Cooperative Manipulation of Objects by Multiple Mobile Robots with Tools *

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In this paper we propose a method that multiple mobile robots use tools to accomplish tasks. To give an actual example, the robots can push and manipulate objects by means of a stick and can pull objects by means of string. We classify tools in view of their characteristic and the robots make use of characteristics of tools to accomplish tasks easily and efficiently. We adopt sticks and strings as tools: by using sticks, objects can be lined up simultaneously and by using strings, objects can be divided into two groups. We construct planning method about these tasks and build the system that mobile robots use tools. We use four wheeled robots equipped with tool handling module. The effectiveness of the proposed method is shown with the experiments of the robots equipped with tools.

Key words: robotics, tool, autonomous robots, multiple mobile robots, motion planning, path planning, cooperation, manipulation, transportation

1. Introduction

It is expected that mobile robots undertake transporting tasks in factories and construction sites. Because flexibility and fault tolerance of tasks is improved, it is proposed that multiple mobile robots accomplish tasks cooperatively [1].

Nevertheless a great deal of studies about the method that multiple mobile robots accomplish tasks cooperatively, in most cases it is assumed that multiple mobile robots don't use any tools and complicate tasks cannot be carried out. Hence it is considered that some means are needed to perform tasks more cooperatively by multiple robots.

In consideration of cooperative tasks of human, to transport and pile stones, sticks made of wood were used as tools, when pyramids were built in ancient Egypt. In this case heavy stones could be lifted by means of a lever and very large power could be liberated to stones by using sticks. And also in recent years, two fishing boats draw in a fishnet cooperatively to catch swarm of fishes simultaneously. In this case it become possible to catch wide-ranging swarm of fishes by using a fishnet as a tool. The above proves that tools are very useful when multiple subjects move while accomplish tasks cooperatively.

Consequently we pay attention to the relationship between tools and cooperative tasks and propose a method that multiple mobile robots use tools to accomplish tasks. To avoid complexity of manipulating tools, we adopt relatively simple things as tools: sticks, plates and strings.

In view of the tasks that robot uses a stick, the use of pushing actions to orient and translate an object in the plane are often studied [2-5]. These papers study about pushing and manipulating one object by using a stick. And there are no studies that multiple mobile robots use string. In these studies about stings and mobile robots, motion-planning methods is proposed for multiple tethered robots [6-7] and there are no studies that strings are utilized to the tasks positively.

In multiple mobile robots system, demands for tasks is generally shown as follows:

(A) To accomplish various kinds of tasks
(B) To accomplish tasks efficiently
(C) To accomplish tasks cooperatively

(A) means that multiple mobile robots can treat objects whose shapes are various. (B) means that multiple mobile robots can manipulate plural objects at the same time. And with regard to (C), when there are some constraints between multiple mobile robots, cooperative tasks can be smoothly accomplished.

Consequently we introduce tools to multiple mobile robots system to satisfy these demands. We regard tools as all-purpose end-effectors that multiple mobile robots can treat plural objects simultaneously. Definitions of tools is shown as follows: (1) tools are the objects that multiple mobile robots can handle cooperatively to accomplish tasks, (2) Multiple mobile robots can change their tools. (3) Tools cannot work by themselves. A schematic view of our proposed system is shown in Fig. 1.

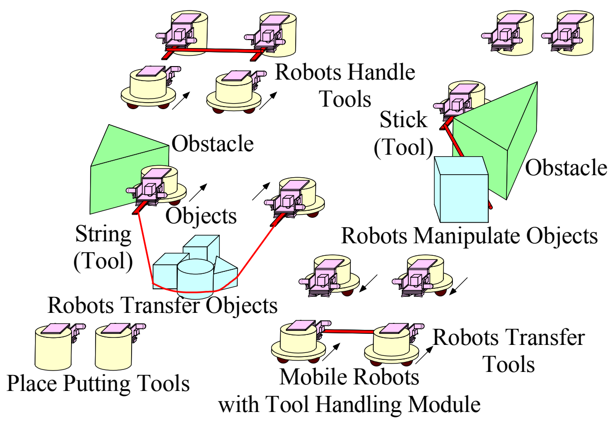

Fig. 1 Schematic view of proposed system

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2. A proposal of methods for tool use

In this section, advantages of using tools when multiple mobile robots work are shown and classify tools from the viewpoint of their characteristics.

2.1 Advantages of using tools

It is considered that there are great advantages when multiple mobile robots work in comparison with not using tools. In this section, some examples of using tools are shown and explain their advantages.

(1) Multiple mobile robots can transport multiple objects at the same time by using tools. In this case, workspace of the robots can be widened by using tools. In Fig. 2, the robots can transport and line up objects at the same time by using a stick. And in Fig. 3, the robots can transport objects by using string where there exist obstacles simultaneously.

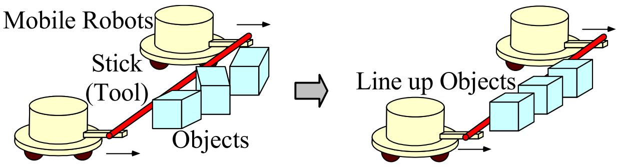


Fig. 2 Robots can line up objects by using a stick

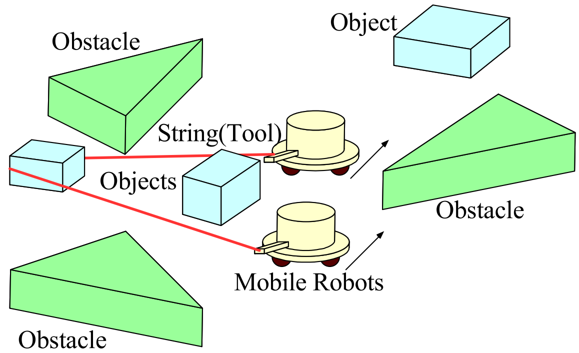


Fig. 3 Robots can transport objects by using string

(2) Multiple mobile robots can touch and manipulate objects that are far from the robots or in narrow spaces. For example, by using a stick, the robots can manipulate an object in a narrow space where the robots cannot approach and the risk that the robots contact the obstacles is decreased (see Fig. 4).

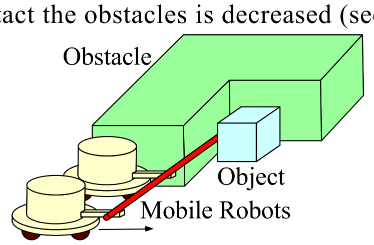


Fig. 4 Robots can manipulate an object in a narrow space by using a stick

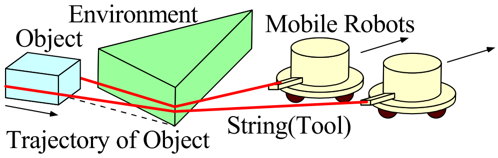


Fig. 5 Robots can pull an object by using string

Similarly by using string, the robots can pull an object that are distant from the robots. And in Fig. 5, the trajectory of an object doesn't change when position errors of the robots occur.

(3) Multiple mobile robots can manipulate a heavy object. By using a stick as a lever, the robots make good use of the environment that stand still and can amplify their power by means of a lever and manipulate a heavy object beyond their abilities (see Fig. 6).

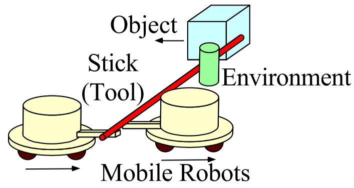


Fig. 6 Robots can manipulate a heavy object by means of a lever by using a stick

(4) It becomes easier to put the force of each robot together to an object. When manipulating an object whose surface area is very small, it is difficult for multiple mobile robots to touch the object at the same time. But by using a stick, force of all robots can be easily worked to the object thorough the stick.

(5) The end effector of the robot can be simplified, for the robot must only handle tools that can be made for robots to easily handle and there is no need to handle various objects. Therefore in comparison with handling various objects, the tool handling module becomes much simpler.

(6) Multiple mobile robots can change their tools according to the environment and tasks. Consequently the robots can accomplish tasks much more efficiently and flexibly.

As mentioned above, there are great advantages of using tools.

2.2 Classification of tools

By considering their characteristics, we classify tools as follows: (1) rigid tools and (2) flexible tools. The characteristics of them are shown in Table 1. The shapes of the rigid tools are constant. Sticks and plates are the rigid tools. And the shapes of the flexible tools are changeable. Strings and clothes are the flexible tools.

Table 1 Classification of Tools

	Rigid Tools	Flexible Tools
Shape	Constant	Changeable
Constraints given to objects	Strong	Weak
Position control of objects	Possible	Difficult
Avoidance of obstacles	Difficult	Easy
Example	Sticks, Plates	Strings, Clothes

About the rigid tools, their strong point is to control the position and orientation of objects. We adopt sticks as typical rigid tools, and the method that multiple mobile robots control the position and orientation of objects by using a stick is proposed.

About the flexible tools, their strong point is to change their shape flexibly. We adopt strings as typical flexible tools, and the method that multiple mobile robots transport objects by using a string in a complicated environment and avoid the obstacle flexibly is proposed.

3. Tasks by using sticks

As mentioned in §2, multiple mobile robots use rigid tools and control the position and orientation of objects. In this paper, we consider that the characteristic of tools is to accomplish tasks efficiently, the method that multiple mobile robots manipulate multiple objects at the same time is proposed. And it is considered that the typical task by using a stick is an arrangement task, we propose a method that the robots transport and lined up objects at the same time (Fig. 2).

3.1 Manipulation of one object

The rotate direction of an object when the robots push an object by using a stick is explained in [2]. The rotate direction of an object is determined by the four vectors Rl, Rr, Rp and Rc (See Fig. 7). Rl and Rr are the left and right boundaries of the contact friction corn. Rp points in the direction of the pushing direction and Rc is the vector from the contact point to the center of mass of the object. The relationship between these four vectors determines the rotate direction of an object.

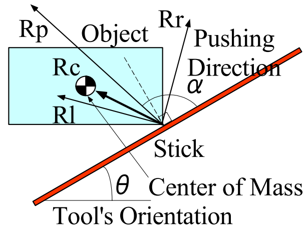
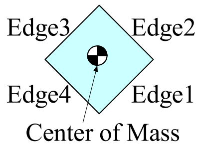
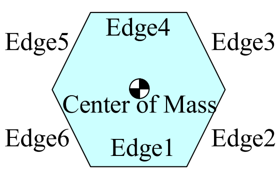


Fig. 7 Vectors related to the rotate direction

And the diagram that indicates the edge that is aligned with a stick when the rotation of an object stops can also be generated [3]. The axis of ordinates (y-axis) means pushing direction and the axis of abscissas (x-axis) means tool's orientation. Object1 (a square: the length of each edge is 500[mm] and a coefficient of friction between a stick and Object1 is 0.25) and Object2 (a hexagon: the length of each edge is 500[mm] and a coefficient of friction between a stick and Object2 is 0.80) are shown in Fig. 8. The diagram of Object1 and Object2 is shown in Fig. 9.

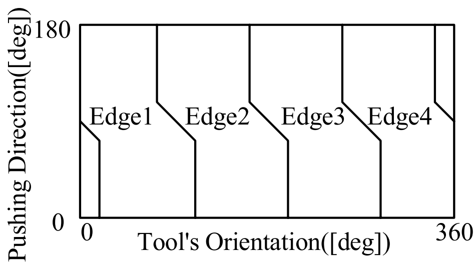


(a) Object1

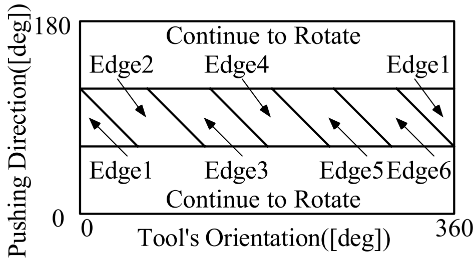


(b) Object2

Fig. 8 Objects



(a) Object1



(b) Object2

Fig. 9 The diagram which indicate the edge that contacts with a stick when the rotation of an object is stopped

The distance that an object slides and slips until the rotation of an object is stopped when the robots push an object by a stick is analyzed in [4]. D is a sliding distance that a stick move in the direction of pushing and the S is a slipping distance along a stick until the rotation of an object stops (see Fig. 10).

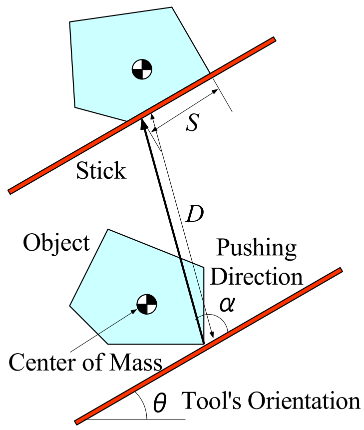


Fig. 10 Distance D and S

3.2 An arrangement task of objects

We proposed a method that multiple mobile robots transport and line up objects at the same time. Our purpose is to determine the parameters of tool's orientation θ and pushing direction α to arrange objects. Two mobile robots handle each end of a stick and line up Object1 and Object2. Initial configuration of objects is shown in Fig. 11.

An objective state is the state that Edge2 of Objcect1 and Edge3 of Object2 is arranged (Edge2 of Objcect1 is parallel to Edge3 of Object2). And a goal direction that is an objective direction of transporting object is 30[deg]. Tool's orientation and pushing direction are determined by the method that utilize the analysis mentioned above.

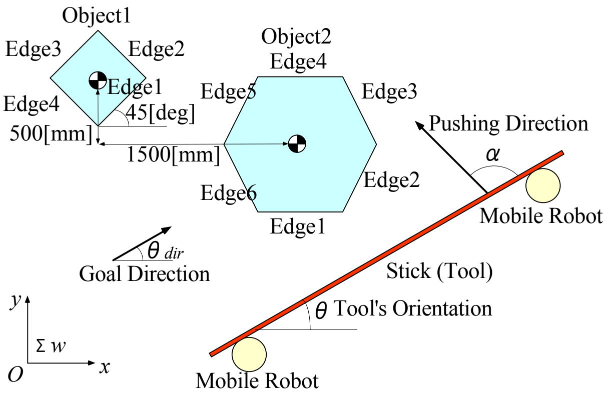


Fig. 11 Initial configuration of objects

A procedure that tool's orientation θ and pushing direction α are determined is shown as follows:

(1) Find a state equal to an object state: The state that Edge4 of Object1 and Edge6 of Object2 are arranged is equal to an objective state in Fig. 11, the state that Edge4 of Object1 and Edge6 of Object2 are arranged is regarded as an objective state.

(2) Obtain the diagrams of all objects (see Fig. 9).

(3) Combine the diagram of all objects and look for an area where the diagram satisfies an objective state (see Fig. 12).

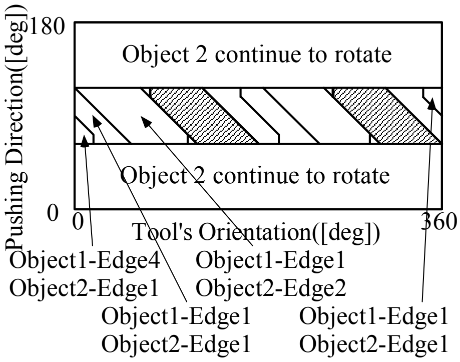


Fig. 12 Combination of diagram

(4) Decide tool's orientation θ and pushing direction α : Choose θ and α , where collision between Object1 and Object2 never occurs. The distance D and S (see Fig. 10) are useful to judge collision between Object1 and Object2.

(5) Consider errors of some parameters and decide θ and α in the existence of errors: It is assumed that there exist error range about coefficient is 50[%], errors about tool's direction and about pushing direction are 10[deg] in Fig. 13.

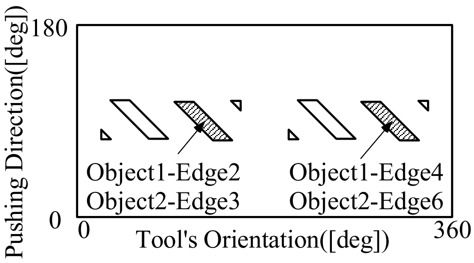


Fig. 13 The Diagram in the existence of errors

Tool's orientation θ =300[deg] and pushing direction α =90[deg] are obtained when we apply our proposed method. The determined value of the parameters and a manner of arrangement are shown in Fig. 14.

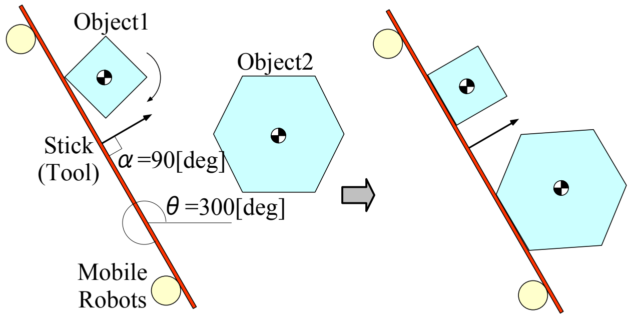


Fig. 14 A result of the arrangement task

4. Tasks by Using Strings

As mentioned in §2, multiple mobile robots use flexible tools and transport objects in the existence of obstacles. In this paper, we consider that the characteristic of tools is to accomplish tasks efficiently, the method that multiple mobile robots transport multiple objects at the same time in the existence of obstacles is proposed. And it is considered that the typical task by using string is a sorting task, we propose a method that the robots divide objects into two groups (Fig. 15).

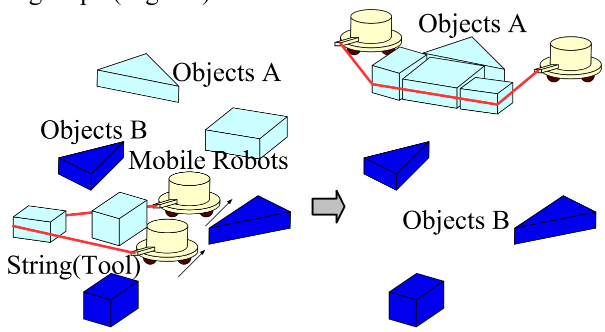


Fig. 15 Robots can divide objects into two groups (Object A and Object B) by using a string

In the situation that the robots divide objects into two groups, Objects A or Objects B are selected to transport simultaneously at the beginning and then remained objects are transported. When Objects A are transported, Objects B are regarded as the obstacles and mobile robots transport Objects A not to contact with Objects B. therefore, at first, we propose a method that multiple mobile robots transport objects in the existence of the obstacles. And then we construct the planning method that the robots divide objects into two groups by using string.

4.1 Transportation in the existence of the obstacles

Initial configuration of objects and mobile robots is shown in Fig. 16. It is purposed that the robots transport Objects A (Object1, 2, 5, 7, 9, 10) at the same time and Objects B (Object3, 4, 6, 8) are regarded as obstacles.

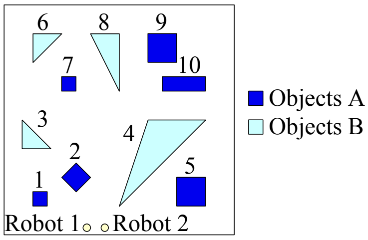


Fig. 16 Initial configuration of objects and mobile robots

A procedure that trajectories of robots are determined is shown as follows (in this case it is assumed that the length of the string is longer than that of total trajectories of the robots):

(1) Construct the Voronoi diagram: It is assumed that each robot can move on only Voronoi edges and Voronoi points (see Fig. 17(a)).
(2) Choose all of the Voronoi edges around Objects A (see Fig. 17(b)).
(3) Shorten the paths: Remove excessive Voronoi edges where the robots must go and return (see Fig. 17(c)).
(4) Combine the paths: Combine the separated Voronoi edges around Object A in Fig. 17(c) (see Fig. 17(d)).
(5) Consider the initial and goal position of the robots and connect the paths (see Fig. 17(e)).
(6) Distribute the path to each robot: Robot1 moves clockwise along the path and Robot2 moves counterclockwise along the path (see Fig. 17(f)).

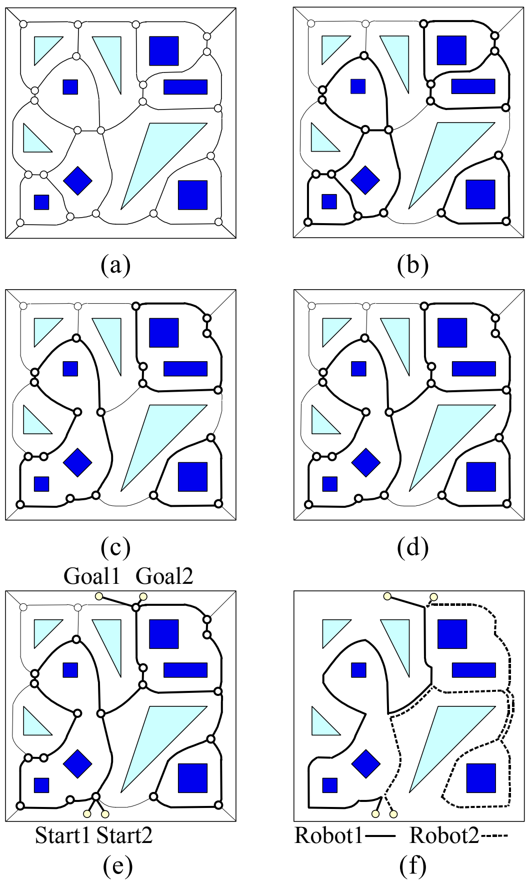


Fig. 17 A method of transporting objects by using string simultaneously

4.2 A sorting task

By Utilizing the method mentioned above, multiple mobile robots divide object into two groups by using string. The trajectories of the robots when transporting Objects A are showed in Fig. 18(a) and Objects B in Fig. 18(b).

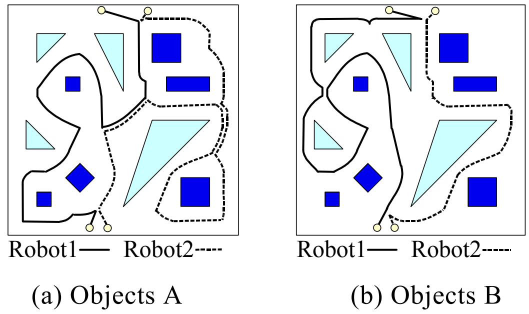


Fig. 18 Paths of mobile robots

After obtaining trajectories when the robots transport Objects A and Object B respectively, the length of total trajectories of the objects is compared and the trajectories whose total length is shorter are selected. In this case, total length of trajectories that the robots transport Objects B is shorter and at first the robots decide to transport Objects B at the same time (see Fig. 18(b))

And there is a possibility that the robots collide with each other. If the robots come within an ace of colliding one robot wait until another robot pass by.

The motion planning of method of using string is constructed above.

When the length of the string is short, the robots cope with decreasing the number of the objects that are transported at the same time. The changes of trajectories is shown in Fig. 19 when the robots transport Objects B. The length of the string is enough in Fig. 19(a) and the length of the string become less and less shorter in Fig. 19(b)-(d).

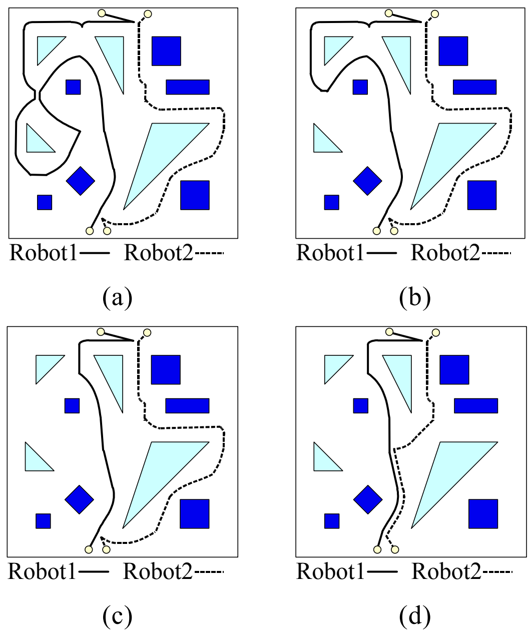
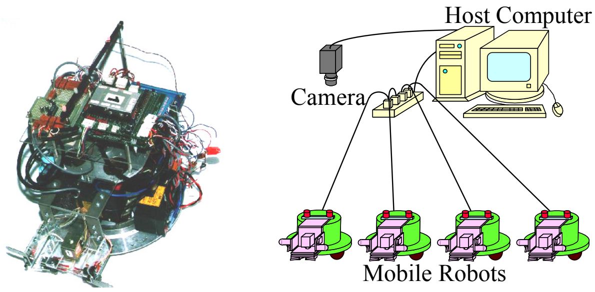


Fig. 19 Trajectories of the robots when the length of string is short compared with the length of trajectories

5. Experiments

Experimental system is consisted of the mobile robots, the CCD camera located in the environment, and the host computer (see Fig. 20).



(a) A mobile robot (b) System architecture

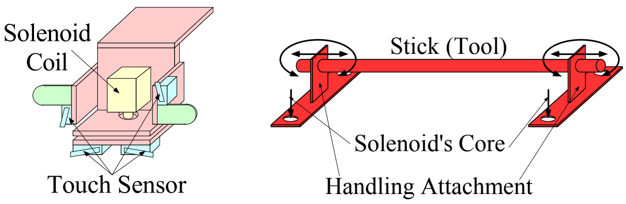
Fig. 20 Experimental system

The mobile robot has CPU board and the CPU board controls its motion. And it has a tool handing module that can handle tools. In its head there is an array of LEDs for easy following through the CCD camera image.

The CCD camera is located on the ceiling that measures and calculates the positions and orientations of the mobile robots.

The host computer gives orders to the mobile robots and corrects the error of position and orientation of the each mobile robot by using the information from the CCD camera located on the ceiling.

A tool handling module is consisted of the solenoid coil and four touch sensors (see Fig. 21(a)). A tool has handling attachments on its each end (see Fig. 21(b)). When the core of the solenoid coil of the tool handling module goes through the hole of the handling attachment of the tool, the mobile robot handles a tool. In the case of handling a tool, to minify the errors of position and orientation between the mobile robot and the place putting tools, the mobile robot obtains an information of its position and handles tools with a use of the local information obtained from the touch sensors. The handling attachment of a tool slides and rotates relatively to the tool itself to avoid applying the excessive force to the tool.

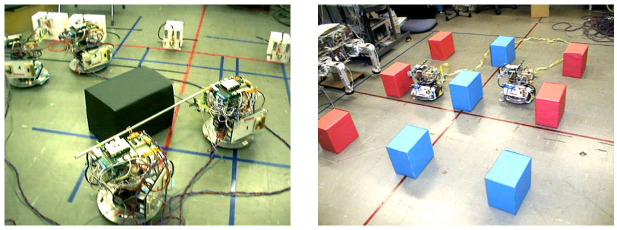


(a) Tool handling module (b) Tool (stick)

Fig. 21 Tool handling module and tool

Experimental views of using tools (a stick and string) are shown in Fig. 22. It is confirmed that when using a stick as a tool, the mobile robots can line up objects stably and when using string as a tool, the mobile robots can divide objects into two groups efficiently.

From the experimental result, it is shown that multiple mobile robots can accomplish cooperative tasks efficiently and stably by using tools.



(a) Stick (b) String

Fig. 22 Experiments of using tools

6. Conclusions

In this paper we paid attention to the fact that multiple mobile robots can treat multiple object at the same time efficiently by using tools. And the method that multiple mobile robots accomplish tasks by using tools cooperatively was proposed. We adopted sticks and strings as tools. We constructed the motion planning method that multiple mobile robots line up objects simultaneously by using a stick and that multiple mobile robots divide objects into two groups. We built the system that multiple mobile robots can use tools cooperatively and the effectiveness of our proposed method is verified by simulations and experiments.

In the future, we will construct the method that multiple mobile robots select tools according to the environment and tasks. And tasks in three dimensions must be studied.

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