Coordinated Motion Control of Multiple Robots without Position Information of Each Robot

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Abstract

In this paper, we propose a decentralized control algorithm of multiple mobile robots transporting a single object in coordination. In this algorithm, each robot is controlled as if it has a caster-like dynamics and transports a single object in coordination with other robots without using the geometric relations among robots. The proposed control algorithm is experimentally applied to multiple mobile robots. Experimental results illustrate the validity of the proposed control algorithm.

1 Introduction

When we would like to transport a large and heavy object, we carry it in cooperation with other people. To utilize multiple robots in coordination is a natural extension of such human behavior to the robots. In this paper, we propose a decentralized control algorithm of multiple mobile robots transporting an object in coordination like humans. Much research has been already done for the motion control of multiple robots handling an object in coordination [1]-[6]*etc*.

Most of these control algorithms have been designed under the assumption that the force/moment applied to a representative point of the object is available and geometric relations among the robots and the representative point are known precisely. The geometric relations are required to implement these algorithms to robots. However, it is not easy to know the geometric relations among them precisely, especially when the robots handle an unknown object in coordination.

When we consider coordination of multiple mobile robots, it is not easy to know the geometric relations among them. Errors in position and orientation of each robot detected by a dead reckoning system are inevitable because of the slippage between wheels and the ground. Even if we knew the geometric information of the object, the motion relations among the robots could not be kept precisely any more because of the errors included in position/orientation information of each robot.

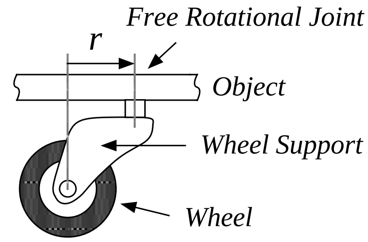


Figure 1: Real Caster

To overcome these problems, we have proposed a motion control algorithm of multiple mobile robots without using the geometric relations among robots [7]. In this algorithm, each robot is controlled as if it has a caster-like dynamics as shown in Figure 1 and transports an object in coordination with other robots. However, it is difficult for this algorithm to be applied to mobile robots more than three. The motion of an object could be constrained completely, when each robot have 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, which could be applied to mobile robots more than three, even if each robot have slippage between its wheels and the ground during a transportation of an object. The proposed control algorithm is experimentally applied to three autonomous omni-directional mobile robots and the experimental results illustrate the validity of the proposed control algorithm.

2 Caster-like Motion

In this section, we consider the transportation of a single object by multiple holonomic mobile robots in coordination without using the geometric relations among robots. We have proposed the leader-follower type control algorithms of multiple holonomic mobile robots to transport a single object in coordination [5],[6]. However, these control algorithms have been designed based on the assumption that the geometrical relations between robots and the representative point of the object or among robots are precisely known.

The dead reckoning system of a mobile robot is not so reliable for these robots in a working environment we consider in this paper. We could not position each robot precisely and could not apply the same control principle proposed in [5],[6], unless the coordinate systems among robots are calibrated in real-time during the transportation of an object. The control system has to be redesigned robust against the inevitable positioning error of each robot.

We have proposed the decentralized motion control algorithm of multiple mobile robots [7]. In this algorithm, each robot is controlled as if it has a dynamics of a caster wheel as shown in Figure 1 and transports an object in coordination with other robots without using the position/orientation information of other robots.

In the case using two mobile robots, all of the motion of an object supported by two mobile robots is characterized by a rotational motion of the object around a certain point based on the heading direction of caster wheel as shown in Figure 2(a) [7].

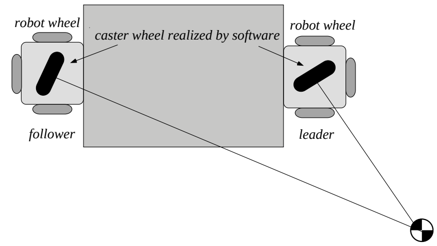
In the case using mobile robots more than three, the motion of an object supported by multiple mobile robots is characterized by two kinds of the motion based on the heading direction of caster wheel. One is a rotational motion of the object around a certain point as shown in Figure 2(a). The other is that a motion of the object is constrained as shown in Figure 2(b) since each robot could not move along the direction of wheel axis.

If the motion of an object supported by multiple robots is a rotational one around a certain point, each robot could transports a single object in coordination with other robots using the algorithm proposed in [7]. However, if the motion of an object supported by multiple robots is constrained, multiple mobile robots could not transport an object in coordination.

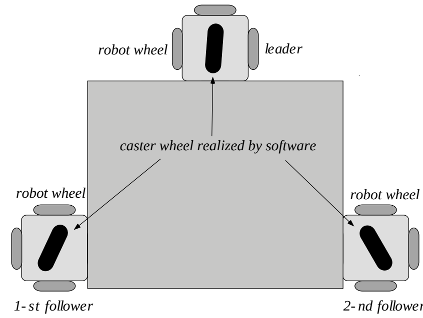
To overcome this problem, we extend the caster-like dynamics proposed in [7] and propose a decentralized motion control algorithm of multiple mobile robots transporting a single object in coordination without position information of each robot.

3 Velocity-based Caster-like Motion

In this section, let us consider the motion of a real caster as shown in Figure 1 to implement the caster-like motion to a mobile robot. A caster consists of a wheel,



(a) Rotational Motion



(b) Constrained Motion

Figure 2: Motion of Object

a free rotational joint and a wheel support, which connects the wheel and the joint.

In the algorithm proposed in [7], each robot is controlled as if it has a dynamics of a caster wheel. Therefore, each robot could not move the direction of caster wheel axis. In this paper, we consider that each robot is controlled as if it has a dynamics of a free rotational joint to generate velocity in all directions.

To realize a dynamics of the free rotational joint, we define three coordinate systems as shown in Figure 3; a base coordinate system ${}^{b}\Sigma_k$, a robot coordinate system ${}^{r}\Sigma_k$ and a caster coordinate system ${}^{c}\Sigma_k$. The origins of these coordinate systems are located at the center of the force/torque sensor. The subscripts $k = l,\ i$ indicate the leader and the i-th follower respectively.

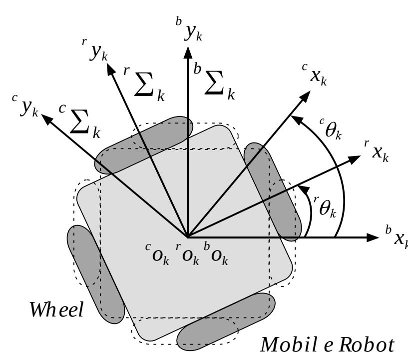


Figure 3: Coordinate System

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 ${}^r\theta_k$ be the rotational angle of the robot coordinate system with respect to the base coordinate system as shown in Figure 3.

The caster coordinate system rotates around its origin to mimic the free rotational motion of caster support. The direction of x-axis of the caster coordinate system is defined as the heading direction of the caster wheel. Let ${}^c\theta_k$ be the rotational angle of the caster coordinate system with respect to the base coordinate system as shown in Figure 3.

A velocity-controlled servomotor drives each wheel of the omni-directional mobile robot and we assume that each wheel rotates with a specified angular velocity. We could generate the translational motion of the caster wheel based on the force applied to the robot as follows;

$$\begin{aligned} {}^{tran}D_l {}^c\Delta\dot{x}_l + {}^{tran}K_l {}^c\Delta x_l &= {}^c f_{xl} \\ &= ({}^r f_{xl} - {}^r f_{xl}^{in})\cos({}^c\theta_l - {}^r\theta_l) \\ &\quad + ({}^r f_{yl} - {}^r f_{yl}^{in})\sin({}^c\theta_l - {}^r\theta_l) \end{aligned} \tag{1}$$

$$\begin{aligned} {}^{tran}D_i {}^c\Delta\dot{x}_i + {}^{tran}K_i {}^c\Delta x_i &= {}^c f_{xi} \\ &= ({}^r f_{xi} - {}^r f_{xi}^{in})\cos({}^c\theta_i - {}^r\theta_i) \\ &\quad + ({}^r f_{yi} - {}^r f_{yi}^{in})\sin({}^c\theta_i - {}^r\theta_i) \end{aligned} \tag{2}$$

where the subscripts l and i indicate the leader and the i-th follower respectively. ${}^{tran}D_l,\ {}^{tran}D_i \in R$ are positive damping coefficients and ${}^{tran}K_l,\ {}^{tran}K_i \in R$ are positive stiffness coefficients. $\Delta x_l,\ \Delta x_i \in R$ are the trajectory deviations of the robots according to the force applied to the robot ${}^c f_{xl},\ {}^c f_{xi} \in R$ along x-axis of the caster coordinate system. ${}^r f_{xl}^{in},\ {}^r f_{yl}^{in}, {}^r f_{xi}^{in},\ {}^r f_{yi}^{in} \in R$ are the specified internal forces applied to the object by the robots with respect to the $k-th$ mobile robot coordinate system.

Let ${}^c x_{dl},\ {}^c x_{ei} \in R$ be the desired trajectories of the leader and the i-th follower respectively and ${}^c x_l,\ {}^c x_i \in R$ be the real trajectories of the leader and i-th follower respectively. Then, the trajectory deviations of the robots are expressed as follows;

$${}^c\Delta x_l = {}^c x_l - {}^c x_{dl} \tag{3}$$
$${}^c\Delta x_i = {}^c x_i - {}^c x_{ei} \tag{4}$$

To mimic the motion of the wheel support, we obtain the angular velocity of the caster coordinate system ${}^c\dot{\theta}_k$ using the following equation and make the caster coordinate system rotate around its origin based on this.

$$\begin{aligned} {}^{cast}D_l {}^c\Delta\dot{\theta}_l + {}^{cast}K_l {}^c\Delta\theta_l &= \frac{1}{r_l} {}^c f_{yl} \\ &= \frac{1}{r_l}\{-({}^r f_{xl} - {}^r f_{xl}^{in})\sin({}^c\theta_l - {}^r\theta_l) \\ &\quad + ({}^r f_{yl} - {}^r f_{yl}^{in})\cos({}^c\theta_l - {}^r\theta_l)\} \end{aligned} \tag{5}$$

$$\begin{aligned} {}^{cast}D_i {}^c\dot{\theta}_i &= \frac{1}{r_i} {}^r f_{yi} \\ &= \frac{1}{r_i}\{-({}^r f_{xi} - {}^r f_{xi}^{in})\sin({}^c\theta_i - {}^r\theta_i) \\ &\quad + ({}^r f_{yi} - {}^r f_{yi}^{in})\cos({}^c\theta_i - {}^r\theta_i)\} \end{aligned} \tag{6}$$

where ${}^{cast}D_l,\ {}^{cast}D_i \in R$ are positive damping coefficients and ${}^{cast}K_l \in R$ is a positive stiffness coefficient. $r_l,\ r_i$ are the caster offsets as shown in Figure 1, and ${}^c f_{yl},\ {}^c f_{yi} \in R$ are the forces applied to the robot along y-axis of the caster coordinate system.

$\Delta\theta_l \in R$ is the direction deviation of the caster coordinate system according to the force applied to the leader ${}^c f_{yl} \in R$ along y-axis of the caster coordinate system. Let ${}^c\theta_{dl} \in R$ be the desired direction of the caster coordinate system of the leader and ${}^c\theta_l \in R$ be the real direction of the caster coordinate system of the leader. The direction deviation of the caster coordinate system of the leader is expressed as follows;

$${}^c\Delta\theta_l = {}^c\theta_l - {}^c\theta_{dl} \tag{7}$$

To realize the caster-like motion around free rotational joint, we generate the motion of the robot based on the angular velocity of the caster coordinate system as follows;

$${}^c\dot{y}_l = r_l {}^c\dot{\theta}_l \tag{8}$$
$${}^c\dot{y}_i = r_i {}^c\dot{\theta}_i \tag{9}$$

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 $n_l,\ n_i \in R$ applied to the leader and i-th follower.

$${}^{rot}D_l \Delta {}^r\dot{\theta}_l + {}^{rot}K_l \Delta {}^r\theta_l = {}^r n_l \tag{10}$$
$${}^{rot}D_i {}^r\dot{\theta}_i = {}^r n_i \tag{11}$$

where ${}^{rot}D_l,\ {}^{rot}D_i \in R$ are positive damping coefficients and ${}^{rot}K_l \in R$ is a positive stiffness coefficients. ${}^r\dot{\theta}_i \in R$ is the real angular velocity of the i-th follower.

Let ${}^r\theta_{dl} \in R$ be the desired orientation of the leader and ${}^r\theta_l \in R$ be the real orientation of the leader. The orientation deviation of the leader $\Delta {}^r\theta_l \in R$ are expressed as follows;

$${}^r\Delta\theta_l = {}^r\theta_l - {}^r\theta_{dl} \tag{12}$$

It should be noted that the relative angle between ${}^r\theta_k$ and ${}^c\theta_k$ is independent of ${}^r\theta_k$.

4 Transportation by Multiple Mobile Robots

In this section, we consider how the followers estimate the desired trajectory given to the leader. When the number of the followers is more than two, it is impossible for the i-th follower to estimate the desired trajectory of the leader by using the estimation algorithm proposed in [7], because the trajectory deviation of the i-th follower is affected by motion of all of other robots.

In this situation, the robots are classified into two groups as shown in Figure 4; one is the i-th follower itself and the other is the rest of the robots including the leader. We refer to the rest of the robots as the i-th virtual leader for the i-th follower. For the i-th follower, the i-th virtual leader behaves as if it was a real leader. Using the concept of the virtual leader, the i-th follower estimates the desired trajectory of the i-th virtual leader based on the estimation algorithm proposed in [7]

We consider how the i-th follower estimates the desired trajectory of the i-th virtual leader along the x-axis of the caster coordinate system of i-th follower. Under the assumption that the external force applied to the object is negligible and the leader and followers are controlled using the same parameters, that is,

$$^{tran}D = {}^{tran}D_l = {}^{tran}D_i \tag{13}$$

$$^{tran}K = {}^{tran}K_l = {}^{tran}K_i \tag{14}$$

We have the following relations with respect to the forces applied to each robot;

$$^{b}f_{lx} + \sum_{j=1}^{n} {}^{b}f_{jx} = 0 \tag{15}$$

$$^{b}f_{ly} + \sum_{j=1}^{n} {}^{b}f_{jy} = 0 \tag{16}$$

where variables with subscript b indicate that the variables are with respect to the base coordinate system of each robot. It should be noted that the base coordinate

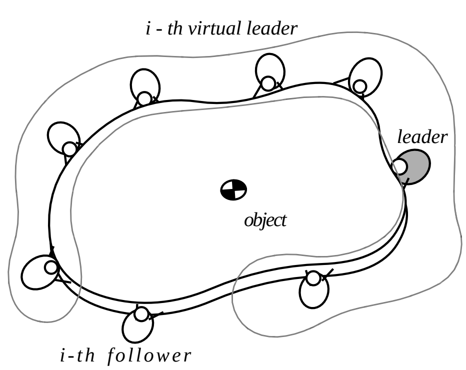


Figure 4: Virtual Leader

system of each robot is the same orientation as the base coordinate system attached to the ground.

We rewrite the dynamics of the i-th follower expressed in eq.(2) as follows with respect to the caster coordinate system of the leader.

$$^{tran}D\cos({}^{c}\theta_i - {}^{c}\theta_l)\Delta\dot{x}_i + {}^{tran}K\cos({}^{c}\theta_i - {}^{c}\theta_l)\Delta x_i = \cos({}^{c}\theta_i - {}^{c}\theta_l){}^{c}f_{xi} \tag{17}$$

From eq.(1), (15) and (17), we obtain the following relation;

$$^{tran}D\left({}^{c}\Delta\dot{x}_l + \sum_{j=1}^{n}\cos({}^{c}\theta_j - {}^{c}\theta_l){}^{c}\Delta\dot{x}_j\right) + {}^{tran}K\left({}^{c}\Delta x_l + \sum_{j=1}^{n}\cos({}^{c}\theta_j - {}^{c}\theta_l){}^{c}\Delta x_j\right) = 0 \tag{18}$$

As time tends to infinity, we obtain the following relationship from eq.(18) with the positive definiteness of the damping coefficient and the stiffness coefficient, even if the initial values of ${}^{c}\Delta x_l + \sum_{j=1}^{n}\cos(\theta_j - \theta_l){}^{c}\Delta x_j$ is not zero.

$$^{c}\Delta x_l + \sum_{j=1}^{n}\cos(\theta_j - \theta_l){}^{c}\Delta x_j = 0 \tag{19}$$

We can derive the dynamics of the i-th virtual leader as follows;

$$^{tran}D\left({}^{c}\Delta\dot{x}_l + \sum_{j=1(j\neq i)}^{n}\cos({}^{c}\theta_j - {}^{c}\theta_l){}^{c}\Delta\dot{x}_j\right) + {}^{tran}K\left({}^{c}\Delta x_l + \sum_{j=1(j\neq i)}^{n}\cos({}^{c}\theta_j - {}^{c}\theta_l){}^{c}\Delta x_j\right) = {}^{c}f_{lx} + \sum_{j=1(j\neq i)}^{n}\cos({}^{c}\theta_j - {}^{c}\theta_l){}^{c}f_{jx} \tag{20}$$

where

$$\sum_{j=1(j\neq i)}^{n} c_j = \sum_{j=1}^{i-1} c_j + \sum_{j=i+1}^{n} c_j \tag{21}$$

The trajectory deviation of the i-th virtual leader $\Delta^{c}x_{li}$ is expressed as follows;

$$^{c}\Delta x_{li} = {}^{c}\Delta x_l + \sum_{j=1(j\neq i)}^{n}\cos({}^{c}\theta_j - {}^{c}\theta_l){}^{c}\Delta x_j \tag{22}$$

From Figure 5, we can derive the relation of the trajectory deviation between the i-th virtual leader and the i-th follower with respect to the caster coordinate system of the i-th follower as follows;.

$$\begin{aligned} {}^c\Delta x_i - {}^c\Delta x_{li}\cos({}^c\theta_i - {}^c\theta_{li}) \\ = {}^c x_{dli}\cos({}^c\theta_i - {}^c\theta_{li}) - {}^c x_{ei} \end{aligned} \quad (23)$$

Eliminating ${}^c\Delta x_{li}$ from eq.(19) and (23), we obtain the estimation error along the x-axis of the caster coordinate system of the i-th follower ${}^c\Delta x_{di}$ as follows;

$$\begin{aligned} {}^c\Delta x_{di} &= {}^c x_{dl}\cos({}^c\theta_i - {}^c\theta_l) - {}^c x_{ei} \\ &= 2U_i{}^c\Delta x_i \end{aligned} \quad (24)$$

where, U_i is expressed as follows;

$$U_i = \frac{1}{2}\{1 + \cos({}^c\theta_i - {}^c\theta_l)\cos({}^c\theta_i - {}^c\theta_{li})\} \quad (25)$$

If the i-th follower could calculate U_i, the i-th follower could estimate the trajectory precisely from eq.(24) using the algorithm proposed in [7]. However, the i-th follower could not calculate the estimation error ${}^c\Delta x_{di}$ because the follower does not know the orientation of the leader θ_l. We design the estimator based on the estimation error expressed by the following equation instead of using eq.(24).

$${}^c\Delta\tilde{x}_{di} = 2\ {}^c\Delta x_i \quad (26)$$

Form eq.(24) and (26), ${}^c\Delta\tilde{x}_{di}$ is expressed as follows;

$${}^c\Delta\tilde{x}_{di} = \frac{1}{U_i}{}^c\Delta x_{di} \quad (27)$$

Let us consider how ${}^c x_{di}$ is estimated using ${}^c\Delta\tilde{x}_{di}$. Let G_i be the transfer function, which estimates ${}^c x_{di}$ as ${}^c x_{ei}$ based on ${}^c\Delta\tilde{x}_{di}$ as shown in Figure 6(a). From eq.(24), Figure 6(a) can be rewritten as a feedback system as shown in Figure 6(b). To eliminate the steady-state position and velocity estimation errors, the transfer function G_i is designed as follows;

$$G_i = \frac{a_i s + b_i}{s^2} \quad (28)$$

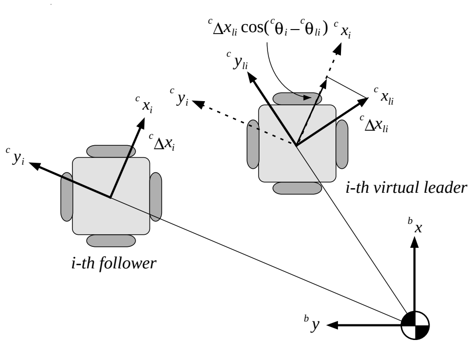


Figure 5: Relationship between i-th Leader and i-th Follower

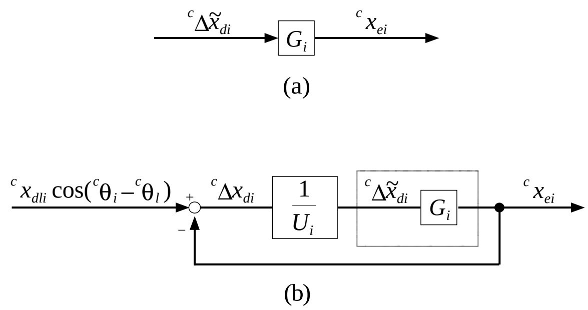


Figure 6: Estimator

By designing G_i to keep the stability of this system for any U_i, the follower can estimate the desired trajectory of the leader. The stability of the system is guaranteed as long as $U_i > 0$ and the estimation parameters $a_i > 0$ and $b_i > 0$ are satisfied. When each robot is controlled by using adaptive caster action proposed in [7], $U_i > 0$ apparently.

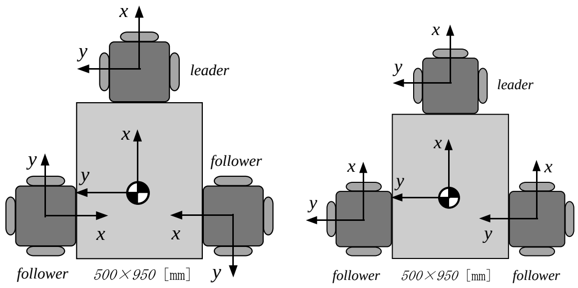
5 Experiments

We did experiments using three autonomous omnidirectional mobile robots, ZEN developed by RIKEN [8] as shown in Figure 7. Each mobile robot has three degrees of freedom of motion and equipped with the Body Force Sensor [9] and the fork lift system, and was driven by a DC servo motor controlled by a velocity servo driver. The control algorithm explained in the previous section was implemented using VxWorks. The sampling rate of each ZEN was 1024[Hz].

In this experiment, we gave an initial orientation of the caster coordinate system to each robot as shown in Figure 8(a). Then, the leader was given the desired trajectory along x-axis of the object coordinate system as shown in Figure 8(a), which was calculated by a fifth order polynomial of time.

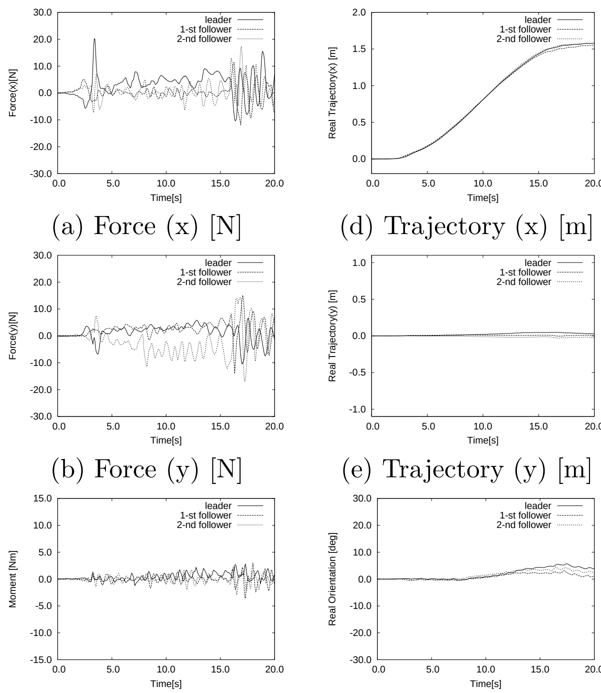
When the leader began to move along x-axis of the object coordinate system, the leader applied the force along x-axis of the object coordinate system to each

Figure 7: Experimental System



(a) (b)

Figure 8: Coordinate System



(a) Force (x) [N] (d) Trajectory (x) [m]

(b) Force (y) [N] (e) Trajectory (y) [m]

(c) Moment [Nm] (f) Orientation [deg]

Figure 9: Experimental Results

follower through the object. The caster coordinate system of the follower rotated instantaneously as shown in Figure 8(b) using the adaptive caster action proposed in [7] and each follower transported a single object in coordination with the leader without the position information among robots. The results are shown in Figure 9. The transportation of a single object by three mobile robots in coordination was achieved successfully.

6 Conclusion

In this paper, we proposed a decentralized motion control algorithm of multiple mobile robots transporting a single object in coordination. In this algorithm, each robot is controlled as if it has a caster-like dynamics and transports a single object in coordination without using the information of the geometric relations among robots. The proposed algorithm was experimentally applied to three mobile robots and the experimental results illustrated the validity of the proposed algorithm.

Acknowledgments

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