Planning Method for Cooperative Manipulation by Multiple Mobile Robots using Tools with Motion Errors

Atsushi YAMASHITA, Kou KAWANO, Jun OTA, Tamio ARAI,
Masaki FUKUCHI, Jun SASAKI, and Yasumichi AIYAMA

Department of Precision Machinery Engineering, The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, JAPAN
Tel: +81-3-5841-6486 Fax: +81-3-5841-8556
E-mail address: *yamasita@prince.pe.u-tokyo.ac.jp*

Abstract

In this paper, we propose a method of an object manipulation by multiple mobile robots using sticks as tools. In the conventional cooperative work by multiple mobile robots, manipulation technique based on force-control has been proposed. However, mobile robots are moving by position-control, and motion errors can easily arise. Then, we build the manipulation technique, which is suitable for mobile robots by position-control. We propose the manipulation method without using sensor information, and consider the motion errors of mobile robots and the indefinite element of environment from the planning stage. We compute the conditions in which the object gets unstable during manipulation, and generate the motion of each mobile robot with these analyses. We verify the effectiveness of our proposed motion planning method through simulations and experiments.

Keywords: *Multiple Mobile Robot System, Planning, Cooperative Manipulation, Tool, Motion Errors*

1. Introduction

It is expected that mobile robots undertake various tasks in manufacturing plants, warehouses, construction sites, and so on. In order to improve flexibility and fault tolerance of tasks, the method that multiple mobile robots accomplish tasks cooperatively are proposed[1,2]. In the future, mobile robots should work in the 3-dimensional real environment. Therefore, not only the path planning on the 2-dimensional plane but also the manipulation planning of the object in the 3-dimensional space (for example, changing the pose of the object) is important.

One of the biggest problems that we have to take into consideration when mobile robots work is the effect of the position errors of robots. Mobile robots, which are free from environment, have a great advantage. That is, they can move freely in the space. However, the motion errors of robots are larger than those of fixed manipulators. Hence the risk of failing tasks under the effect of the error is very large.

There are many studies about cooperative transportation[3-6] and manipulation of objects[7-9] with multiple mobile robot system. In these studies, the force sensor's information and image information from the camera are fed back to correct the motion errors. Rus, et al.[3] built the object pushing and transporting method using the sensor information. The method is based on the knowledge obtained conventionally in the research field of the pushing manipulation[10-13]. Kube et al.[4] prevented the failure of task which is caused by the motion errors of robots, by adopting behavior-based robots. However, there is no guarantee that behavior-based robots can perform the objective task. Kosuge et al.[5] and Miyata et al.[6] aimed at transporting an object by lifting and adopted the feedback control method using the information of robots' force sensors. Khatib et al.[7] and Desai et al.[8] controlled inner force that is applied to an object and adopted the stable handling strategy to compensate the motion errors of robots. Sawasaki et al.[9] realized rolling pose change of an object with two mobile manipulators, by using sensor feedback method from the information of the force sensors attached with robots' hands.

As mentioned above, in the previous researches, the motion errors of mobile robots are avoided by on-line method. And excessive inner force that is applied to an object is avoided by force control-approach. In other words, feedback control approach has been adopted to manipulate an object by multiple mobile robot system. However, it is difficult for mobile robots to measure force correctly and to manipulate an object by force-control method like fixed manipulators during they move.

Then, in this research, we propose the robust manipulation planning method for the motion errors by taking into consideration of the motion errors in a motion planning stage. We aim at constructing the planning method of manipulation that is suitable for the mobile robots under position-control. To accomplish tasks easily by position-controlled mobile robots with the motion errors, our proposed method has two major characteristics; (1) introduction of tools to multiple mobile robot system[14], and (2) planning method for manipulating an object, which is suitable for mobile robots.

The composition of this paper is detailed below. In chapter 2, the manipulation method by using sticks as tools is explained. In chapter 3, we perform analysis for stable manipulation of an object, and in chapter 4, the planning method of manipulating an object is proposed. We verify the method by simulations. In chapter 5, we also verify our method with experiments and chapter 6 describes conclusions.

2. Approach to Cooperative Manipulation

2.1 Concept of Using Tools

When multiple mobile robots treat large objects, it is difficult to handle and manipulate the object like fixed manipulators[15]. Therefore, we propose that robots manipulate an object by pushing using sticks as tools in multiple mobile robots system (Fig. 1). It becomes easier to put the force of each robot together to an object by using sticks as tools. And when the manipulating tasks are carried out, the stability of operation is improved because the contact area to the object becomes larger [14].

There occur position errors when position controlled mobile robots move. Therefore, there exists a risk that multiple mobile robots apply excessive inner force to an object when they touch the object at the same time. Then, in this research, more than two tools cannot contact with the object at any time to avoid excessive inner force when the robots move.

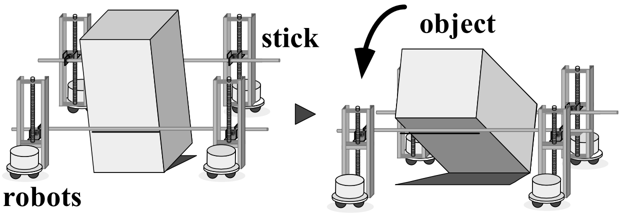


Fig. 1 Manipulation by Using Sticks as Tools

Since it is difficult for mobile robots to lift up a large or heavy object, they manipulate the object without lifting up operation. Therefore the object always contacts with the environment (a floor). The robots can move the sticks up and down. And pushing and tumbling operations are adopted here.

2.2 Problem Settlement

In this research, we propose the method that multiple mobile robots change the pose of an object by using sticks. The robots tumble the object to change its face that contacts with the floor from one face to the next one. By repeating this tumbling operation, it is possible to change the pose of the object that arbitrary face of the object contacts with the floor. And the robots tumble the object while one edge (this edge is the center of rotation) always contacts with the floor. Therefore, 2-dimentional model can express this situation. Example manipulations of objects are depicting in Fig. 2.

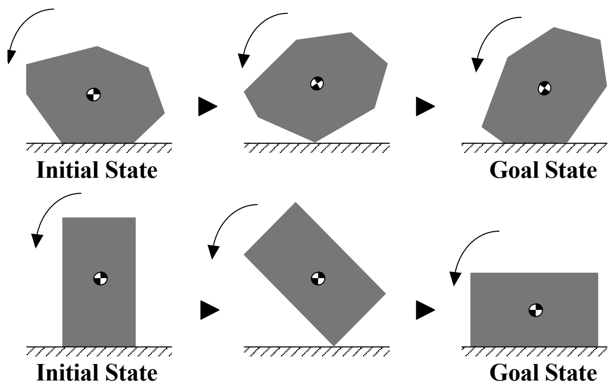


Fig. 2 Pose Change Manipulation

We make the following assumptions for our analysis:

・ All motions are quasi-static.
・ All objects are convex polyhedrons.
・ The geometry of an object and the location of its center of mass are known.
・ Coefficient of friction between the object and the floor and between the object and the stick are known.
・ All frictional interactions of an object are described by Coulomb's law of friction.

2.3 Outline of Planning Method

Here we describe the outline of our planning method for an object manipulation.

First, we compute the position of the stick where an object is stable. We make use of the stable domain graph that expresses the range where the object is stable. In this analysis, the motion errors of mobile robots are considered. Hence the robustness for the motion errors can be realized. The stable domain graph does not hold an information about force, but holds position of the sticks. Therefore, this graph is suitable for mobile robots, which are working under position control. It is described in chapter 3.

Next, we extract characteristic states from the stable domain graph and extract states are expressed as nodes. By using these nodes, the operation graph is generated. We can gain the manipulation method by solving the shortest path problem in the operation graph. The operating way of the object is generated in sequence. After that, we compute the orbit of the sticks and the motion of each robot. The orbit can be easily realized by the robots without complicated control of the sticks. Therefore, good planning method of manipulation that is suitable for multiple mobile robots system can be constructed.

3. Formulation of Manipulation

3.1 Problem Formulation

Under assumptions in section 2.2 and this situation mentioned as in Fig. 3, these constraints can be described.

$$\mathbf{F_s} + \mathbf{F_e} + \mathbf{G} = \mathbf{0} \tag{1}$$

$$\mathbf{p_s} \times \mathbf{F_s} + \mathbf{p_c} \times \mathbf{G} = \mathbf{0} \tag{2}$$

where

$\mathbf{F_s}$: force at stick point (S)
$\mathbf{F_e}$: force at contact point (O)
$\mathbf{G} = (0, -mg)$: force at center of the mass (G)
$\mathbf{P_s} = (x, y)$: position of the stick
$\mathbf{P_g} = (x_g, y_g)$: center of the mass of the object

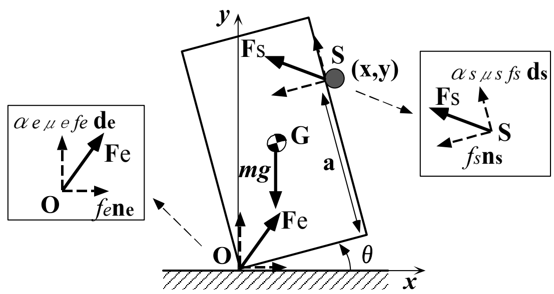


Fig. 3 2D Object Model

Let f_s be the normal contact force at S, and let f_e be the normal contact force at O.

$$\mathbf{F_e} = f_e \mathbf{n_e} + \alpha_e \mu_e f_e \mathbf{d_e} \tag{3}$$

$$\mathbf{F_s} = f_s \mathbf{n_s} + \alpha_s \mu_s f_s \mathbf{d_s} \tag{4}$$

where

$\mathbf{n_s} = (u_n, v_n)$

$\mathbf{d_s} = (u_d, v_d)$

From Equations (1-4), we obtain

$$f_s u_n + \alpha_s \mu_s f_s u_d + \alpha_e \mu_e f_e = 0 \tag{5}$$

$$f_s v_n + \alpha_s \mu_s f_s v_d + f_e - mg = 0 \tag{6}$$

$$\begin{aligned} &f_s (x v_n - y u_n) + \alpha_s \mu_s f_s (x v_d - y u_d) \\ &\quad - mg(x_g \cos\theta - y_g \sin\theta) = 0 \end{aligned} \tag{7}$$

$$f_e > 0 \quad \text{and} \quad f_s > 0 \tag{8}$$

$$|\alpha_e| < 1 \quad \text{and} \quad |\alpha_s| < 1 \tag{9}$$

$$f_s < F_{\max} \tag{10}$$

where

f_s : force at S

f_e : force at O

$F_{\max}$: maximum force of robot

m : mass of the object

μ_s : coefficient of friction at S

μ_e : coefficient of friction at O

θ : angle of the object

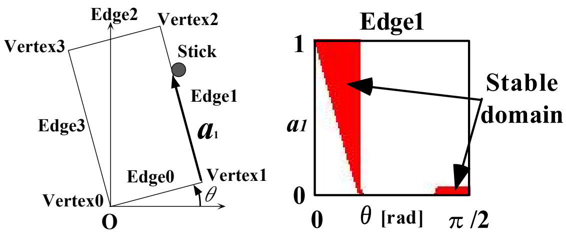
We can know whether the object is stable or not by solving Equation (5-7) under constraint of Inequalities (8-10). Inequality (8) means that the object does not detached from the stick and the floor. Inequality (9) means that the object does not slip and keep stable. Inequality (10) means that the robots do not apply the force to the object beyond their ability.

We can obtain the stable domain graph by solving these formulas about the position of a stick $\boldsymbol{a}_i$, and the angle of an object θ.

3.2 Stable Domain Graph

The stable domain graph indicates the position of the stick and the angle of the object when the object is stable. The axis of ordinate (y-axis) means the parameter $\boldsymbol{a}_i$ showing the contact position with the object, and axis of abscissas (x-axis) means the parameter θ showing the angle of the object.

The parameter $\boldsymbol{a}_i$ ($0 < \boldsymbol{a}_i < 1$) expresses the contact point of the stick at Edge i of the object. For example, when $\boldsymbol{a}_1=0$, the stick contacts the object at Vertex 1. And when $\boldsymbol{a}_1=0.5$, the stick contacts the object at the center of Edge 1.



(a)Parameter $\boldsymbol{a}_i$ and θ (b)Stable Domain Graph

Fig. 4 Stable Domain of Edge 1

The object is stable, if the parameter (θ, $\boldsymbol{a}_i$) is in stable domain. Therefore, if the object is operated in this domain, manipulation of the object will not fail.

Because the number of edge is four in the case of the rectangle, four stable domain graphs which shows stable domain of each edge are generated (Fig. 5).

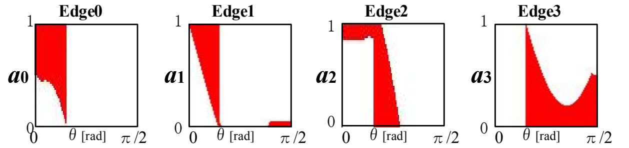
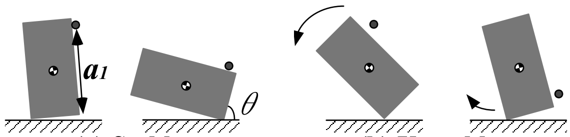


Fig. 5 Stable Domain Graph of Each Edge

For example, in Fig. 6(a), the object can stand still, if the position of the stick and the angle of the object in stable domain. In Fig. 6(b), the parameters are out of stable domain and the object cannot stand still.



(a) Stable (b) Unstable

Fig. 6 Stable and Unstable State

3.3 Effect of Motion Errors

The effect of motion errors the mobile robots and environmental indefiniteness are taken into consideration. As the error factor which influences a stable domain is; (i) the motion errors of mobile robots, and (ii) change of a coefficient of friction.

About the former problem, we search a domain where the stability of the object is maintained if the position error ($\pm\Delta x$, $\pm\Delta y$) exists on the position of the stick (Fig. 7).

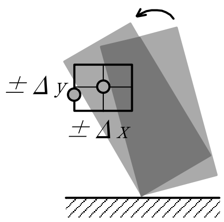


Fig. 7 Motion Error of Robot

About the latter problem, we search a domain where the stability of the object is maintained if a coefficient of friction $\mu_{s,e}$ changes within the range of $\pm\Delta\mu_{s,e}$.

The stable domain graph considering the motion errors is shown in Fig. 8. In Fig. 8, the domain reduced as compared with Fig. 5 is a domain in which work fails, when there are motion errors. We utilize the stable domain graph and construct the robust manipulation method for the motion errors.

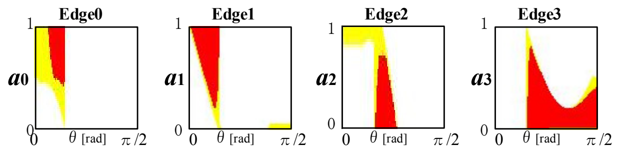


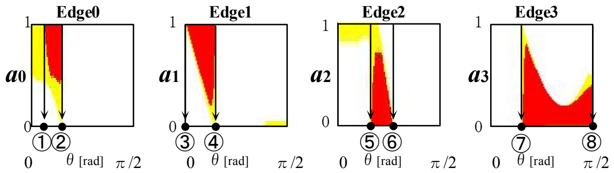
Fig. 8 Stable Domain Graph with Motion Errors

4. Motion Planning Method

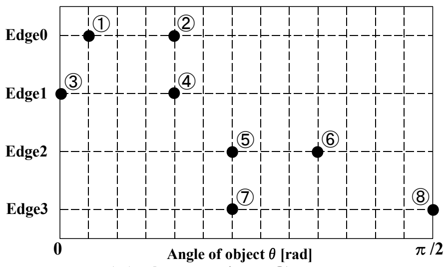
4.1 Operation Graph

We generate the operation graph and utilize it to plan the motions of the robots efficiently.

The procedure of generating the operation graph is as follows. First, we select characteristic points where the operation method may change from the stable domain graph. Concretely, we choose the points whose θ values are largest and smallest in stable domain (Fig. 9(a)). And these points are regarded as nodes in operation graph. Therefore, in operation graph, all nodes that have physical meanings are collected (Fig. 9(b)). Information that nodes hold in the operation graph is edge number and the angle of the object θ. In operation graph, information about $\boldsymbol{a}_{\mathrm{i}}$ is not considered to plan the motions of the sticks efficiently.



(a) Characteristic Value θ



(b) Operation Graph

Fig. 9 Generation of Operation Graph

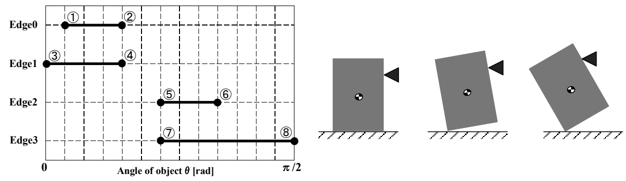
In the operation graph, by moving from one node to other node, the pose change of the object is planned. In the rectangle case shown in Fig. 3, the pose change is performed by moving from node ③(θ= 0 [rad]) to node ⑧($\theta=\pi/2$ [rad]).

In operation graph, the arc between two nodes indicates three types of operation method, (a) continuous operation, (b) hand-over operation, and (c) transfer operation.

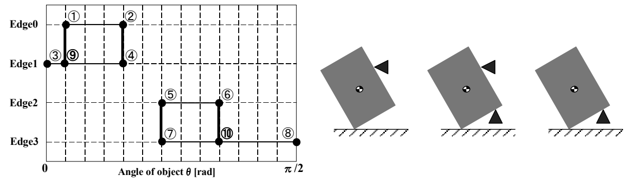
The arc that is a horizontal line between two nodes indicates the continuous operation (Fig. 10(a)). In this operation, it is possible to change the angle of the object without changing the edge that the stick contacts with. During the continuous operation, the contact point of the stick continuously changes. It means that $\boldsymbol{a}_i$ in the stable domain graph changes continuously.

The perpendicular arc indicates the hand-over operation (Fig. 10(b)). In this operation, it is possible to change the edge that the stick contacts with without changing the angle of the object. Node ⑨ and ⑩ are newly generated in the operation graph.

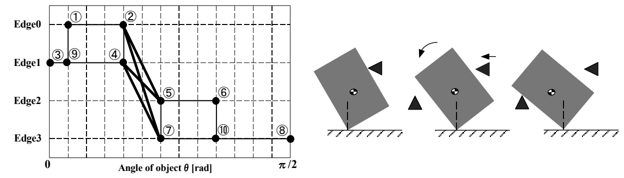
The oblique arc indicates the transfer operation (Fig. 10(c)). In this operation, it is possible to change both the angle of the object and the edge that the stick contacts with. This operation is performed when there is no stable domain between two nodes.



(a) Continuous Operation



(b) Hand-over Operation



(c) Transfer Operation

Fig. 10 Operation Graph and Operation

To express the difficulties of these operations, the distance of the arc, which means moving cost between two nodes, is introduced. Then, the problem of choosing the manipulation method among three operations comes back to the shortest path problem. Long distance from the start node to the goal one means that the pose changing operation of the object is difficult. Therefore, we choose the shortest path, because the pose-changing task can be performed easily. The distance (cost) of the each arc is determined as follows; cost (a) < cost (b) < cost (c).

The cost of continuous operation is lower, because it is the easiest way to manipulate the object. This operation can be accomplished with one stick and total time of operation is the shortest compared to other operations. And the cost of transfer operation is higher, because this operation is most difficult, because this operation needs two sticks and the object is not stable during this operation. When this operation is performed, greater effect of uncertain factor of the environment must be considered compared with other operations.

After the costs of arcs are determined, Dijkstra's algorithm is used to solve the shortest path-planning problem. From the result of search, the shortest path is gained; ③(initial state)→⑨→④→⑦→⑩→⑧(goal state). Path ③→⑨→④ means the continuous operation on Edge 1. Path ④→⑦ means the transfer operation between the stick on Edge 1 and Edge 3. Path ⑦→⑩→⑧ means the continuous operation on Edge 3.

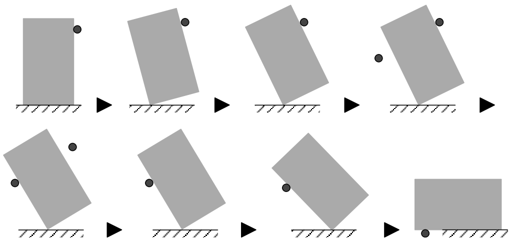


Fig. 11 Order of Operation

The operation order gained from above is shown in Fig. 11. It is not determined the position where the stick contacts with each edge ($\boldsymbol{a}_i$). The result obtained here is the order of the operation where the stick contacts.

The orbit of a stick is not determined at the present. In the next section, the orbit of the stick is determined by considering the characteristics of mobile robots.

4.2 Determination of Orbit of the Stick

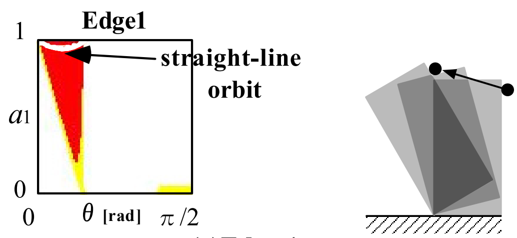
In this research, the orbit of the stick is determined after a procedure of object operation is determined. If it is the manipulation method for fixed manipulators, the orbit of the contact position where the force applied to the stick is always minimized may be good. For example, when the stick contacts with Edge 1, the continuous operation where $\boldsymbol{a}_1$ is near 0 leads to the situation where control force is minimum.

However, when optimizing the control force, the orbit of a stick becomes nearly circle shape. In this case the perpendicular and the horizontal speed of the stick need to be controlled in complicated way every time. This has the risk of failing tasks conversely, for it is inconvenient for mobile robots to make complicated operation.

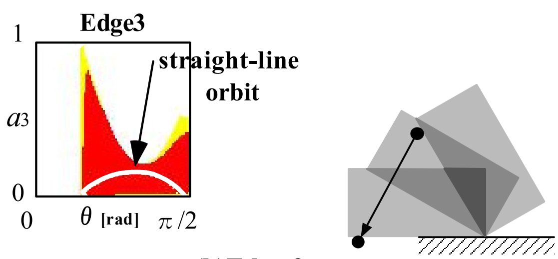
Then, the stick orbit forms that mobile robots can easily control. In this research, a straight-line orbit is adopted.

The stick positions when the continuous operation begins and ends are determined to minimize the force at these points, and the meantime is connected linearly.

In the rectangle operation dealt with here, it turns out that the locus of each stick respectively is shown in Fig. 12 and the orbit is in a stable domain.



(a)Edge 1



(b)Edge 3

Fig. 12 Orbit of the Stick (Straight-line Orbit)

When the orbit is out of the stable domain, the stick position of the beginning and the end are changed suitably. Then solution that the orbit is always in the stable domain is searched.

The manipulation method of the object shown in Fig. 13 is off-line-planned by the proposed method.

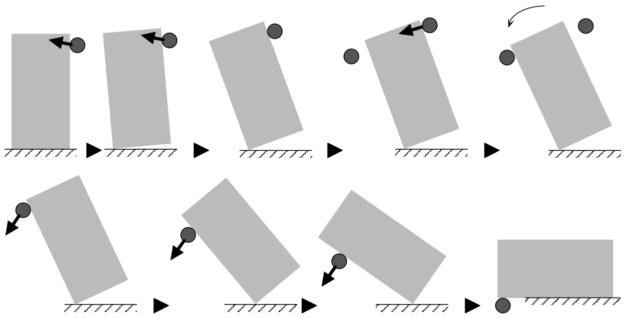


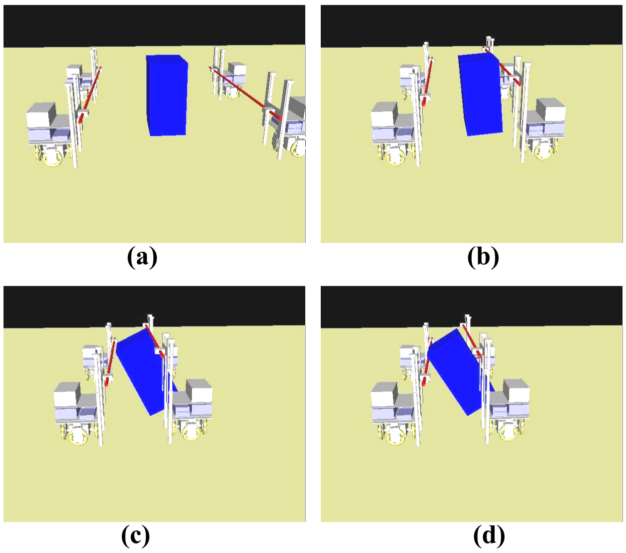
Fig. 13 Planned Manipulation Method

4.3 Simulation

We verified by the simulation about the object operation method proposed in this paper. Table 1 shows parameters for the simulation. In this simulation environment, we set up that the motion errors and uncertainty of the environment, such as change of a friction coefficient, might occur.

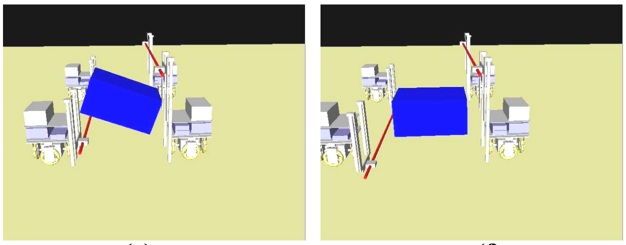
Table 1 Parameters for the Simulation

Size of the object	0.50[m]×1.00[m]
Weight of the object	4.0[kg]
Friction coefficient between The floor and the object The stick and the object	 0.20 0.20
Friction coefficient error	±10[%]
Motion errors of robots	(±0.04[m], ±0.01[m])
Number of robot	4



(a) **(b)**

(c) **(d)**



(e) (f)

Fig. 14 Simulation Results

Simulation results are shown in Fig. 14. There is an object at the center. And two mobile robots handle one stick. Fig. 14(a) shows initial state. In Fig. 14(b), the right robot contacts with the object and has started operation. In Fig. 14(c), the transfer operation is performed and in Fig. 14(d) it is finished. Then, the continuous operation is performed in Fig. 14(e) and the task finish successively in Fig. 14(f).

In this simulation, objective task has been realized without failure, such as the object slips or falls down under the motion errors of robots and environmental indefiniteness.

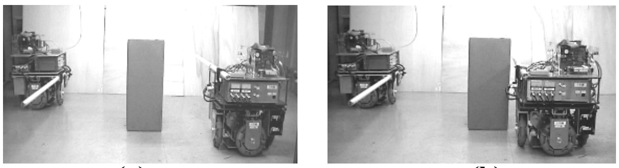
5. Experiments

We applied the proposed planning method of manipulating an object to real robot system. The mobile robot has the stick as a tool. They can move in all the directions. The external-world sensor is not carried in the mobile robot. And the motion velocity of robots is set slow enough to keep quasi-static motion. Table 2 shows parameters for experiment. Under these conditions the pose change experiment of the object was performed.

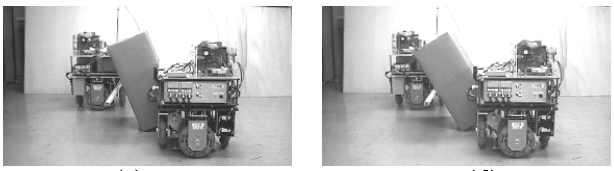
An Experimental result is shown in Fig. 15. Here, it can be checked that objective operation can be performed without using sensor information, and the validity of this method was shown.

Table 2 Parameters for the Experiment

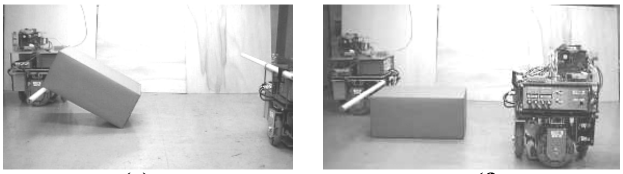
Size of the object	0.25[m]×0.60[m]
Weight of the object	1.2[kg]
Coefficient between The floor and the object The stick and the object	 0.31 0.29
Number of robot	2



(a) (b)



(c) (d)



(e) (f)

Fig. 15 Experimental Results

6. Conclusions

In this paper, the planning method of robust manipulation for mobile robots with motion errors is proposed. We take into consideration the motion errors in a planning stage beforehand, and build the manipulation technique that is suitable for position-controlled mobile robots. In this study, we introduce the domain stable graph to consider the motion errors, and create the operation graph to generate the motions of robots efficiently. Simulations and experiments have verified the effectiveness of proposed planning method.

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