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Motion Control of Multiple Autonomous Mobile Robots Handling a Large Object in Coordination

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Abstract

In this paper, we discuss a problem relating to the force/moment transformation for the handling of a large object by multiple mobile robots in coordination. We propose a control algorithm using geometrical constraints among the grasping points and the representative point of the object, which reduce the effect of noise amplified by force/moment transformation. We extend this algorithm to the decentralized control algorithm of multiple robots handling an object in coordination. The proposed control algorithm is experimentally applied to the mobile robots. Experimental results illustrate the validity of the proposed control algorithm.

1 Introduction

The coordination of multiple robots has some advantages similar to the case of a task executed by humans in coordination. Multiple robots in coordination can execute tasks which could not be done by a single robot. Many control algorithms of robots have been proposed for the handling of a single object by multiple robots in coordinations [1]-[4], etc.

Most of the control algorithms proposed so far have been designed under the assumption that the force/moment applied to a representative point of the object is available. The force/moment applied to the object is usually calculated from the force/moment detected by a force sensor attached to each robot. When the representative point is located far from the force sensor, the calculation amplifies the sensor noise included in the force/moment information from the force sensor and lower the equivalent sensor resolution at the representative point especially when we consider the problem of handling a large object.

In this paper, we propose a control algorithm for handling of a large object in coordination. In the following part of this paper, we briefly review the compliance-based control algorithm of multiple robots, which we proposed in [5]. And We discuss the problem relating to the force/moment transformation. We propose a control algorithm using geometrical constraints among the grasping points and the representative point of the object which reduces the effect of sensor noise. We extend this algorithm to a decentralized control algorithm of multiple mobile robots handling a single object in coordination. The control algorithm is experimentally implemented in the autonomous omnidirectional mobile robots, ZEN. The experimental results illustrate the effectiveness of the proposed control algorithm.

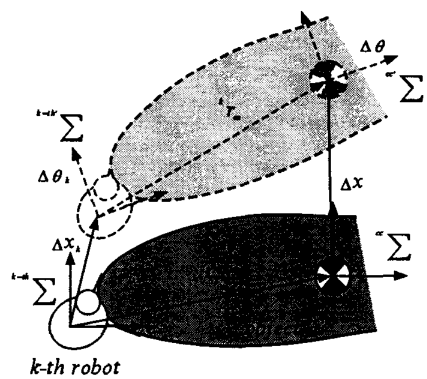

Figure 1: Coordinate system

2 Coordinate systems

Consider a problem to handle a rigid object by n mobile robots in coordination. We define coordinate systems as shown in Figure 1; the object coordinate system ${}^{cc}\Sigma$, and the k-th mobile robot coordinate system ${}^{k-th}\Sigma$. The object coordinate system is attached to a representative point of the object and moves together with the object. The k-th mobile robot coordinate system is attached to the grasping point of the k-th mobile robot and its coordinate axes are defined parallel to those of the object coordinate system. Under the assumption that each robot holds the object firmly and no relative motion between the object and the robot occurs, the k-th mobile robot coordinate system also moves together with the object coordinate system without changing their geometrical relation.

Assume that external force/moment is applied to the object. $\Delta x \in R^2$ and $\Delta\theta \in R$ is position deviation and orientation deviation of the object coordinate system with respect to the original object coordinate system as shown in Figure 1. $\Delta x_k \in R^2$ and $\Delta\theta_k \in R$ is position deviation and orientation deviation of the

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k-th mobile robot coordinate system, with respect to ${}^{cc}\Sigma$, corresponding to the motion of the object coordinate system Δx and $\Delta\theta$. ${}^{k-th'}\Sigma$ and ${}^{cc'}\Sigma$ express the mobile robot coordinate system and the object coordinate system respectively, after the deviational motion, and correspond to ${}^{k-th}\Sigma$, ${}^{cc}\Sigma$, respectively before the deviation.

3 Compliance-based coordinated motion control algorithm

First, let us review the compliance-based coordinated motion control algorithm we proposed in [5]. In [5], we assumed that each robot is driven by velocity-controlled actuators and its impedance around the representative point attached to the object is controlled so as to have the following dynamics;

$$\begin{bmatrix} {}_kf^{ext} \\ {}_kn^{ext} \end{bmatrix} = \begin{bmatrix} {}_kD & 0 \\ 0 & {}_kD_\theta \end{bmatrix}\begin{bmatrix} \Delta\dot{x} \\ \Delta\dot{\theta} \end{bmatrix} + \begin{bmatrix} {}_kK & 0 \\ 0 & {}_kK_\theta \end{bmatrix}\begin{bmatrix} \Delta x \\ \Delta\theta \end{bmatrix} \quad (1)$$

where , $\begin{bmatrix} {}_kD & 0 \\ 0 & {}_kD_\theta \end{bmatrix}$, and $\begin{bmatrix} {}_kK & 0 \\ 0 & {}_kK_\theta \end{bmatrix}$ are a 3×3 damping matrix, and a 3×3 stiffness matrix, respectively. In eq.(1) we assumed that the translational motion and the rotational motion are decoupled each other. ${}_kf^{ext} \in R^2$, ${}_kn^{ext} \in R$ represent the external force and moment born by the k-th mobile robot respectively at the representative point with respect to the nominal object coordinate system.

Next, we derive the equivalent impedance of each mobile robot at the grasping point. To simplify the discussion, we assume that the force sensor of each mobile robot is located at its grasping point and directly detects force/moment applied to the robot at its grasping point. Considering the homogeneous coordinate transformation from ${}^{cc'}\Sigma$ to ${}^{k-th}\Sigma$, we have the following relation;

$$\left[\begin{array}{c|c} E & {}^kr_{cc} \\ \hline 0 & 1 \end{array}\right]\left[\begin{array}{c|c} Rot(\Delta\theta) & \Delta x \\ \hline 0 & 1 \end{array}\right] = \left[\begin{array}{c|c} Rot(\Delta\theta_k) & \Delta x_k \\ \hline 0 & 1 \end{array}\right]\left[\begin{array}{c|c} E & {}^kr_{cc} \\ \hline 0 & 1 \end{array}\right] \quad (2)$$

where $Rot(\Delta\theta)$ and $Rot(\Delta\theta_k)$ are 2×2 rotation matrices corresponding to $\Delta\theta$ and $\Delta\theta_k$ respectively. E is the 2×2 identity matrix. ${}^kr_{cc} \in R^2$ is the position vector from the origin of ${}^{k-th}\Sigma$ to the origin of ${}^{cc}\Sigma$ with respect to ${}^{cc}\Sigma$. The left-hand side of eq.(2) represents the homogeneous coordinate transformation from ${}^{cc'}\Sigma$ to ${}^{k-th}\Sigma$ via ${}^{cc}\Sigma$, and the right-hand side of eq.(2) represents the homogeneous coordinate transformation from ${}^{cc'}\Sigma$ to ${}^{k-th}\Sigma$ via ${}^{k-th'}\Sigma$. Under the assumption that each robot grasps the object firmly and no relative motion between the grasping point and the object occurs, we have

$$\Delta\theta = \Delta\theta_k \quad (3)$$

From eq.(2), eq.(3),and Figure 1, we have

$$\begin{aligned} \Delta x_k &= \Delta x - (Rot(\Delta\theta) - E)^k r_{cc} \\ &\cong \Delta x - \Delta\theta\, {}^kR^T \end{aligned} \quad (4)$$

where, we assumed that the rotational deviation $\Delta\theta$ is small. ${}^kR, {}^kR'$ are matrices defined by the element of the position vector ${}^kr_{cc} = (r_x, r_y)^T$ as follows;

$${}^kR = [\ -r_y \quad r_x\ ], \quad {}^kR' = [\ r_y \quad -r_x\ ]^T \quad (5)$$

We also have the following relations for force and moment;

$${}_kf^{ext} = f_k^{ext}, \quad {}_kn^{ext} = -{}^kr_{cc} \times f_k^{ext} + n_k^{ext} \quad (6)$$

where f_k^{ext} and n_k^{ext} are equivalent force and moment vectors at the origin of ${}^{k-th}\Sigma$, or the grasping point, corresponding to ${}_kf^{ext}$, ${}_kn^{ext}$.

Substituting eq.(3) eq.(4) , and eq.(6) into eq.(1) , we have the impedance dynamics of the k-th mobile robot around its grasping point as follows;

$$\begin{bmatrix} f_k^{ext} \\ n_k^{ext} \end{bmatrix} = \begin{bmatrix} {}_kD & -{}_kD^kR' \\ {}^kR_kD & {}_kD_\theta - {}^kR_kD^kR' \end{bmatrix}\begin{bmatrix} \Delta\dot{x}_k \\ \Delta\dot{\theta}_k \end{bmatrix} + \begin{bmatrix} {}_kK & -{}_kK^kR' \\ {}^kR_kK & {}_kK_\theta - {}^kR_kK^kR' \end{bmatrix}\begin{bmatrix} \Delta x_k \\ \Delta\theta_k \end{bmatrix} \quad (7)$$

Eq.(7) represents the impedance dynamics of each mobile robot at its grasping point when the compliance-based coordinated motion control algorithm is implemented. Translational motion and rotational motion are strongly coupled in eq.(7) through off-diagonal block matrices $-{}_kD^kR'$, ${}^kR_kD$, $-{}_kK^kR'$ and ${}^kR_kK$, which involve terms concerned with a vector cross product relating to the distance ${}^kr_{cc}$ between the coordinate systems ${}^{cc}\Sigma$ and ${}^{k-th}\Sigma$. When a large object is handled, these terms lead to the amplification of the sensor noise and the reduction of the force/moment resolution for the implementation of the control algorithm. A numerical example will be given in the section 5. Note that this problem is inevitable for any control algorithm which requires force/moment information at a representative point attached to the object.

To solve the above problem, suppose that each mobile robot has the following decoupled impedance at its grasping point.

$$\begin{bmatrix} f_k^{ext} \\ n_k^{ext} \end{bmatrix} = \begin{bmatrix} D_k & 0 \\ 0 & D_{\theta k} \end{bmatrix}\begin{bmatrix} \Delta\dot{x}_k \\ \Delta\dot{\theta}_k \end{bmatrix} + \begin{bmatrix} K_k & 0 \\ 0 & K_{\theta k} \end{bmatrix}\begin{bmatrix} \Delta x_k \\ \Delta\theta_k \end{bmatrix} \quad (8)$$

Substituting eq.(3) , eq.(4) and eq.(6) into eq.(8) , we can derive the apparent impedance of the object around its representative point as follows;

$$\begin{bmatrix} \sum D_k & \sum D_k{}^kR' \\ \sum -{}^kRD_k & \sum(D_{\theta k} - {}^kRD_k{}^kR') \end{bmatrix}\begin{bmatrix} \Delta\dot{x} \\ \Delta\dot{\theta} \end{bmatrix} + \begin{bmatrix} \sum K_k & \sum K_k{}^kR' \\ \sum -{}^kRK_k & \sum(K_{\theta k} - {}^iRK_k{}^kR') \end{bmatrix}\begin{bmatrix} \Delta x \\ \Delta\theta \end{bmatrix} = \begin{bmatrix} f^{ext} \\ n^{ext} \end{bmatrix} \quad (9)$$

where, f^{ext} and n^{ext} are external force and moment applied to the object and born by all of the mobile robots;

$$f^{ext} = \sum_{k=1}^{n} {}_k f^{ext} = \sum_{k=1}^{n} f_k^{ext} \quad (10)$$

$$n^{ext} = \sum_{k=1}^{n} {}_k n^{ext} = \sum_{k=1}^{n} (-{}^k r_{cc} \times f_k^{ext} + n_k^{ext}) \quad (11)$$

As shown by eq.(9), the behavior of the object is very complex. We could not use the decoupled impedance expressed by eq.(8) as it is to specify the apparent impedance of the handled object, although the decoupled impedance, eq.(8), is not affected by the distance between the grasping point and the representative point. In the following, we propose a control algorithm for multiple mobile robots handling a large object in coordination. To lessen the effect of the force/moment transformation problems, we will use geometrical constraints as well as the decoupled impedance.

4 Algorithm with geometrical constraints

In this section, we propose a control algorithm for the handling of an object by multiple mobile robots in coordination. The algorithm utilizes geometrical constraints as well as the decoupled impedance at grasping points so that the apparent impedance of the handling object is specified.

Consider to specify a decoupled impedance of the handling object at the representative point of the object using decoupled impedance expressed by eq.(8). As mentioned in the previous section, in general, we could not specify the apparent impedance of the object as long as each mobile robot has a decoupled impedance at its grasping point. In the following part of this section, we will show that the apparent impedance will be specified for a special case satisfying certain geometrical constraints. Consider the case where D_k and K_k are expressed as follows;

$$D_k = d_k E, \qquad K_k = k_k E \quad (12)$$

where $d_k \in R$, $k_k \in R$ are positive real numbers and E is the 2×2 identity matrix. Assume that the following conditions on ${}^k r_{cc}$, d_k and k_k are satisfied;

$$\sum_{k=1}^{n} d_k {}^k r_{cc} = 0, \qquad \sum_{k=1}^{n} k_k {}^k r_{cc} = 0 \quad (13)$$

Then, the resultant impedance of the object expressed by eq.(9), is rewritten as follows;

$$\begin{bmatrix} \sum D_k & 0 \\ 0 & \sum(D_{\theta k} - {}^k R D_k {}^k R') \end{bmatrix} \begin{bmatrix} \Delta\dot{x} \\ \Delta\dot{\theta} \end{bmatrix} + \begin{bmatrix} \sum K_k & 0 \\ 0 & \sum(K_{\theta k} - {}^k R K_k {}^k R) \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta\theta \end{bmatrix} = \begin{bmatrix} f^{ext} \\ n^{ext} \end{bmatrix} \quad (14)$$

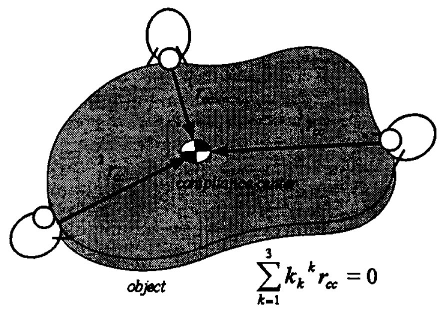


Figure 2: Handling using three mobile robots

To specify apparent impedance of the rotation, we modify eq.(8) as follows;

$$\begin{bmatrix} f_k^{ext} \\ n_k^{ext} \end{bmatrix} = \begin{bmatrix} D_k & 0 \\ 0 & D_{\theta k} + {}^k R D_k {}^k R' \end{bmatrix} \begin{bmatrix} \Delta\dot{x}_k \\ \Delta\dot{\theta}_k \end{bmatrix} + \begin{bmatrix} K_k & 0 \\ 0 & K_{\theta k} + {}^k R K_k {}^k R' \end{bmatrix} \begin{bmatrix} \Delta x_k \\ \Delta\theta_k \end{bmatrix} \quad (15)$$

where $D_{\theta k} + {}^k R D_k {}^k R'$, $K_{\theta k} + {}^k R K_k {}^k R'$ are a positive real numbers to control the robot in stable manner. The resultant apparent impedance of the object is expressed by

$$\begin{bmatrix} \sum D_k & 0 \\ 0 & \sum D_{\theta k} \end{bmatrix} \begin{bmatrix} \Delta\dot{x} \\ \Delta\dot{\theta} \end{bmatrix} + \begin{bmatrix} \sum K_k & 0 \\ 0 & \sum K_{\theta k} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta\theta \end{bmatrix} = \begin{bmatrix} f^{ext} \\ n^{ext} \end{bmatrix} \quad (16)$$

Since eq.(15) does not have off-diagonal blocks ,the translational motion caused by the external force f_k^{ext} and the rotational motion caused by the external moment n_k^{ext} is decoupled completely. The elimination of direct coupling largely reduces the vibration caused by the force/moment transformation. The geometrical constraints expressed by eq.(13) says that the representative point should be located at the centroid of the system which consists of n mobile robots. The centroid could be specified by selecting the impedance parameters as shown by eq.(13). To satisfy eq.(13), the following relation should be satisfied.

$$\alpha d_k = \beta k_k \quad (k = 1, 2 \cdots, n) \quad (17)$$

where α and β are constant real numbers. Figure 2 illustrates the relation among the grasping points and the representative point.

5 Effect of noise included in force/moment

In this section, we calculate the effect of sensor noise on the mobile robot velocity to illustrate the validity of the proposed control algorithm. We evaluate the velocity $[\Delta\dot{x}_k \ \Delta\dot{\theta}_k]^T$ of the grasping point of the k-th mobile robot for a given sensor noise expressed by

$$\left| \begin{matrix} f_k^{ext} \\ n_k^{ext} \end{matrix} \right| \le 1 \quad (18)$$

Let us express the relation between the sensor noise and the grasping point velocity by

$$F = Dv \tag{19}$$

where $F = [f_k^{ext}\ n_k^{ext}]^T$, $v = [\Delta\dot{x}_k\ \Delta\dot{\theta}_k]^T$ and D is a damping matrix. From eq.(18) and eq.(19) , we have

$$|F|^2 = F^T F = v^T D^T D v \leq 1 \tag{20}$$

Let λ_i and e_i $(i = 1, 2, 3)$ be the eigenvalue and the corresponding eigne vector of the matrix $D^T D$. As is well known, eq.(20) represents an ellipsoid whose principal axes are expressed by the eigne vectors e_i with the magnitude of $1/\sqrt{\lambda_i}$ $(i = 1, 2, 3)$.

Using this ellipsoid, we will show how much the effect of sensor noise will be decreased for the experimental system as shown in Figure 6(a). In case of the proposed control algorithm, the relation between the sensor noise F and the velocity v is expressed by eq.(15). In case of the conventional algorithm, the relation is expressed by eq.(7). The ellipsoids for both cases are shown in Figure 3. This figure shows that the effect of sensor noise included in the force/moment from a force sensor is decreased by the proposed algorithm.

6 Decentralized motion control algorithm in coordination

6.1 Design of controller for each robot

In this section, we extend the proposed algorithm explained in the previous section to a decentralized control algorithm of mulitiple mobile robots handling a single object in coordination. We assume that each robot is controlled by its own controller in a decentralized way. The desired trajectory of the object is given to the leader, and the follower estimates the desired motion of the object commanded to the leader to transport the object in coordination with the leader.

We assume that each robot has the dynamics as shown in eq.(15), where $k = l, i$. The subscripts l and i indicate that the leader robot and the i-th follower robot respectively. Let $x_{ld}, x_{ie} \in R^2$, $\theta_{ld}, \theta_{ie} \in R$ be the desired trajectories of the leader and the i-th follower respectively. $x_{dl}, x_{ei} \in R^2$, $\theta_{dl}, \theta_{ei} \in R$ indicate the trajectories of the representative point attached to the object which are calculated by transfoming the coordination of the desined trajectories of the leader and the i-th follower respectively. $x \in R^2, \theta \in R$ is the real trajectory of the object. Under the assumption that each robot holds the object firmly and no relative motion between the object and each robot occurs, the relation between the deviation of each robot and the deviation of representative point is expressed as follows;

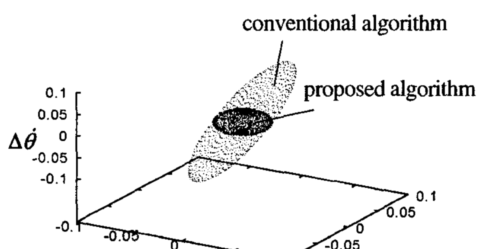


Figure 3: Effect of noise for mobile robot

$$\Delta x_l = \Delta x_{ol} - \Delta\theta_{ol}\ {}^l R^T, \quad \Delta\theta_l = \Delta\theta_{ol} \tag{21}$$

$$\Delta x_i = \Delta x_{oi} - \Delta\theta_{oi}\ {}^i R^T, \quad \Delta\theta_i = \Delta\theta_{oi} \tag{22}$$

where Δx_{ol}, $\Delta\theta_{ol}$, Δx_{oi}, $\Delta\theta_{oi}$ are deviation relating to the position and the orientation of representative point of the object corresponding to the motion of each robot, and are expressed as follows;

$$\Delta x_{ol} = x - x_{dl} \tag{23}$$

$$\Delta\theta_{ol} = \theta - \theta_{dl} \tag{24}$$

$$\Delta x_{oi} = x - x_{ei} \tag{25}$$

$$\Delta\theta_{oi} = \theta - \theta_{ei} \tag{26}$$

${}^l R^T, {}^i R^T$ are defined by eq.(5) and indicate matrices expressed by the element of the position vectors with respect to the leader and the i-th follower respectively.

For the simplicity of discussions, we rewrite the parameters of the leader and the follower simply as follows;

$$\begin{bmatrix} D_k & 0 \\ 0 & D_{\theta k} + {}^k R D_k {}^k R' \end{bmatrix} = D_k' \tag{27}$$

$$\begin{bmatrix} K_k & 0 \\ 0 & K_{\theta k} + {}^k R K_k {}^k R \end{bmatrix} = K_k' \tag{28}$$

$$\begin{bmatrix} \Delta x_k \\ \Delta\theta_k \end{bmatrix} = \Delta X_k \tag{29}$$

$$\begin{bmatrix} f_k^{ext} \\ n_k^{ext} \end{bmatrix} = F_k^{ext} \tag{30}$$

where $k = l, i$, $(x_{ld}, \theta_{ld})^T = X_{ld}$, $(x_{ie}, \theta_{ie})^T = X_{ie}$, $(x_{dl}, \theta_{dl})^T = X_{dl}$, $(x_{ei}, \theta_{ei})^T = X_{ei}$, and $(x, \theta)^T = X$ Then, the resultant impedance of the leader robot and i-th follower robot expressed by eq.(15) is rewritten as follows.

$$D_l' \Delta\dot{X}_l + K_l' \Delta X_l = F_l^{ext} \tag{31}$$

$$D_i' \Delta\dot{X}_i + K_i' \Delta X_i = F_i^{ext} \tag{32}$$

6.2 Handling of a single object by two robots in coordination

For the simplicity of explanation, we consider the case of two autonomous omnidirectional mobile robots, that is $i = 1$ in eq.(32). Under the assumption that the external force applied to the object is negligible, consider the geometric constraints expressed by eq.(13), and the leader and the followers are controlled using the same parameters, that is,

$$D_l' = D_i' = D \tag{33}$$

$$K_l' = K_i' = K \tag{34}$$

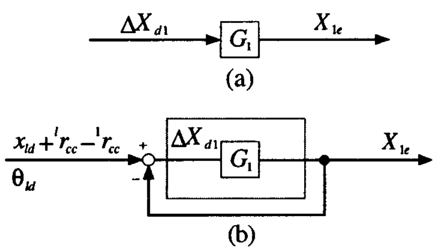


Figure 4: Estimator

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

$$F_l^{ext} \quad + \quad F_1^{ext} = 0 \tag{35}$$

From eq.(31), eq.(32), eq.(33), eq.(34) and eq.(35), we obtain the following relation;.

$$D(\Delta\dot{X}_l + \Delta\dot{X}_1) + K(\Delta X_l + \Delta X_1) = 0 \tag{36}$$

As time tends to infinity, we obtain the following relationship from eq.(36) and the positive definiteness of the damping matrix and the stiffness matrix, even if the initial values of $\Delta X_l + \Delta X_1$ is not zero.

$$\Delta X_l \quad + \quad \Delta X_1 = 0 \tag{37}$$

Subtracting eq.(21) from eq.(22) and eliminating X, we have following relation;

$$\Delta X_1 - \Delta X_l \quad = \quad X_{dl} - X_{e1} \tag{38}$$

Let ΔX_{d1} be the difference between the trajectories of the object X_{dl} with respect to the desired trajectories of the leader X_{ld} and the trajectory of the object X_{e1} with respect to estimated trajectories of the follower X_{1e}. From eq.(37) and eq.(38) ΔX_{d1} is expressed as

$$\Delta X_{d1} = X_{dl} - X_{e1} = 2\Delta X_1 \tag{39}$$

It should be noted that the follower can calculate ΔX_{d1} using observable variable ΔX_1.

Let us consider how X_{ld} is estimated using ΔX_{d1}. Let G_1 be the transfer function, which estimates X_{ld}, as X_{1e}, based on ΔX_{d1} as shown in Figure 4(a). From eq.(39), Figure 4(a) can be rewritten as a feedback system as shown in Figure 4(b). To eliminate the steady-state position and velocity estimation errors, the transfer function G_1 is designed as follows;

$$G_1 = \frac{a_1 s + b_1}{s^2} \tag{40}$$

6.3 Handling by $n+1$ mobile robots in coordination

6.3.1 Forces and trajectory deviations

We extend the result in the previous section to a general case. First, we consider the relationship among trajectory deviations. We assumed that the external force applied to the object is negligible and consider the geometric constraints expressed by eq.(13). We have the following relations with respect to the forces applied to each robot;

$$F_l^{ext} \quad + \quad \sum_{j=1}^{n} F_j^{ext} = 0 \tag{41}$$

As time tends to infinity, we obtain the following relationship from eq.(31), eq.(32), eq.(41) and the positive definite of the damping matrix and the stiffness matrix, even if the initial values of $K_l^{'}\Delta X_l + \sum_{j=1}^{n} K_j^{'}\Delta X_j$ is not zero.

$$K_l^{'}\Delta X_l + \sum_{j=1}^{n} K_j^{'}\Delta X_j = 0 \tag{42}$$

6.3.2 Dynamics of Virtual Leader

It is impossible for the i-th follower to estimate the desired trajectory of the leader because the trajectory deviation of the i-th follower, which was used for the estimation of the desired trajectory of the leader in previous case, is affected by motions of all of the robots. Therefore, for the i-th follower, the robots is classified into two groups as shown in Figure 5(a); one is the i-th follower itself and the other is the rest of the robots including the leader. In this paper, we referred to the rest of the robots as the i-th virtual leader. The i-th virtual leader consists of the leader, and j-th followers ($j = 1, \ldots, i-1, i+1, \ldots, n$). For the i-th follower, the i-th virtual leader behaves as if it is a real leader as shown in Figure 5(b). Using the concept of the virtual leader, the i-th follower estimate the desired trajectory of the i-th virtual leader based on the estimation algorithm in the previous section.

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

$$\begin{aligned} D_l^{'}\Delta\dot{X}_l \quad &+ \sum_{j=1(j\neq i)}^{n} D_j^{'}\Delta\dot{X}_j \\ &+ \quad K_l^{'}\Delta X_l + \sum_{j=1(j\neq i)}^{n} K_j^{'}\Delta X_j \\ &= \quad F_l^{ext} + \sum_{j=1(j\neq i)}^{n} F_j^{ext} \end{aligned} \tag{43}$$

where

$$\sum_{j=1(j\neq i)}^{n} c_j = \sum_{j=1}^{i-1} c_j + \sum_{j=i+1}^{n} c_j \tag{44}$$

The trajectory deviation of the i-th virtual leader ΔX_{li}, $\Delta\dot{X}_{li}$ are expressed as follows;

$$\Delta\dot{X}_{li} = \frac{1}{D_i^{'}}\{D_l^{'}\Delta\dot{X}_l + \sum_{j=1(j\neq i)}^{n} (D_j^{'}\Delta\dot{X}_j)\} \tag{45}$$

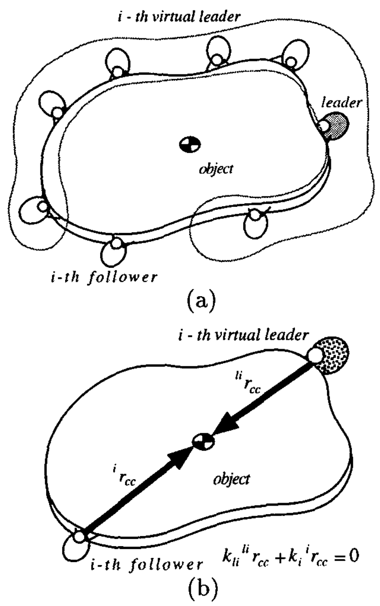


Figure 5: Virtual Leader

$$\Delta X_{li} = \frac{1}{K_i^{'}}\{(K_l^{'}\Delta X_l + \sum_{j=1(j\neq i)}^{n}(K_j^{'}\Delta X_j)\} \quad (46)$$

As time tends to infinity, from eq.(42), we obtain the following relationship, regardless of the desired trajectory given to the leader X_{ld}.

$$\Delta X_{li} + \Delta X_i = 0 \quad (47)$$

The force and moment applied to the i-th virtual leader F_{li}^{ext} is expressed as follows;

$$F_{li}^{ext} \;=\; F_l^{ext} + \sum_{j=1(j\neq i)}^{n} F_j \quad (48)$$

From eq.(41), we also have

$$F_{li}^{ext} \;+\; F_i^{ext} = 0 \quad (49)$$

From eq.(45), eq.(46) and eq.(48), (43) is rewritten as

$$D_i^{'}\Delta\dot{X}_{li} + K_i^{'}\Delta X_{li} = F_{li}^{ext} \quad (50)$$

It should be noted that eq.(50) expresses the behavior of the i-th virtual leader.

Let X_{di} be the desired trajectory of the representative point attached to the object which are calculated by transforming the coordination of the desired trajectories of the i-th virtual leader. Then, $\Delta X_{li} = (\Delta x_{li}, \Delta\theta_{li})^T$ are expressed as

$$\Delta x_{li} = \Delta x_{oli} - \Delta\theta_{oli}\ {}^{li}R^T \qquad \Delta\theta_{li} = \Delta\theta_{oli} \quad (51)$$

where Δx_{oli}, $\Delta\theta_{oli}$ are deviation relating to the position and the orientation of representative point of the object corresponding to the motion of the i-th virtual leader,and are expressed as follows;

$$\Delta x_{oli} = x - x_{di} \qquad \Delta\theta_{oli} = \theta - \theta_{di} \quad (52)$$

6.3.3 Estimation

Using the concept of the virtual leader, the i-th follower can estimate the desired trajectory of the i-th virtual leader based on the estimation algorithm which we discussed in the previous section because eq.(50) and eq.(51) have the form as (31) and (21).

We define ΔX_{di} as the estimation error of the i-th virtual leader estimated by the follower. ΔX_{di} is expressed as

$$\Delta X_{di} = X_{di} - X_{ei} \;=\; 2\Delta X_i \quad (53)$$

It should be noted that ΔX_{di} is calculated by each follower based on the observable state of each follower ΔX_i. Using this $\Delta X_{di}$and the transfer function matrix G_i which we design in previous section, the i-th follower can estimate the desired trajectory of the i-th virtual leader. We design the transfer function matrix G_i similar to the case of previous section. The transfer function matrix G_i is expressed as follows;

$$G_i = \frac{a_i s + b_i}{s^2} I_3 \quad (54)$$

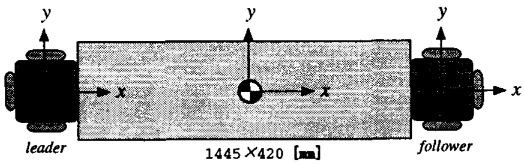
The stability of the resultant system is shown similar to [5].

7 Experiments

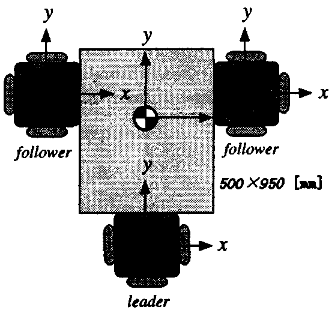
First, we did two types of experiments to compare the conventional algorithm proposed in [5] and the proposed algorithm explained in the previous section to handle a large object in coordination. We did these experiments using two autonomous omnidirectional mobile robots as shown in Figure 6(a). Second, we did the experiment using three autonomous omnidirectional mobile robots with the proposed algorithm explained in the previous section as shown in Figure 6(b). The control algorithm was implemented in the autonomous omnidirectional mobile robots, ZEN, developed by RIKEN[7]. Each mobile robot has three degrees of freedom of motion and equipped with the Body Force Sensor[8]. The control algorithm is implemented using VxWorks. The sampling rate is 1024Hz.

7.1 Experimental results based on conventional algorithm

In this experiment with the conventional algorithm, the leader was given a desired trajectory along y-axis which was calculated by a fifth order function. The orientations of all of the robots were kept constant during the transportation of the object. The results are shown in Figure 7. You can see that the moment detected by each robot include vibratory part. The vibratory part caused estimation error and the follower could not follow the leader accurately.

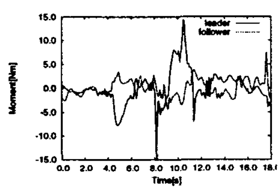


(a) Experiment by two mobile robots

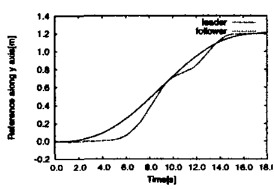


(b) Experiment by three mobile robots

Figure 6: Experimental system



(a) Moment [Nm]

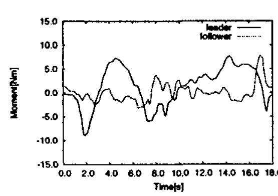


(d) Reference(y) [m]

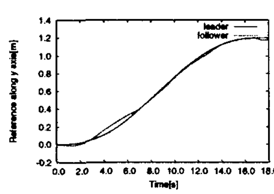
Figure 7: Experiment using conventional algorithm

7.2 Experimental results using proposed control algorithm

This experiment was done using the same desired trajectory of the object and the same impedance parameters as the previous experiment. The results are shown in Figure 8. You can see that the moment of each robot include little vibration. The less estimation error was observable than the previous experiment and the transportation of the large object was successfully achieved.

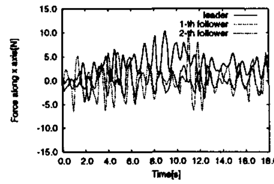


(a) Moment [Nm]

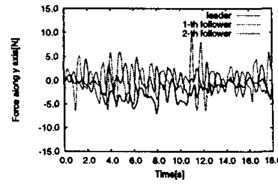


(d) Reference(y) [m]

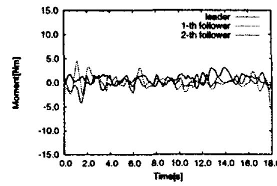
Figure 8: Experiment using proposed algorithm



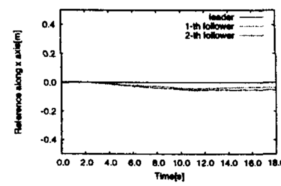
(a) Force(x) [N]



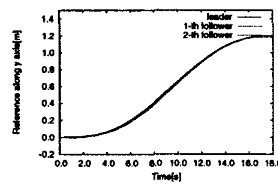
(d) Force(y) [N]



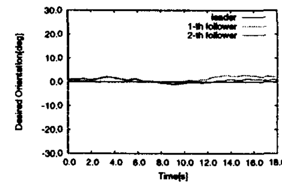
(b) Moment [Nm]



(e) Reference(x) [m]



(c) Reference(y) [m]



(f) Desired Orientation [deg]

Figure 9: Experimental results by three mobile robots

7.3 Experimental results using 3 mobile robot

In the experiment using three autonomous omnidirectional mobile robots, the leader was given the desired trajectory along y-axis which was calculated by a fifth order function and each follower estimated the desired trajectory of its own virtual leader using the algorithm proposed in the previous section. The results are shown in Figure 9. The three robots transported the large object in coordination successfully.

Figure 11 shows an example of the experiments. In this figure, the desired trajectory of the object was commanded to the leader as shown in Figure 10

8 Conclusions

In this paper, we pointed out a problem relating to the force/moment transformation for the coordinated motion control problem of multiple mo-

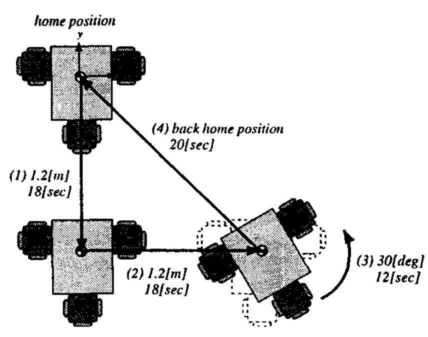


Figure 10: Desired trajectory in Figure11

bile robots handling a large object in coordination. The control algorithm with geometrical constraints expressed by eq.(15) was proposed to overcome this problem. This algorithm is efficient to lessen the effect of noises caused by force/moment transformation, since most of the impedance parameters do not include the vector cross product terms with respect to the distance between the grasping point and the representative point.With the algorithm, we could specify the apparent impedance of the handling object completely.

We extend this algorithm to the decentralized control algorithm of multiple robots handling a single object in coordination. The proposed decentralized control algorithm is experimentally applied to the omnidirectional mobile robots, ZEN. Experimental results illustrate the validity of the proposed control algorithm.

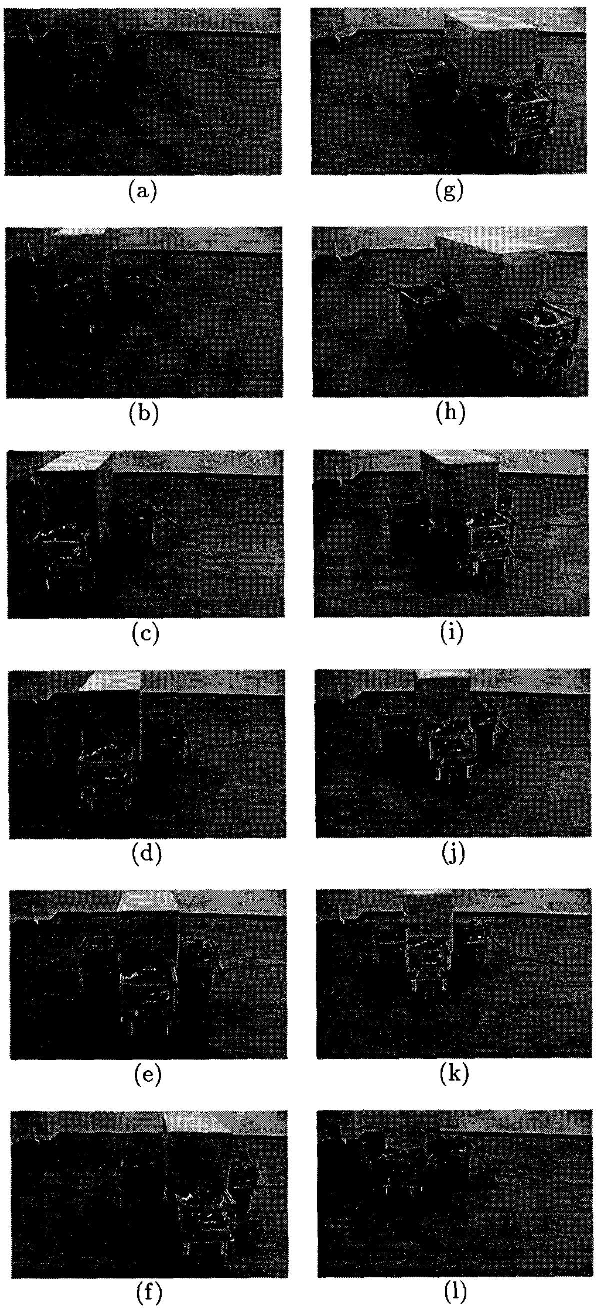


Figure 11: Example of experiment

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