the validity of the proposed control algorithm is illustrated by the experimental results.

1 Introduction

In these days, several kinds of robots such as the mobile manipulators or humanoid robots have been developed. Theses robot systems have a mobility using wheels or legs, and manipulators to realize various tasks. Many researchers have been proposed many control algorithms for them. However, most of the control algorithms proposed so far have been designed for a single robot to do some tasks such as maintenance in nuclear fields, transportation of an object, cooperation tasks with a human, and so on.

The coordination of multiple robots has some advantages similar to the case of humans doing a task in coordination. Multiple robots in coordination can execute tasks, which could not be done by a single robot. In the research of multiple robots coordination, many control algorithms have been proposed for the handling of a single object [1]-[5]*etc*. In these control algorithms, however, the handling of a single object is realized by multiple manipulators without mobile base or the simple mobile robots without manipulators.

If we realize the coordination by using the mobile manipulators or the humanoid robots, which have both manipulator and mobile base, several kinds of tasks could be realized. Especially, multiple mobile manipulators or humanoid robots could realize the complicated manipulation of the object in 3-D space by using the manipulators. In this paper, we restrict our attention to the handling of a single object in 3-D space by using the mobile robots with dual manipulators.

To realize the coordination of mobile manipulators, we should mainly consider two problems for the coordination. One is the coordination between the mobile base and the manipulators of each robot. The other is the coordination among mobile robots. In the following part of this paper, first, we introduce a developed mobile robot with dual manipulators and propose the coordination control algorithm between the mobile base and the dual manipulators of each robot. Second, we consider the coordination among the mobile robots, and propose the leader-follower type control algorithm based on the caster-like dynamics.

2 Mobile Robot with Dual Manipulators

We developed two mobile robots with dual manipulators as shown in Figure-1. Each robot consists of an omni-directional mobile base and two 7-DOF manipulators. The manipulators are the PA-10, which are commercially available from Mitsubishi Heavy Industries Corp. The six-axis force/torque sensors are installed to the wrist of each manipulator. The body force sensor[9], which is the parallel-link

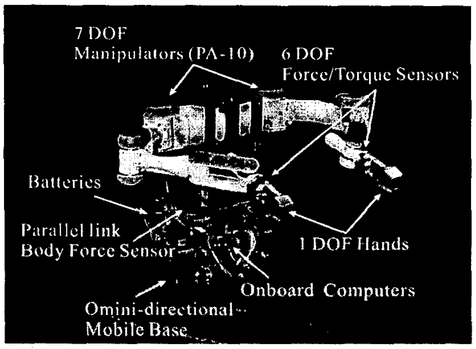

Figure 1: Developed mobile robot with dual manipulators

type force/torque sensor, is attached to the body to detect the force/moment applied to the body of the robot. The on-board PC/AT-compatible system is used to control each robot.

We also briefly discuss a coordinated control algorithm between the manipulators and the mobile base. In this algorithm, first we specify a representative point to each robot and the motion control of the dual manipulators of each robot is designed around this point. In this research, we design the caster-like dynamics around its point for handling a single object in coordination. This algorithm will be introduced in the following section. The position of the representative point is also calculated by considering the maximum manipulability for the dual manipulators with respect to a plane as shown in Figure 2.

In the coordination between the manipulators and the mobile base, the caster-like dynamics designed around the representative point of the mobile base is specified directly with respect to the world coordinate system, and the apparent impedance of the mobile base is also specified relative to a coordinate system, which is kept with constant pose displacement from the pose of the representative point of the manipulators as shown in Figure 3. By using this control algorithm, multiple manipulators could handle the object without being disturbed by the motion of the mobile base, even if the mobile base avoid the obstacles automatically by using the external sensors such as the force/torque sensor, ultra sonic sensor, and so on.

We show a example of the coordination between the manipulators and the mobile base. The experiment is shown in Figure 4. In this experiment, a human applied a force to the body force sensor and the mobile base moved based on this force. In this case, the representative point of the manipulators was not influenced by the motion of the mobile base.

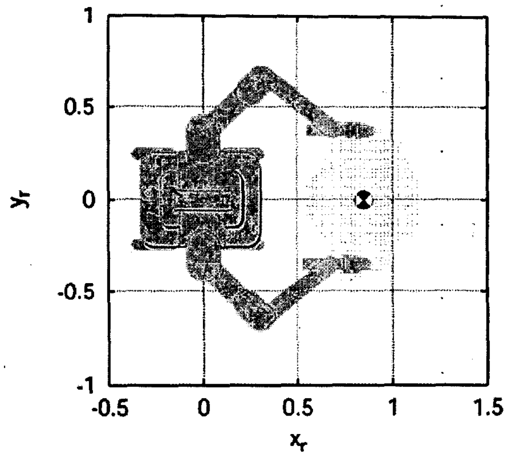

Figure 2: Manipulability of Manipulators

3 Coordination Among Robots

3.1 Caster-like Dynamics

In this section, we consider the coordination among mobile manipulators. Several control algorithms of multiple mobile robots have been proposed for handling a single object in coordination. Especially, Khatib has proposed the control algorithm of multiple mobile manipulators [6]. Most of these control algorithms proposed so far have been designed under the assumption that the geometric relations among the robots are known precisely. However, it is not easy to know the geometric relations among them precisely, especially when the robots handle an unknown object in coordination.

In addition, if we utilize the robots such as the mobile robots, mobile manipulators, and humanoid robots, which have mobility based on wheels or legs, the errors in position/orientation of each robot detected by a dead reckoning system are inevitable, because of a slippage between wheels/legs and the ground. Even if we knew geometric relations among the robots, the geometric relations could not be kept precisely any more because of the errors included in position/orientation information of each robot.

To overcome these problems, we have to design a coordinated motion control algorithm for multiple mobile robots robustly against the inevitable positioning errors. In this research, let us consider the case where we move an object with multiple casters. A chair is

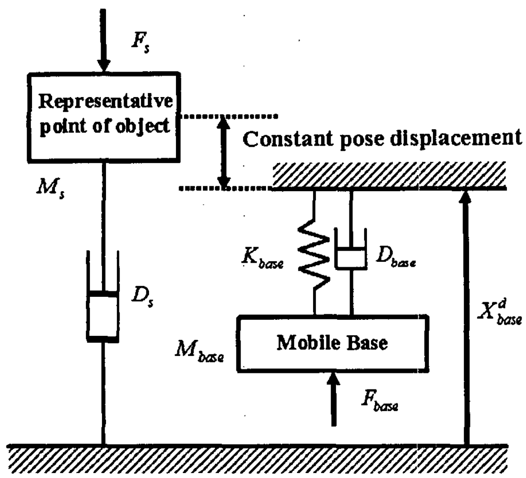

Figure 3: Cooperation Model between Manipulators and Mobile Base

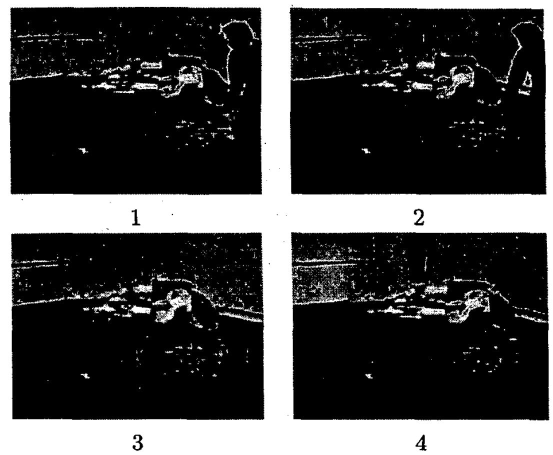

Figure 4: Experimental results of the robot motion when the external force is applied to the mobile base

a good example of such an object. The caster has a mechanism attached to the chair through its free rotational joint. When a force/moment is applied to the chair by a human, the wheel of each caster rotates around the free rotational joint to the direction of the applied force, and then, the chair could move toward the direction. It should be noted that each caster does not need to know the geometric relations among casters.

If each mobile manipulator grasps the object firmly and behaves as if it was a real caster, the manipulated object could move as if multiple casters supported it. With such a concept, we extend the motion of the real caster to the virtual caster-dynamics in 3-D space for realizing the handling of an object in cooperation among robots in 3-D space. If we could design such kinds of algorithms, the multiple robots could realize the handling of an object in coordination without considering the shape of the object, or the slippage between the ground and the wheels.

In this paper, we apply the virtual caster in 3-D space referred to as virtual 3-D caster to the leader-follower type control algorithm to handle a single object by multiple mobile manipulators in coordination without using the geometric relations among them. In the leader-follower type control algorithm, the motion command of the object is given to one of the robots referred to as leader and the leader apply a force to the object based on the desired trajectory similar to the human. The other robots referred to as follower are controlled so as to have a caster-like dynamics in 3-D space, and its virtual caster rotate to the direction of the force applied by the leader, and then estimate the desired trajectory of the leader along the heading direction of the virtual 3-D caster, so that the handling of a single object could be realized by multiple mobile manipulators in coordination.

In this section, we introduce the virtual 3-D caster proposed in [8] , which is designed for a human-robots cooperation system. To realize the motion of the virtual 3-D caster, we design the virtual 3-D caster as shown in Figure 5, which is consists of a special wheel, a wheel support and a free spherical joint. Similar to the motion of the real caster on 2-D plane, the three kinds of motion of the virtual 3-D caster can be defined as follows; The first one is the translational motion of the wheel along its heading direction based on a force applied to the free spherical joint along its heading direction as shown in Figure 5(a), the second one is the rotational motion of the wheel around a rotational axis based on a force applied to the free spherical joint perpendicular to the heading direction of the wheel as shown in Figure 5(b), and the third one is the rotational motion of the free spherical joint around its own based on a moment applied to its free special joint as shown in Figure 5(c).

To discuss the motion of the virtual 3-D caster, we define three coordinate systems as shown in Figure 6; a wheel coordinate system Σ_w, a wheel support coordinate system Σ_s and a free spherical joint coordinate system Σ_f. Σ_w is fixed on the wheel, Σ_s is fixed on the point of the free spherical joint of the wheel support and Σ_f is fixed on the free spherical joint. The

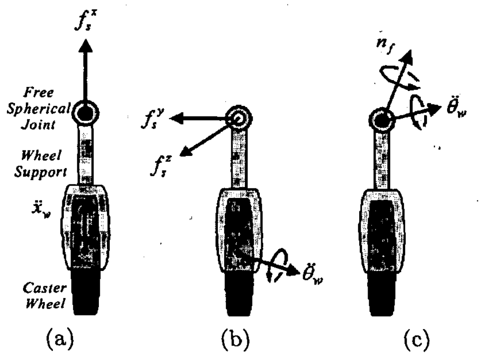

Figure 5: Three Types of Virtual 3-D Caster Motion

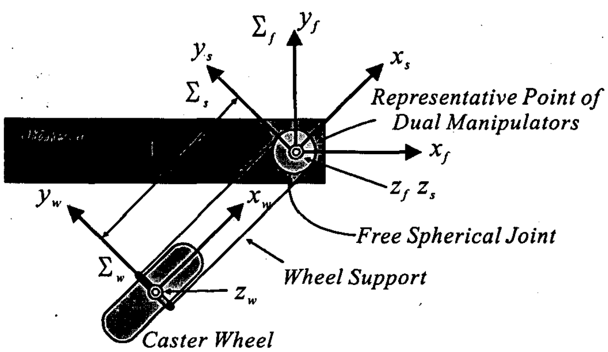

Figure 6: Coordinate Systems for Virtual 3-D Caster

direction of x-axis of the wheel coordinate system and the wheel support coordinate system are defined as the heading direction of the caster wheel as shown in Figure 6. The motion of the free spherical joint coordinate system is also independent of the motion of the wheel coordinate system and the motion of the wheel support coordinate system.

The virtual 3-D caster dynamics can be expressed as follows;

$$
\begin{aligned}
{}^w\mathbf{T}_s\mathbf{F}_s &= \mathbf{M}_w({}^s\mathbf{C}_w)^{-1}\ddot{\mathbf{X}}_s + \mathbf{D}_w({}^s\mathbf{C}_w)^{-1}\dot{\mathbf{X}}_s \quad (1)\\
\mathbf{N}_f &= \mathbf{I}_f\ddot{\mathbf{\Theta}}_f + \mathbf{D}_f\dot{\mathbf{\Theta}}_f \quad (2)
\end{aligned}
$$

where $\mathbf{M}_w$, $\mathbf{D}_w \in R^{6\times6}$ are the inertia matrix and the damping matrix with respect to the wheel of the virtual 3-D caster respectively. ${}^s\mathbf{C}_w \in R^{6\times6}$ is the matrix which convert the velocity and acceleration with respect to Σ_w into the velocity and acceleration with respect to Σ_s. ${}^w\mathbf{T}_s \in R^{6\times6}$ is the matrix which convert the force/moment with respect to Σ_s into the force/moment with respect to Σ_w. The elements of both convert matrices include the offset L of the virtual caster, which is the distance between the virtual caster wheel and the virtual free spherical joint. $\mathbf{F}_s \in R^6$, $\mathbf{N}_f \in R^3$ are the force/moment applied to the wheel support coordinate system and the free spherical joint coordinate system. $\dot{\mathbf{X}}_s$, $\ddot{\mathbf{X}}_s \in R^6$ are the velocity and acceleration with respect to the translation and the rotation of the wheel support coordinate system. $\mathbf{I}_f$, $\mathbf{D}_f \in R^{3\times3}$ is the inertia matrix and the damping matrix with respect to the rotation of the free spherical joint. $\dot{\mathbf{\Theta}}_f$, $\ddot{\mathbf{\Theta}}_f \in R^3$ are the angular velocity and the angular acceleration with respect to the free spherical joint.

When the representative potion of each manipulator is controlled so as to have these dynamics expressed by eq.(1), (2) and make the wheel support coordinate system rotate around its origin based on the angular acceleration and the angular velocity expressed in eq.(1), the representative point of each mobile manipulator realize the motion of the virtual 3-D caster under the assumption that each joint of the manipulator rotates with a specified angular acceleration and an angular velocity.

3.2 Leader-follower type Control System

In this section, we consider a leader-follower type control algorithm of multiple mobile manipulators for handling a single object in coordination. In this algorithm, the desired trajectory of the object is given to one of the mobile manipulators referred to as leader, and the other robots referred to as follower estimate the desired trajectory of the leader to handle the object in coordination with the leader.

3.2.1 Control Algorithm of Follower

When the followers are controlled based on the virtual 3-D caser expressed in the previous section and the leader applies the force/moment to the object similar to the human-robots cooperation system proposed in [8], the multiple mobile manipulators could handle the object in coordination based on the force control method. Deferent from the case of human, the leader robot could control so as to have a specified dynamics using an impedance control, a damping control and so on. If the leader could be controlled as if it has a specified dynamics, the follower could estimate the desired trajectory of the leader similar to the algorithm proposed in [4], so that multiple mobile manipulators could handle a single object more precisely based on the trajectory of the object compared with the handling based on the force control method realized in the human-robot cooperation system.

To apply the virtual 3-D caster expressed in eq.(1), (B(2) to the leader-follower type control algorithm proposed in [4], we modify the dynamics of the representative point of each follower with respect to the heading direction of the virtual 3-D caster expressed in eq.(1) as follows;

$$ {}^i m_s {}^i\Delta\ddot{x}_s ?+? {}^i d_s \, {}^i\Delta\dot{x}_s + {}^i k_s {}^i\Delta x_s = {}^i f_s \tag{3} $$

where i indicate the i-th follower. ${}^i m_s$, ${}^i d_s$, ${}^i k_s \in R$ are the inertia coefficient, the damping coefficient and the stiffness coefficient with respect to the heading direction of the virtual 3-D caster. ${}^i f_s \in R$ is the force applied to the representative point of each follower with respect to the heading direction of the virtual 3-D caster. ${}^i\Delta x_s \in R$ is the motion deviation with respect to the heading direction of the virtual 3-D caster and is expressed as follows;

$$ {}^i\Delta x_s = {}^i x_s - {}^i x_s^e \tag{4} $$

where ${}^i x_s \in R$ is the real trajectory of i-th follower with respect to the heading direction of the virtual 3-D caster and ${}^i x_s^e \in R$ is the estimated trajectory of the follower derived by the estimation algorithm with respect to the heading direction of virtual 3-D caster.

3.2.2 Control Algorithm of Leader

We also control the representative point of the leader according to the following equation;

$$ {}^l\mathbf{M}_r {}^l\Delta\ddot{\mathbf{x}}_r + {}^l\mathbf{D}_r {}^l\Delta\dot{\mathbf{x}}_r + {}^l\mathbf{K}_r {}^l\Delta\mathbf{x}_r = {}^l\mathbf{F}_r \tag{5} $$

where ${}^l\mathbf{M}_r$, ${}^l\mathbf{D}_r$, ${}^l\mathbf{K}_r \in R^{6\times 6}$ are the inertia matrix, the damping matrix and the stiffness matrix with respect to the representative point of the leader. ${}^l\mathbf{F}_r \in R^6$ is the force/moment applied to the representative point of the leader. ${}^l\Delta\mathbf{x}_r \in R^6$ is the motion deviation of the representative point of the leader and is expressed as follows;

$$ {}^l\Delta\mathbf{X}_r = {}^l\mathbf{X}_r - {}^l\mathbf{X}_r^d \tag{6} $$

where ${}^l\mathbf{X}_r \in R$ is the real trajectory of the leader and ${}^l\mathbf{X}_r^d \in R$ is the desired trajectory of the leader. It should be noted that the x-axis of the leader robot coordinate system is always defined as the direction tangential to the desired trajectory.

3.2.3 Estimation of Desired Trajectory

In this section, we discuss how the followers estimate the motion of the leader. Assuming that each virtual 3-D caster of the followers points its heading direction towered the direction of the force applied to the grasping point instantaneously using the adaptive caster action proposed in [7], we have only to consider how followers estimate the motion of the leader along its heading direction of the virtual 3-D caster.

We have proposed the leader-follower type control algorithms of multiple holonomic mobile robots to handle a single object in coordination [4][5]. These control algorithms have been designed under the assumption that the geometrical relations among the robots are known precisely. However, if we restrict our attention to the handling of an object with respect to a 1-DOF motion of the object, we can use these algorithms without the geometrical relations among the robots.

Even if any motion command is given to the leader, the motion of the virtual 3-D caster of the follower can be considered a 1-DOF motion with respect to the heading direction of the virtual 3-D caster. Therefore, we can apply the algorithm proposed in [4] to the virtual 3-D caster system. By using this algorithm, each robot could estimate the reference motion of the leader along the heading direction of the virtual 3-D caster and handle a single object in 3-D space without using the geometric relations among the robots.

4 Experiments

We did experiment using two mobile robots with dual manipulators as shown in Figure 7. In this experiment, the desired trajectory of the leader along y_0-axis of the coordinate system as shown in Figure 8 from 0[m] to 2.5[m] for 30[sec] was given to the representative point of the leader and the pose of the representative point of the leader was kept constant during the object handling experiment.

When the leader began to move along y_0-axis, the leader applied the force to the follower through the object. The virtual 3-D caster of the follower rotated its heading direction towered the direction of the force instantaneously using the control method based on the adaptive caster action proposed in [7], and the follower

Figure 7: Mobile Robots with Dual Manipulators

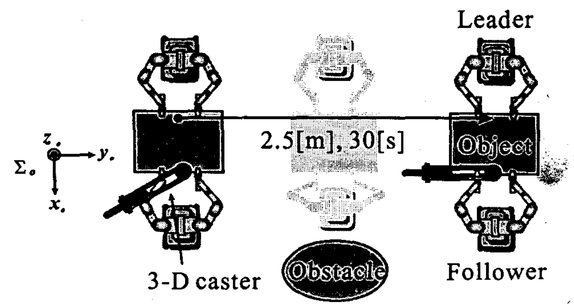

Figure 8: Experimental conditions for collision avoidance

transported the object along its heading direction with the leader by estimating the desired trajectory of it.

In addition, we gave the position of an obstacle to the follower so that the follower avoided the obstacle by moving the mobile base as shown in Figure 8. In this case, the mobile base of the robot generated the avoiding motion without influencing the motion of the dual manipulators as shown in Figure 4. A example of experiments is shown in Figure 9. As shown in these figures, the handling a single object by two mobile robots with dual manipulators in coordination was almost achieved.

5 Conclusions

In this paper, we proposed the concept of the virtual 3-D caster and the leader-follower type control algorithm for multiple mobile robots with dual manipulators to handle a single object in coordination without using the geometric relations among the robots. The proposed control algorithm was experimentally applied to two mobile robots with dual manipulators and the validity of the proposed control algorithm was illustrated by the experimental results.

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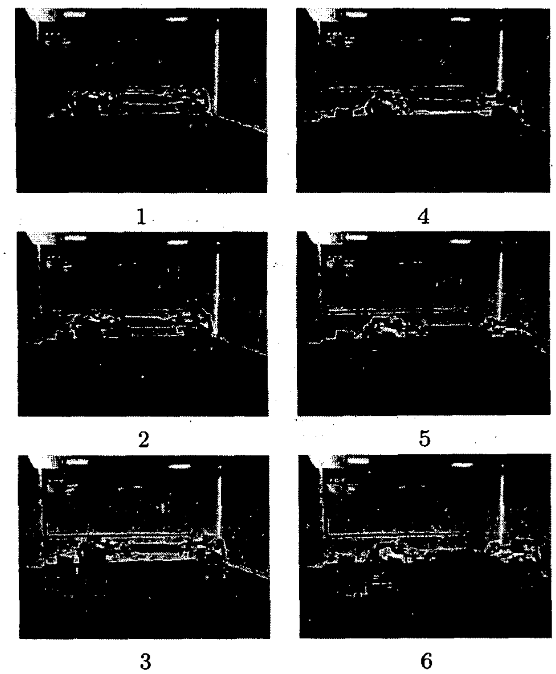

Figure 9: Experimental results of collision avoidance

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