COOPERATIVE MANIPULATION AND TRANSPORTATION OF A LARGE OBJECT BY MULTIPLE MOBILE ROBOTS

Atsushi Yamashita [*] Jun Ota [**] Tamio Arai [**] Keisuke Ichikawa [**] Kazuhiro Kamata [**] Hajime Asama [***]

[*] *Department of Machinery Engineering, Shizuoka University, 3–5–1 Johoku, Hamamatsu-shi, Shizuoka 432–8651, Japan*
[**] *Department of Precision Machinery Engineering, The University of Tokyo, 7–3–1 Hongo, Bunkyo-ku, Tokyo 113–8656, Japan*
[***] *The Institute of Physical and Chemical Research (RIKEN), 2–1 Hirosawa, Wako-shi, Saitama 351–0198, Japan*

Abstract: In this paper, we propose a new motion planning method for an object transportation by multiple mobile robots in a complicated environment. To accomplish this task, a planning method of an obstacle avoidance and a stable manipulation is needed. We divide a motion planner into a global path planner and a local manipulation planner to reduce computational costs. As to the global path planner, we reduce the dimensions of the configuration space and find a solution using the potential field. The constraints of the manipulation are considered as the cost function in A^* search. As to the local manipulation planner, we build a manipulation technique, which is suitable for mobile robots by position-control, and generate the robot motion considering motion errors and indefinite factors.

Keywords: Multiple mobile robots, Motion planning, Cooperation, Transportation, Manipulation, Gross motion planning, Fine motion planning

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 concept of cooperation by multiple mobile robots is proposed. In the future, mobile robots should work in a real 3 dimensional environment. Therefore, not only must they change an object position, but also they must change its pose. This means they must transport and manipulate the object (see Fig. 1).

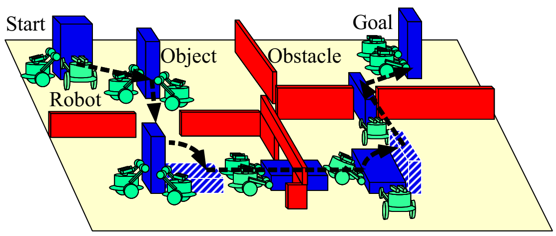


Fig. 1. The cooperative manipulation and transportation of a large object by multiple mobile robots.

In this complicated situation, a good motion planning method is very important to accomplish tasks efficiently. Therefore, we propose a motion planning method for cooperative transportation of a large object by multiple mobile robots. And we realize the transportation task by real robot system. However, this task has various kinds of problems. For example, we must plan paths of the object to avoid obstacles, construct a stable manipulation method, and decide robots' motions. The motion plannng in a 3 dimensional environment is very difficult because of the high dimensional configuration space (C-space). There are many studies about a motion planner with high dimensional C-space Latombe (1991); Hwang and Ahuja (1992a); Gupta and Pobil (1998). Barraquand and Latombe (1991) constructed a randomized planner, and Gupta and Guo (1995) proposed a backtracking method by solving problems with many degrees of freedom. Kavraki et al. (1996) proposed a probabilistic roadmap method. These conventional path planning methods can find a path of an object or a robot efficiently. However, they consider only geometrical and topological conditions in particular, such as shapes of obstacles and robots. They don't consider statics and dynamics of the object when robots manipulate it. As to the manipulation method, Kosuge et al. (1997) aime at transporting an object by lifting, and adopted the feedback control method using the information of robots' force sensors. Khatib et al. (1999) controlled inner force that is applied to an object and adopted the stable handling strategy to compensate the motion errors of robots. These methods can create a path of an object and robots or a manipulation way of the object in a 2 dimensional environment by using sensor data. In a 3 dimensional environment, the dimension of the C-space is too large for these methods to plan motion of an object and robots.

In previous works, both of geometrical and kinematics condition cannot consider at the same time. Accordingly, we divide a motion planner into a global path planner and a local manipulation planner. The former plans paths of an object and robots. The latter treats how to manipulate the object. To integrate two planners, constraints of the object manipulation are considered in the path planner. In other words, we aim at integrating a gross motion planner and a fine motion planner. And we execute transport tasks by real muti-robot system.

2. COOPERATIVE MANIPULATION AND TRANSPORTATION STYLE

We propose that robots manipulate an object by pushing with sticks in multiple mobile robots system (see Fig. 2). When the manipulating tasks are carried out, the stability of operation is improved because the contact area to the object becomes larger. The robots tumble the object to change its face that contacts with the floor from one face to the next one.

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 floor. The robots can move the sticks up and down. And pushing and tumbling operations are adopted here.

And the robots transport the object around it. While transporting the object, robots don't change their positions to the object. The robots depart from the object when they manipulate it and they keep close to the object when they transport it.

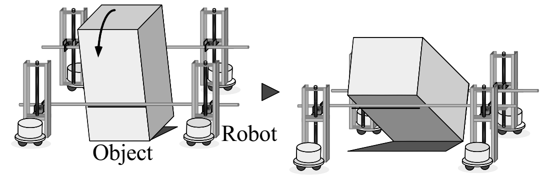


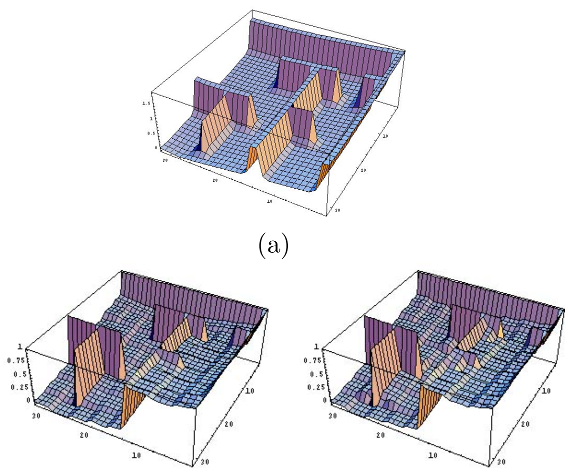
Fig. 2. The tumbling manipulation of a large object by multiple mobile robots.

3. GLOBAL PATH PLANNER

For the global motion planner, the biggest problem is an explosion of the computation time that results from the high dimensional C-space. In this paper, we reconstruct the C-space and reduce the dimension of C-space by considering the feature of transportation task by mobile robots. All things (an object, robots and obstacles) are represented by an octree method that is the approximate cell decomposition method for 3 dimensional environment. And we can find a solution with A^* search in this smaller dimensional C-space. A graph search is performed by using the following evaluation function f.

$$f(n) = w_g \sum_{i=n_s}^{n} g(i) + w_h \sum_{i=n}^{n_g} h(i) \qquad (1)$$

where $g(n)$ is a cost function, $h(n)$ is a heuristic function, n_s is a start node, n_g is a goal node, w_g is a weight coefficient of a cost function $g(n)$, w_h is a weight coefficient of a heuristic function $h(n)$. A weight coefficient of a cost function w_g is set as 1 or 0. When $w_g = 1$, we can find an optimal path. And when $w_g = 0$, we can find a path quickly, but cannot find an optimal path. When $w_h = 0$, a graph search method is same as Dijkstra's search. We use a potential function to estimate $h(n)$. The potential field is constructed with a repulsive force from obstacles and attractive force from a goal configuration. In this paper, we adopt three potential fields: (A) Euclid potential, (B) Wavefront potential, and (C) Skeleton wavefront potential. As to the Euclid potential filed, we adopt the potential field mentioned in Hwang and Ahuja (1992b), which is one of the simplest potential functions. As to the wavefront potential field, we use the concept of the wavefront expansion mentioned in Latombe (1991). As to the skeleton wavefront potential field, we generate the potential fields with skeleton method and wavefront expansion Barraquand and Latombe (1991). The three potential fields are shown in Fig. 3. And this potential function is normalized with the velocity of robots.



(a) (b) (c)

Fig. 3. Three potential fields. (a) Euclid potential. (b) Wavefront potential. (c) Skeleton wavefront potential.

The evaluation function f defined in eauation (1) is not always the heuristic function that has a monotonicity. Therefore, we can make an admissible heuristics with a pathmax equation (2). In equation (2), n' is a child node of n Yamashita et al. (2000).

$$f(n') = max(f(n), g(n') + h(n')) \qquad (2)$$

We verified the global path planner through the simulation. The motion planner computes the paths that two robots transport an L-shape large object in a three-dimensional.

Simulation results are shown in Fig. 4 and in Fig. 5. The positions (a) - (j) shown in Fig. 4 correspond to Fig. 5(a) - (j). When the robots pass through a narrow space (for example, a → c, c → d, f → g), the robots execute the orientation change operations and the arrangement change operations. When the robots must pass through very narrow space (for example, h → j), the robots execute the pose change operation in a wide space (g → h).

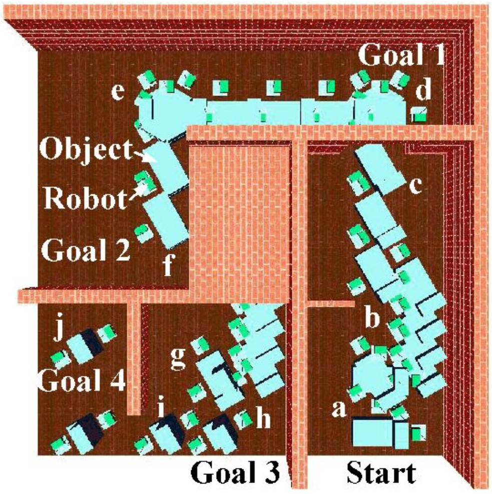


Fig. 4. Simulation result. A path from the start position to the goal position.

4. LOCAL MANIPULATION PLANNER

For the local manipulation planner, the biggest problems when mobile robots work is the effect of the robots' position errors. 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. The quasi-static manipulation method is formulated and we analyze the stable state of the object and the robots. The stable state is represented as a graph that is constructed with nodes and arcs. We consider three types of manipulation way: continuous operation, hand-over operation, and transfer operation (see Fig. 4).

After that, the problem of choosing the manipulation method comes back to the shortest path problem. A Dijkstra's algorithm is used to solve the shortest path planning problem and the orbit of sticks are determined Yamashita et al. (1999).

Table 1 shows parameters for simulations of an

Table 1. Parameters for manipulation.

Size of Object	$500mm$ x $1000mm$
Mass of Object	$4.0kg$
Friction coefficient	0.20
Max Force of Robot	$2N$
Condition 1	Without errors
Condition 2 Motion Errors of Robots Mass, Friction Coeffficient Center of Mass of Object	Consider errors $(\pm 0.04m, \pm 0.01m)$ $\pm 10\%$ $(\pm 0.01m, \pm 0.01m)$
Condition 3 Range of Stick Height	With Limitation $0mm$ – $500mm$

object manipulation. The manipulation method of the object shown in Fig. 7 is off-line-planned by the local manipulation planner.

In a condition 1, motion errors of robots are not considered. Therefore, the dangerous manipula-

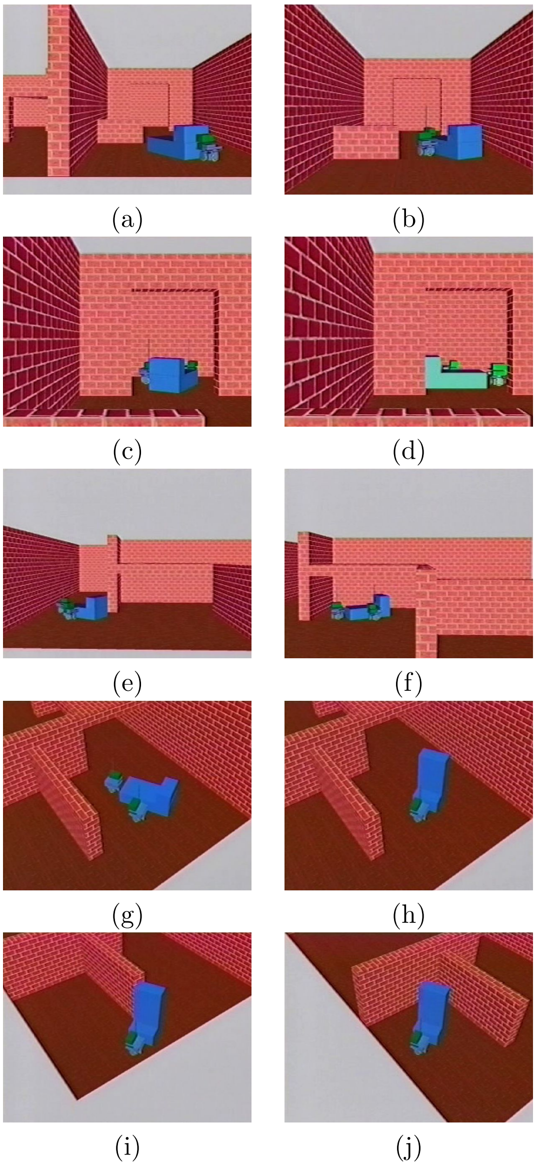


Fig. 5. Simulation results. The overview of the robots and the object in each step.

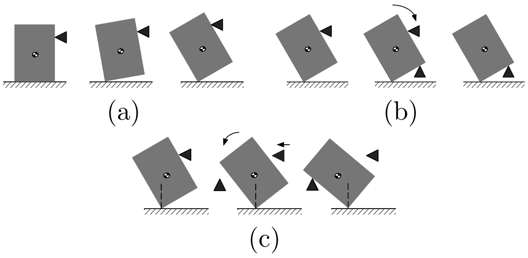


Fig. 6. Three types of operation. (a) Continuous operation. (b) Hand-over operation. (c) Transfer operation.

tion method is planned and the robots contact with the vertexs (Fig. 7(a)). If there are very little motion errors, the manipulation fails. In a condition 2, motion errors of robots are considered. The manipulation method is robust for the motion errors (Fig. 7(b)) for touching with the edges with margins. The orbit of sticks in this case (planning result with motion errors) is shown in Fig. 8. In a condition 3, limitations of movable range of the sticks and motion errors of robots are considered (Fig. 7(c)). When the stick cannot move to a high position, the robots touch with low positions and realized the manipulation.

The results of simulations shows that our proposed local manipulation planner can cope with various situations.

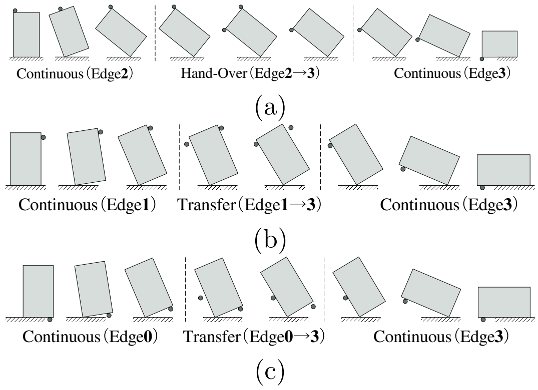


Fig. 7. Planned manipulation method. (a) Without errors. (b) With errors. (c) With limitation of stick movable range.

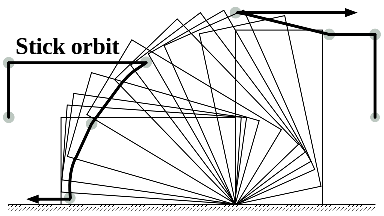


Fig. 8. Orbit of sticks in the case of Fig. 6.

5. SIMULATIONS AND EXPERIMENTS

5.1 Simulation Results

We verified the proposed planner in this paper through the simulation. The motion planner computes the paths that two robots transport an L-shape large object. Simulation results of the global path planner and the local manipulation planner are shown in Fig. 9 and in Fig. 10. In Fig. 9, the robots transport the object while avoiding obstacles. And they change the pose of the object at points A and B. In Fig. 10, the manipulation way of the object at point A is computed.

5.2 Comparison of Three Potential Fields

We set the parameter $w_g = 1$ and $w_h = 1$, and compare the performance of three potential fields. The motion planning becomes difficult when the goal is far from start position. We set four goals shown in Fig. 4.

In Table 2, we show the number of the open node N_{open}. N_{open} becomes larger, the computation

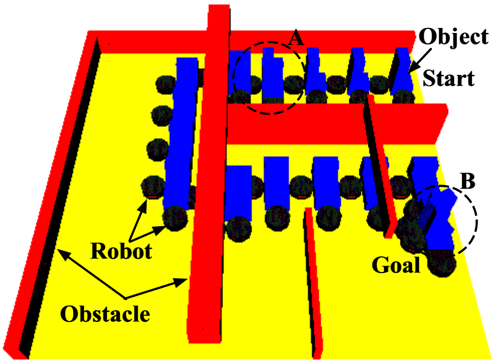


Fig. 9. The result of the global path planning.

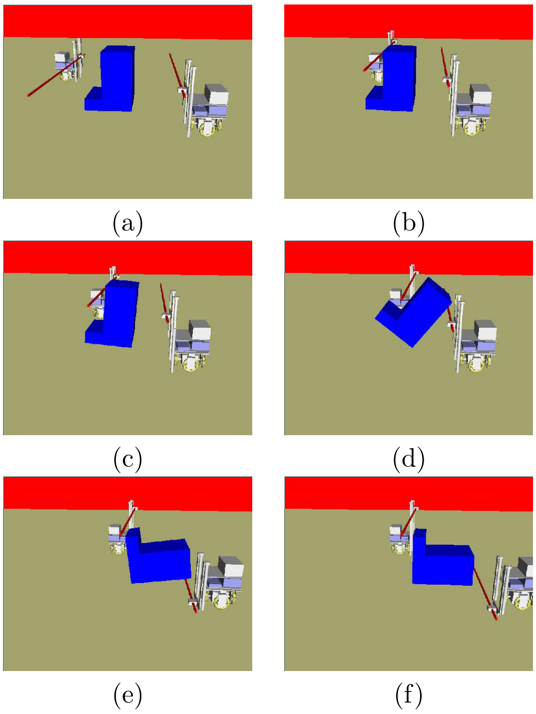


Fig. 10. The result of the local manipulation planning.

time becomes longer. We define $N_{open} = 1.00$ when the goal position is Goal1 and the potential field is Euclid potential function (A), and normalized N_{open} in other situations. When the problem is easy (the goal position is Goal1), the difference between three potential functions is not large. But the problem becomes difficult (the goal position is Goal4), the difference between Euclid potential function and the other potential functions becomes large.
When we compare with the wavefront potential (B) and the skeleton wavefront potential (C), N_{open} value of the skeleton wavefront potential is about 10% smaller than that of the wavefront potential.
An octree method generates many nodes near obstacles. The skeleton method creates the potential to avoid the obstacles. Therefore, the skeleton wavefront potential is good for the planning method that is a combination of an octree and A^* search.

Table 2. N_{open} value of three potential fields.

Potential	Goal1	Goal2	Goal3	Goal4
(A)	1.00	1.36	2.96	4.09
(B)	0.90	1.53	2.32	3.21
(C)	0.83	1.37	2.16	3.06

5.3 Conditions of Parameters w_g and w_h

We set that the goal position is Goal4 and use the skeleton wavefront potential function. And we change the parameters wg and wh shown in Table 3. N_{open} is the number of open nodes and normalized that N_{open} is 1.00 in Strategy 1. The evaluation value f is also normalized in Strategy 1.
In Strategy 1, for heuristics function w_h equals 0, the search method is Dijkstra's search algorithm that can search an optimal path. In Strategy 2, the search method is A^* search that can search an optimal path. A^* search can search the optimal path about twice times faster than Dijkstra's algorithm. When an optimal path is not considered (Strategy 3), N_{open} becomes 5% in compare with using Dijkstra's algorithm. But the evaluation value f becomes 2.5 times. This means that the time to accomplish the transportation task becomes 2.5 times, and a number of doing difficult manipulation increases. Therefore, search strategy is not realistic for the real task.
In Strategy 4, the parameter turning is done. When w_h equals 0.5, N_{open} becomes smaller (60% comparison to Strategy 2). The optimal value of wh depends on the environment. Therefore, we must determine wh while searching the solution.

Table 3. Condition of parameters w_g and w_h.

Strategy	w_g	w_h	N_{open}	f
1	1.0	0.0	1.00	1.00
2	1.0	1.0	0.45	1.00
3	0.0	1.0	0.05	2.50
4	1.0	0.5	0.27	1.00

5.4 Computation Time

It takes about 3000 CPU time to compute the path of the object and robots with Ultra SPARC-II (334MHz) in the global path planning. And it takes about 600 CPU time to compute one manipulation way in the local manipulation planner. The whole computation time is about 6000 CPU time when we adopt Strategy 2 and the skeleton wavefront potential. The environment is 12.8 x 12.8 x 12.8m.The resolution of the global path planning is 0.1m and that of the local manipulation planning is 0.01m and 1deg.

This shows that our proposed planner can find appropriate solutions within a practical time efficiently despite of complexity of the problem.

5.5 Experiments

We applied the proposed planning method of manipulating an object to real robot system. The mobile robot can move in all directions Asama et al. (1995). The robot have a lift-up mechanism. The lift-up mechanism consists of a L-shape plate and a stick. Stick's movable range is higher than the robot height (see Fig. 11).

A result of a transportation experiment is shown in Fig. 12. Here, it can be checked that objective operation can be performed, and the validity of this method is shown.

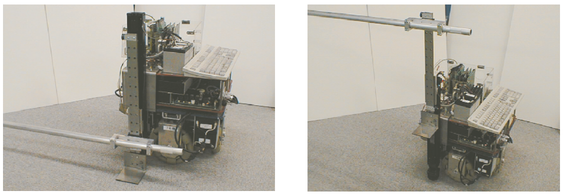


Fig. 11. The mobile robot with the lift-up mechanism.

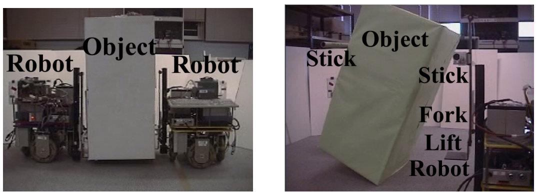


Fig. 12. The result of the experiments: The left figure shows the way of the transportation and the right figure shows the way of the manipulation.

6. CONCLUSION

In this paper, we propose a motion planning method for a cooperative transportation of a large object by multiple mobile robots in a 3 dimensional space. We divide the motion planner into a local manipulation planner and global motion planner. And as to the global motion planner, we reduce the dimensions of the C-space and can find a solution with searching in this smaller dimensional C-space using the potential function. As to the local manipulation planner, we consider the motion errors in a planning stage beforehand, and build the manipulation technique that is suitable for position-controlled mobile robots. After constructing two planners respectively, we integrate them. Simulations and experiments have verified the effectiveness of proposed planning method.

REFERENCES

H. Asama, M. Sato, L. Bogoni, H. Kaetsu, A. Matsumoto, and I. Endo. Development of an omni-directional mobile robot with 3 dof decoupling drive mechanism. *Proceedings of the 1995 IEEE International Conference on Robotics and Automation*, pages 1925–1930, 1995.

J. Barraquand and J.-C. Latombe. Robot motion planning: A distributed representation approach. *The International Journal of Robotics Research*, 10(6):628–649, 1991.

K. Gupta and A. P. D. Pobil. *Practical Motion Planning in Robotics.* John Wiley & Sons, 1998.

K. K. Gupta and Z. Guo. Motion planning for many degrees of freedom: Sequential search with backtracking. *IEEE Transactions on Robotics and Automation*, 11(6):897–906, 1995.

Y. K. Hwang and N. Ahuja. Gross motion planning – a survey. *ACM Computing Surveys*, 24 (3):219–291, 1992a.

Y. K. Hwang and N. Ahuja. A potential field approach to path planning. *IEEE Transactions on Robotics and Automation*, 8(1):23–32, 1992b.

L. E. Kavraki, P. Svestka, J.-C. Latombe, and M. H. Overmars. Probabilistic roadmaps for path planning in high-dimensional configuration spaces. *IEEE Transactions on Robotics and Automation*, 12(4):566–580, 1996.

O. Khatib, K. Yokoi, O. Brock, K. Chang, and A. Casal. Robots in human environments: Basic autonomous capabilities. *The International Journal of Robotics Research*, 18:684–696, 1999.

K. Kosuge, T. Oosumi, and K. Chiba. Load sharing of decentralized-controlled multiple mobile robots handling a single object. *Proceedings of the 1997 IEEE International Conference on Robotics and Automation*, pages 3373–3378, 1997.

J.-C. Latombe. *Robot Motion Planning.* Kluwer Academic Publishers, 1991.

A. Yamashita, M. Fukuchi, J. Ota, T. Arai, and H. Asama. Motion planning for cooperative transportation of a large object by multiple mobile robots in a 3d environment. *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, pages 3144–3151, 2000.

A. Yamashita, K. Kawano, J. Ota, T. Arai, M. Fukuchi, J. Sasaki, and Y. Aiyama. Planning method for cooperative manipulation by multiple mobile robots using tools with motion errors. *Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 978–983, 1999.