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Cooperative Conveyance of an Object with Tethers by Two Mobile Robots

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Abstract: This paper deals with cooperative conveyance by two mobile robots with tethers. First, a tether-winding unit that maintains a constant tension is developed for stable conveyance of an object. Second, three types of methods for marching of two mobile robots are proposed for examination of effective cooperative conveyance. Performances of these methods are evaluated by computer simulations. Third, the best method smoothly tugging the object is adopted for implementation of an actual robot system. The demonstration shows the validity of the algorithm so that two mobile robots cooperatively avoid an obstacle tugging an object.

Keywords: Cooperative conveyance, Group robots, Tether, Marching of robots, Super-Mechano Colony

1 Introduction

The purpose of this study is to develop a new mechanical system that mobile robots cooperatively convey an object in an exploration field. There are many studies on cooperative mobile robotics [1]. Most of them are computer simulations to examine new algorithms on path planning, formation and marching of the robots. Several studies experimentally examined cooperative conveyance[2-4]. However, there are few studies that robots used tools such as bars or tethers for effective conveyance of objects although usefulness of tools was pointed out [5].

Our study focuses on cooperative conveyance of two mobile robots with tethers. Cooperative motion with tethers enables the mobile robots to convey a heavy object that one mobile robot cannot move. Tethers can handle various shapes of objects. They are also compact in storage and easy to carry them. It is therefore useful for collecting objects in exploration field.

The mobile robots were developed by several research groups including us at Tokyo Institute of Technology. Figure 1 shows overview of the mobile robots. Each robot has same motion mechanism and information functions. It is in the shape of regular octagonal prism that diameter is 260 mm and the height is 400 mm. It moves at about 100 mm/sec in any direction driven by two wheels. A CCD camera is mounted on the top of the robot for visual recognition functions. The observing distance is about 1500 mm and angle of sight is about 120 degrees. Visual recognition and mobile control are autonomously performed by a CPU board built in the robot. The mechanical details are described in the reference[6].

This study mainly deals with a subject that two mobile robots pull an object with tethers and convey it to an assigned place avoiding obstacles on the way of conveyance.

Figure 1 Overview of the mobile robot

2 Algorithm to Avoid an Obstacle

Figure 2 shows the schematic diagram of a robot system that consists of two mobile robots and an object. The two mobile robots tug an object with two tethers. The robots must avoid an obstacle located in a flat field tugging the object.

Basic algorithm to avoid an obstacle consists of the following two steps. As step 1, robot A or B detects the edge of the obstacle. To determine a marching direction of the two robots, we introduce the following evaluation function.

$$I(\theta) = \frac{1}{d(\theta)} \tag{1}$$

Where, d is distance between a CCD camera on a mobile robot and the edge of the obstacle at an angle of θ. Each mobile robot acquires the value $I(\theta)$ when it detects an obstacle.

As step 2, mobile robots individually calculate the indication S by the equation (2) summing up $I(\theta)$ with small angle $\Delta\theta$ and compare them each other. As the indication S denotes risk of collision with the obstacle, a robot with a smaller value has priority for decision to determine the marching direction. The marching direction to avoid the obstacle is determined by θ_o that minimizes the evaluation function $I(\theta)$ at the priority robot. Then the priority robot gives a command of the marching direction to other robot. In case of Figure 2, robot B has the priority and determines the direction.

$$S = \sum I(\theta) \tag{2}$$

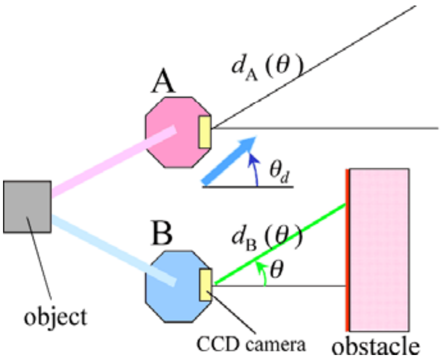


Figure 2 Schematic diagram of a robot system avoiding an obstacle in a flat field (from top view)

The above method only determines a direction to avoid an obstacle. Two robots must go to their target over the obstacle. If there is no obstacle in the field, going straight with keeping target direction θ_t is the best way. Here, we propose the following equation (3) to obtain a comprehensive direction θ_d for the robot system marching to the target avoiding obstacles.

$$\theta_d = k\theta_o + (1-k)\theta_t \tag{3}$$

Where, k is a parameter that changes depending on distance to the obstacle. The parameter k takes a value in accordance with the following conditions.

$$\begin{aligned} &\text{If } d_m \le 200 \quad \text{then } k = 1, \\ &\text{If } 750 \ge d_m > 200 \text{ then } k = 0.7, \\ &\text{If } d_m > 750 \quad \text{then } k = 0 \end{aligned} \tag{4}$$

Where, d_m [mm] is a kind of criteria to start avoidance action that is related to a distance between the robot system and the obstacle. We determined the above numbers simulating behaviors of the robot system under various conditions.

Simultaneous actions of the robots determined by the above basic algorithm are expected to be a cooperative formation. However, only θ_d is not enough to determine motion of robots because tensions of tethers are not considered. The next chapter discusses simulation method.

3 Simulation Method and Related Hardware

This chapter first explains the simulation method for motions of robots, second describes a mathematical model to convey an object, third proposes a concrete mechanism to execute the conveyance in hardware and forth explains an image processing for safe avoidance of obstacles.

3.1 Procedure of simulation

Validity of the proposed algorithm is examined by computer simulation. The procedures of the simulation are the following steps as shown in Figure 3.

In the beginning, positions of robots A and B at the next step are calculated by velocities of the two robots. Next the new positions are replaced as new arrangement of robots. Tensions of tethers are obtained as described in the next section. Then, acceleration of the object is calculated and a position of the object at the next step is estimated. These iterative calculations are executed by a discrete time step.

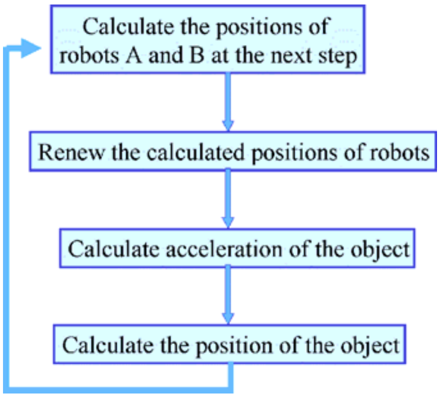


Figure 3 Procedures of computer simulation

3.2 Tension of tethers in tugging

In the above-mentioned procedures, extensions of tethers are important values for calculating the motion of the object. The value is determined by the following way. Acceleration of the object is calculated by balance of tensions of tethers. Figure 4 shows tensions of two tethers exerted on the object. In the figure, T_1 and T_2 denote tensions of the tethers.

In this situation, we assume that a tether is elastic and produces a constant force F_0 for expansion as in Figure 5. In the figure, L_0 is an initial length of tether. Such mechanical property can be realized by use of a constant force spring mechanism as explained in the next section.

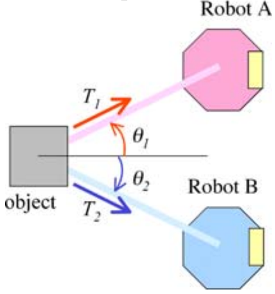


Figure 4 Tensions exerted on the object

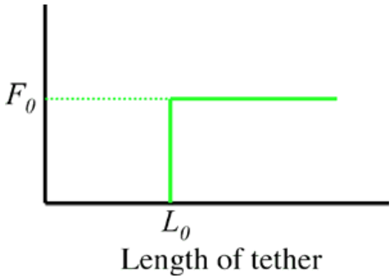


Figure 5 Produced tether's force by extension

If the tethers are rigid and are not stretched by any force, tensions of tethers quickly change during even small motions of robots or an object. To respond the quick change of the tensions, it usually uses force control with high-speed rate, which needs a high performance computational system. However, processing power of the computer system mounted on the mobile robot is limited.

Our solution is to provide a mechanical device that produces a constant tension in the tether as described in the next section. It does not need force sensors for measuring tensions of tethers. This means the control method about tethers become remarkably easy.

From the elastic property of tethers as shown in Figure 5, T_1 and T_2 are calculated by the next equation.

$$\text{If } L < L_0 \text{ then } T = 0 \text{ otherwise } T = F_0 \tag{5}$$

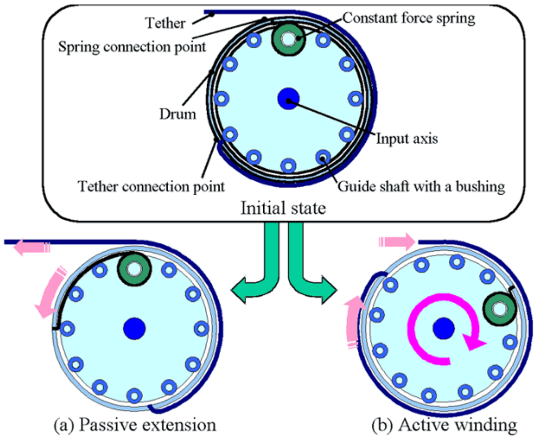
Then, exerted force F to the object is calculated by the following equation considering force balance as shown in Figure 4.

$$\text{If } (T_1 \cos\theta_1 + T_2 \cos\theta_2) > \mu_s Mg \text{ then } F = (T_1 \cos\theta_1 + T_2 \cos\theta_2 - \mu_k Mg) \text{ otherwise } F = 0 \tag{6}$$

Where, g: gravitational constant, M: mass of object, μ_s: coefficient of static friction, μ_k: coefficient of kinetic friction. Using the exerted force F, the acceleration of the object is calculated by the Newton equation of motion.

3.3 Mechanism of tether-winding unit

We propose a tether-winding unit that maintains a constant force when a mobile robot tugs an object. Figure 6 shows the concrete mechanism. A constant force spring is built in a drum for winding a tether. The device always produces a same force whether passive extension or active winding. Figure 7 shows a developed unit device that is mounted on each mobile robot.



(a) Passive extension

(b) Active winding

Figure 6 **Mechanism of a tether-winding unit**

Figure 7 **Developed tether-winding unit**

3.4 Visual function of mobile robot

In the actual robot system, the two mobile robots take visual images for each 250 mm movement to avoid obstacles, and they check existence of an obstacle detecting edge of the shape, and then march in formation tugging the object with tethers.

For safe avoidance, we introduce virtual imaging technique as shown in Figure 8. The robot B views the solid rectangular area and calculates a moving direction, which is denoted with the dotted arrow. However, the direction has danger of collision with the obstacle because scale of the mobile robot is not considered.

To solve the problem, we propose a virtual image processing. The processing shifts the real image to the outer side by scale of each mobile robot. This means that virtual robot B’ is virtually placed at the right side robot B. The solid arrow from robot B’ is obtained as a safe direction determined by the virtual image. This method directly output a safe direction without considering scale of the mobile robot during the image processing.

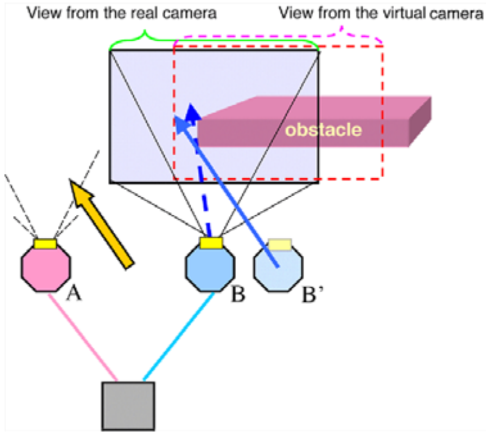


Figure 8 **View from a virtual camera**

4 Simulation Tests

We propose three types of method for marching of the robot system and examine the performance by computer simulation step by step. For the computer simulation, we provide the following conditions.

The simulation field is 2000 mm by 4000 mm and has two rectangular obstacles in it. The two mobile robots are placed on the left side as the first position. The mission of the robots is to move to the right direction and to reach the final goal at right side of the field avoiding the two

obstacles tugging an object with tethers. The following parameters were set up for the computer simulation.
L_0: 500 mm, M: 2.5 kg, μ_s: 0.15, μ_k: 0.1, F_0: 20 N.

4.1 Simulation by method 1

The first method is the easiest way, which keeps the conveyance form of the two robots with same direction and velocity while ongoing. The two robots take a regular alignment in movement as shown in Figure 9(a).

Figure 9(b) shows the simulation result. The line plotted by squares corresponds to the motion of robot A, the line plotted by circles is for robot B and the line plotted by smaller circles is the orbital course of the object. The produced courses of the robots seem to be good as they show smooth lines. The course of the objects is however not placed in the center of the robots. This means that either tether is too extended, which causes irregular motions of the object.

4.2 Simulation by method 2

To improve the improper tugging by the first method, we propose the second method that keeps lengths between robots and the object as shown in Figure 10(a). The robots rotate to adjust direction before going forward so that the object is most always placed in the center position of two robots.

Figure 10(b) shows the simulation result. As the generated course of object is almost in the center of the robots, the result tells us that two tethers maintain almost same length. However, the motions of the two robots show complex. It means that the two robots waste energy in conveyance.

4.3 Simulation by method 3

To decrease the wasteful motions of child robots by method 2, we propose the third method that keeps configuration of robots using a control point as shown in Figure 11(a). The control point at the next step is determined by the direction θ. Then the configuration of robots at the next step is determined based on the control point.

Figure 11(b) shows the simulation result. Courses of the two robots and the object are almost smooth and the object was almost in the center of robots. This means that the object is equally pulled. The third method is evaluated to be the best among the three methods.

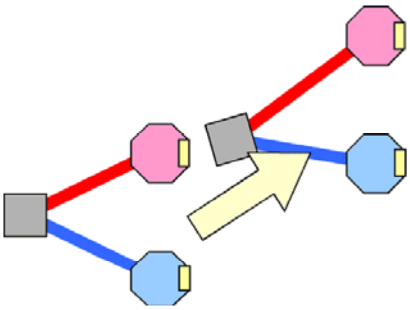


Figure 9 (a) Method 1: keeping the arrangement of robots

Two robots keep a same posture so that they face an obstacle in the same direction determined by equation (3) during conveyance of the object.

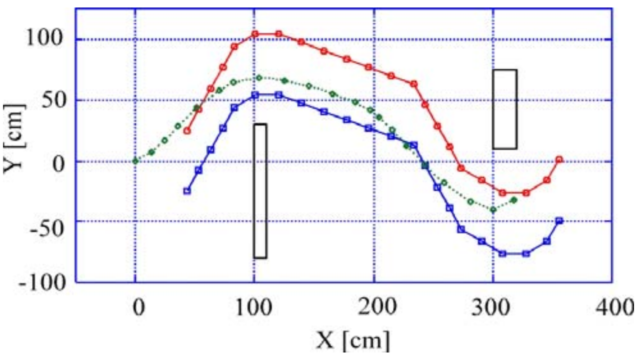


Figure 9 (b) Simulation result by method 1

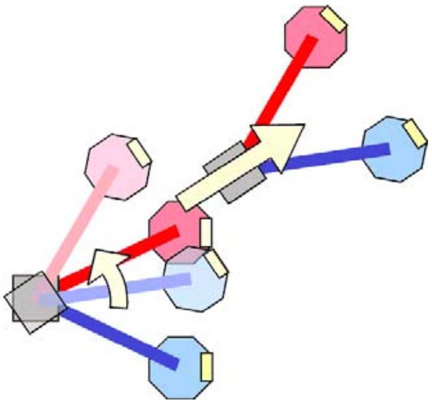


Figure 10 (a) Method 2: keeping conveyance form. Two robots rotate before ongoing and march straight

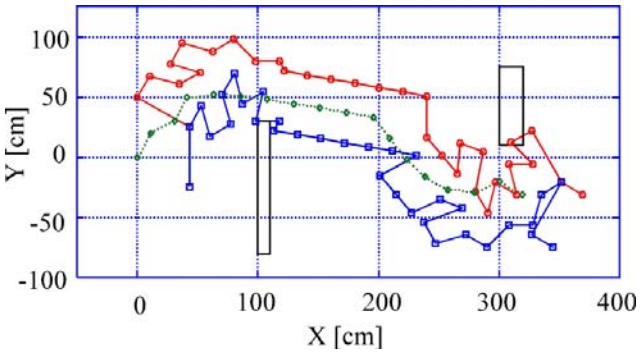


Figure 10 (b) Simulation result by method 2

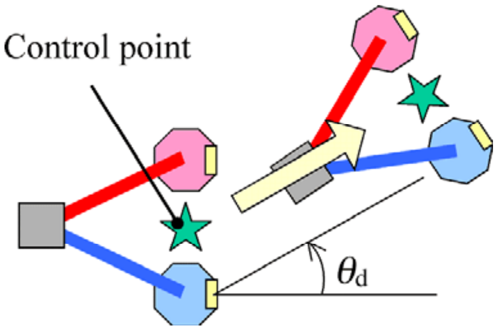


Figure 11 (a) Method 3: keeping the control points

The green stars denote control points. Position of the control point at the next step is calculated referring the direction θ_d by equation (3).

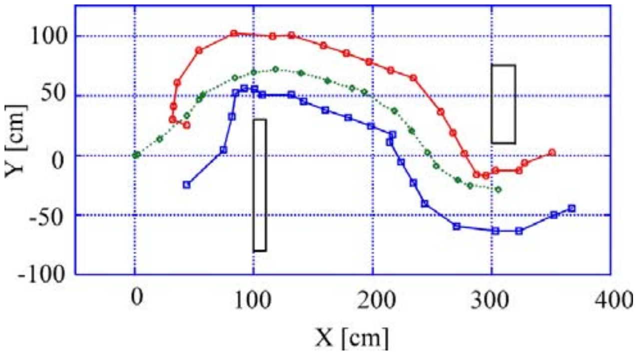


Figure 11 (b) Simulation result by method 3

5 Experimental Demonstration

Using the third method, we have demonstrated actual performance of the robot system. To realize cooperative conveyance, two robots must share information about obstacles and positions of each robot. Figure 12 shows a flow chart to perform cooperative actions.

In the beginning, two robots measure the position of the obstacle by CCD camera. Robot B is preprogrammed to be a leader for information management. Robot A thereby sends obstacle information to robot B. Next, robot B determines the direction of movement taking account of both obstacle information, and sends the information of the movement to robot A. Finally both robots move synchronously.

For the experimental study, about 4000 mm by 5000 mm flat field was provided. An obstacle was placed in the field. Position of the final goal was given to the mobile robots before starting.

Figure 13 is a snapshot of the robot system. Two mobile robots successfully tugged the object with tethers avoiding the obstacle. The motions of the two robots and the object were taken by a video camera equipped on the ceiling. Figure 14 shows the trajectories of the motions. The experimental result shows that the two robots took smooth trajectories and the trajectory of the object is most in the center of them. This means that the object is equally pulled by the two robots.

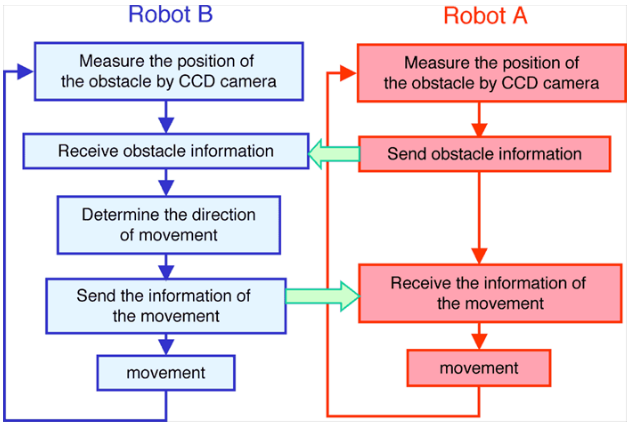


Figure 12 Flow chart of cooperative conveyance.

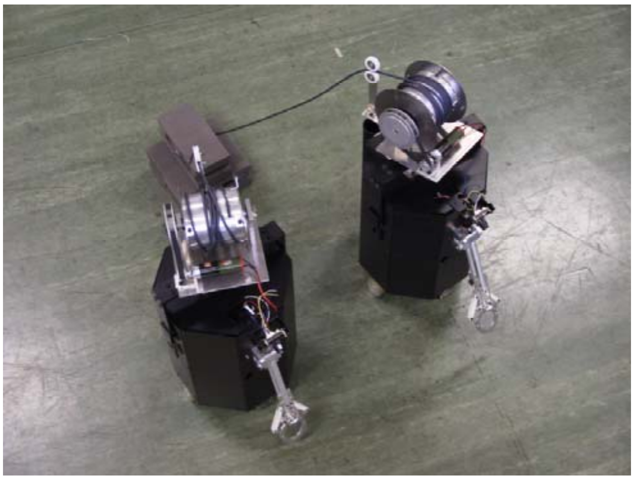


Figure 13 The mobile robots tugging an object with tethers

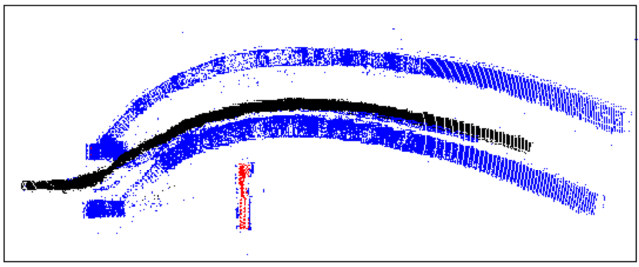


Figure 14 Trajectories of the two robots and the object

Vertical narrow rectangle in the figure denotes an obstacle.

6 Conclusions

Cooperative conveyance of two child robots with tethers was discussed. Three methods of cooperative conveyance were proposed and examined by computer simulations. Tethers were assumed to have constant force property that made robot control easy. To realize the control method, tether-winding unit was developed.

The simulation results showed that the method keeping a control point is the most reasonable among the three methods. Based on the simulation result, we implemented the performance using an actual robot system. The demonstration of the actual robot system successfully performed the conveyance of an object.

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References

1. Cao Y. U., Fukunaga A. S. and Kahng A. B.: Cooperative Mobile Robotics: Antecedents and Directions, Autonomous Robotics 4 :7-27, 1997
2. Arkin R. C., Behaivior-Based Robotics, The MIT Press, 1998
3. Takeda H. and Kosuge K.: Transporting a Single Object by Two Tracked Mobile Robots in Coordination Considering the External Force of an Object, *2001 JSME Conference on*

Robotics and Mechatronics 2P2-L7 in CD-ROM, 2001

4 . Miyata N., Motohashi M., Asama H., Kawabata K., Kaetsu H. and Kosuge K.: Cooperative Transport by Multiple Mobile Robots Involving Contacts with Surroundings, *2001 JSME Conference on Robotics and Mechatronics* 2P2-L5 in CD-ROM, 2001

5. Yamashita A., Sasaki J., Ota J. and Arai T.: Cooperative Manipulation of Objects by Multiple Mobile Robots with Tools, *Proceedings of the 4th Japan-France/2nd Asia-Europe Congress on Mechatronics* pp.310-315, 1998

6. Hirose S., Damoto R. and Kawakami A.: Study of Super-Mechano-Colony (Design of Experimental Model and Its Fundamental Experiments, *Proceedings on TITech COE/Super Mechano-Systems Symposium 2000,* pp.83-89,2000