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Cooperative Object Transportation Using Virtual Electric Dipole Field

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***Abstract*—This paper presents a new cooperative object transportation technique with obstacle avoidance. A key idea of proposed technique is to create a corridor around objects by lining up two rows using multiple robots. The multiple robots generate an extended corridor to a goal by following a unified field which consists of a virtual electric dipole field and potential fields. Two pusher robots push the object from behind and two leader robots in front of team lead the robot team to the goal. Simulation results are presented for verifying the proposed technique.**

***Index Terms*—object transportation, electric dipole field, obstacle avoidance, multi-robot team**

I. Introduction

Cooperative object transportation is a useful and valuable application in the robotics field. Initially, many researchers tried to solve the object transportation problem using a single robot [1]. However, it is difficult to transport a large object or multiple objects using a single robot. In addition, the object transportation is impossible if a robot has broken down, and a single robot should have all functions for object transportation, such as sensing, transportation technique, and precise control. Multiple robots, on the other hand, are able to transport large or multiple objects using cooperative control. Also, the object transportation can be succeeded when several robots are out of order because other robots can be substituted for the faulty robots. Each robot of multi-robot team has specialized woks, e.g., sensing robot, pusher robot, leader robot, which improves the efficiency of object transportation.

There are four major techniques in the cooperative object transportation methods: *grasping*, *pushing*, *caging*, and *tool-using*. First, multiple robots grasp an object using manipulators and then transport it to a goal, as shown Fig. 1(a) [2]. This technique enables to robust transportation, but a large or an irregular-shaped object cannot be transported because robots should tightly grasp an object in advance. Second, multiple robots manipulate an object using their bodies by pushing behavior, as shown in Fig. 1(b) [3]. Preliminary gripping action is unnecessary in the pushing technique, which enables robots to manipulate a large or an irregular-shaped object by simple actions. Third, multiple robots wrap and transport an object to a goal by maintaining a regular formation, as shown in Fig. 1(c) [4], [5]. This technique is based on a pushing behavior and transports an object by enclosing the object. However, this technique requires the caging identification, the positions of object and robots, and the shape of the object in real time. Lastly, there are tool-using techniques in the cooperative object transportation. Multiple robots can use diverse tools for transportation, such as a stick [6] or a rope [7], as shown in Fig. 1(d) and Fig. 1(e), respectively. Specialized tools are applied to facilitate transportation, which enables the robots to manipulate a large or multiple objects to a goal.

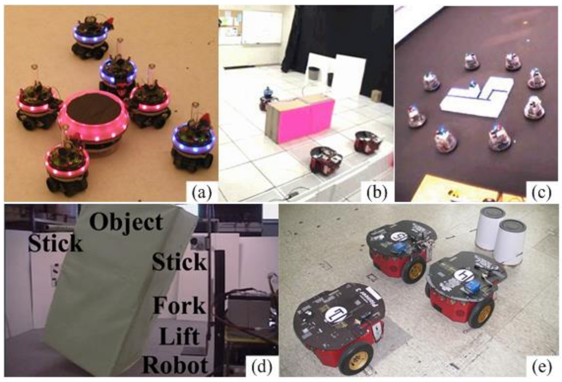

Figure 1. Various object transportation techniques. (a) Multiple robots grasp an object using a manipulator and transport it to a goal [2]. (b) Two robots push an object using their bodies for transportation [3]. (c) Multiple robots surround, enclose and transport an object by maintaining regular formation [5]. (d) Robots use a stick to transport an object by means of lifting behavior [6]. (e) Two robots tow multi-object using a rope and a leader robot lead the multi-robot team [7].

This paper presents cooperative multi-object transportation technique using a virtual electric dipole field and potential fields. Multiple robots create a corridor by lining up two rows and push the objects into the corridor to manipulate them to the goal. A virtual electric dipole field is applied to create the corridor and this field is modified by Potential Field Method (PFM) for obstacle avoidance [8].

II. Research Overview

The proposed multi-robot team consists of three different kinds of robots according to their functionality: *guide*, *leader* and *pusher* robots. The guide robots prevent the objects from escaping and transport the objects to the goal by lining up with two rows, as shown in Fig. 2. Some of the guide robots have other names: *head* and *tail* robot. The head and tail robots are located at the first and

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last line of each row, respectively. The tail robots in the two rows move to the head robots by following the unified field. Two rows are extended toward the goal by executing above processes iteratively until all objects arrive in the goal. The leader robots have a global path and order the head robots to create a unified field according to the global path. The pusher robots located between the tail robots push the objects from behind. Practical pushing forces are derived by the pusher robots.

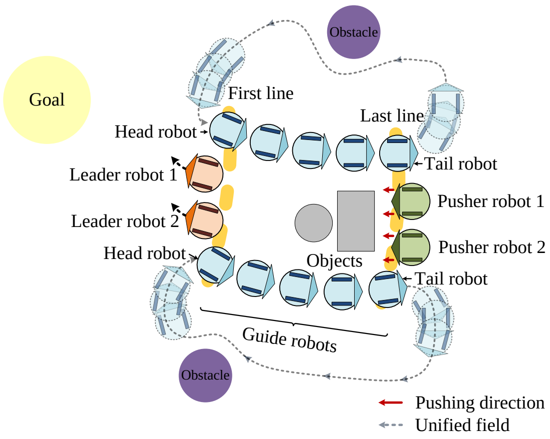

Figure 2. Conceptual description of multi-object transportation. Guide robots extend two rows toward the goal by following the unified field, two leader robots lead the multi-robot team according to the global path, and two pusher robots push the objects from behind.

III. The Generation of a Unified Field

A. Electric Dipole Field Generation

We adopt a virtual electric dipole field to generate the approaching path of the tail robot. In physics, the electric dipole field is created by positive and negative electric charges or opposite currents within spitting distance [9]. The simple inducement of electric dipole field is described as follows:

$$f^{ev}(x,y)=\begin{bmatrix}\mathrm{E}_x\\ \mathrm{E}_y\end{bmatrix}=-\cos\theta\times\begin{bmatrix}-\cos\theta\\ -\sin\theta\end{bmatrix}+\sin\theta\times\begin{bmatrix}-\sin\theta\\ -\cos\theta\end{bmatrix}=\begin{bmatrix}\cos 2\theta\\ \sin 2\theta\end{bmatrix} \quad (1)$$

where θ is the angle with respect to the origin which is the center of head robot.

B. Path Generation Using Phase Portraits

The electric dipole field generated in previous section is inappropriate when a successor robot is located immediately in front a predecessor robot, as shown in Fig. 3(c). In the extreme case, the successor robot should move infinitely long path because θ is $0°$ in (1): $f^{ev}(x,y)=[1,\ 0]^{\mathrm{T}}$. Thus, we adopt a new vector field which is based on the phase portraits with complex eigenvalues.

First, consider the linear time-invariant system [10] for generating the phase portraits:

$$\dot{x}=Ax \quad (2)$$

where A is 2×2 real matrix. The solution of (2) is as follow:

$$x(t)=Me^{J_r t}M^{-1}x(0) \quad (3)$$

where $x(0)$ is the initial state, J_r is the real Jordan form of A, and M is a real nonsingular matrix such that $M^{-1}AM=J_r$. The real Jordan form is described as follow when the eigenvalues of A are complex numbers:

$$J_r=\begin{bmatrix}\beta & -\gamma\\ \gamma & \beta\end{bmatrix} \quad (4)$$

where β and γ are a real and an imaginary number, respectively. Equation (3) is transformed to (5) when $z=M^{-1}x$:

$$\dot{z}_1=\beta z_1-\gamma z_2,\ \dot{z}_2=\gamma z_1+\beta z_2 \quad (5)$$

The shape of phase portraits by (5) is a circle or a spiral. We use two opposite directional circles to shorten the travel distance of robots. Fig. 3(a) shows clockwise circular fields when $\beta=0$ and $\gamma=-1$. In the clockwise circular field, we extract the vector field $f^{cw}(x,y)$ in the fourth quadrant region for turning to the right when the successor robot is located in the fourth quadrant region. In a similar manner, Fig. 3(b) shows counterclockwise circular fields when $\beta=0$ and $\gamma=1$. We extract the vector field $f^{ccw}(x,y)$ in the first quadrant region for turning to the left when the successor robot is located in the first quadrant.

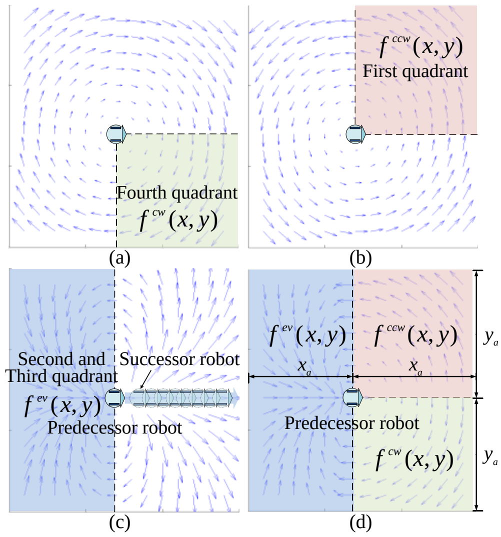

Figure 3. Unified field generation by combining the electric dipole field and the phase portraits. (a) Phase portrait with complex eigenvalues when $\beta=0$ and $\gamma=-1$. (b) Phase portrait with complex eigenvalues when $\beta=0$ and $\gamma=1$. (c) In the electric dipole field, a successor robot should move infinitely long path when the successor robot is located in front of a predecessor robot. (d) A total vector field by combining the electric dipole field and phase portraits with complex eigenvalues.

Lastly, we combine the electric dipole field by (1) and two opposite directional phase portraits by (5), as shown in Fig. 3(d). The only second and third quadrant regions in the electric dipole field are used for the path generation.

C. Potential Field Generation for Obstacle Avoidance

We modify the unified field which is generated in the section B for obstacle avoidance [6]. Repulsive forces are generated around the static obstacles. The magnitude of the repulsive force by obstacle is given by:

$$F_i^{so}(x,y) = \eta / \{(x-x_i)^2 + (y-y_i)^2\} \quad (6)$$

where (x_i , y_i) is the position of i^{th} obstacle and η is a positive constant value. The angle of the repulsive force by i^{th} obstacle is described by:

$$\theta_i^{so} = \tan^{-1}((y_i - y)/(x_i - x)) \quad (7)$$

Thus, repulsive force f_i^{so} by i^{th} obstacle is described by:

$$f_i^{so}(x,y) = [F_i^{so}\cos\theta_i^{so} \quad F_i^{so}\sin\theta_i^{so}]^{\mathrm{T}} \quad (8)$$

If the number of static obstacles is n, total repulsive force f^{so} by all static obstacles is described by:

$$f^{so}(x,y) = \sum_i^n f_i^{so}(x,y) \quad (9)$$

Finally, a modified vector field f^{uv} which is combined with the unified field and the repulsive force by static obstacles is described by:

$$f^{uv}(x,y) = f^{e}(x,y) + f^{SO}(x,y) \quad (10)$$

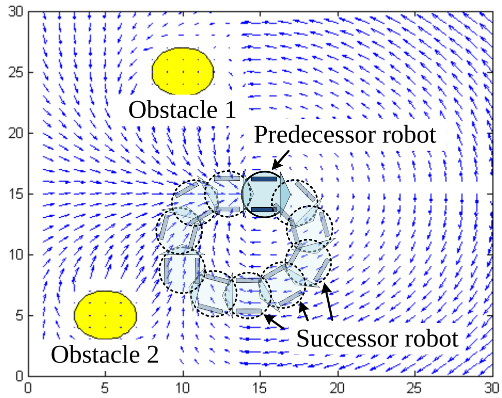

Figure 4. A unified vector field by two static obstacles. The two obstacles generate repulsive force, which lead to modify the original electric dipole field.

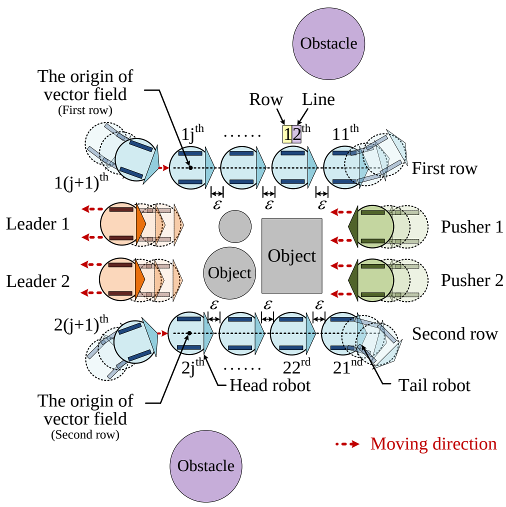

Figure 5. Multi-object transportation process

Fig. 4 shows the modified vector field which is generated by f^{uv}. Two static obstacles are located at (5, 5) cm and (10, 25) cm, and they radiate the repulsive forces. The repulsive force modifies the neighboring fields of static obstacles.

IV. Cooperative Object Transportation Process

Fig. 5 shows the proposed object transportation process. First, two head robots in each row generate modified vector fields f^{uv}, and then two tail robots in each row follow the modified vector fields, respectively. Second, two pusher robots begin to push the objects when the tail robots begin to start. If $(x_{p,k}, y_{p,k})$ is the position of k^{th} pusher robot and n_p is the number of pusher robots, the desired position of k^{th} pusher robot is given by:

$$\begin{bmatrix} x_{p,k} \\ y_{p,k} \end{bmatrix} = \frac{1}{n_p+1}\begin{bmatrix} (n_p-k+1)x_2^{tail} + kx_1^{tail} \\ (n_p-k+1)y_2^{tail} + ky_1^{tail} \end{bmatrix} \quad (11)$$

where (x_1^{tail}, y_1^{tail}) and (x_2^{tail}, y_2^{tail}) are the positions of tail robots, respectively. The pusher robots use attractive force to approach the desired positions (11). The magnitude of attractive force $F_{p,k}^{att}$ is described by:

$$F_{p,k}^{att}(x,y) = -\xi\{(x-x_{p,k})^2 + (y-y_{p,k})^2\} \quad (12)$$

where ξ is positive constant. The angle of attractive force $\theta_{p,k}$ is $\tan^{-1}((y_{p,k}-y)/(x_{p,k}-x))$. Therefore, the attractive force of pusher robot is given by:

$$f_{p,k}^{att}(x,y) = [|F_{p,k}^{att}|\cos\theta_{p,k}^{att} \quad |F_{p,k}^{att}|\sin\theta_{p,k}^{att}]^{\mathrm{T}} \quad (13)$$

When $f_{p,k}^{rep}$ is generated by combining the repulsive forces of other robots and obstacles, the controller of k^{th} pusher robot is $u_{p,k}(x,y) = f_{p,k}^{att}(x,y) + f_{p,k}^{rep}(x,y)$.

The leader robots are analogous to the pusher robots except departure time. The leader robots in two rows begin to move when the tail robots arrived in the head robots, respectively. The desired position of k^{th} leader robot is given by:

$$\begin{bmatrix} x_{l,k} \\ y_{l,k} \end{bmatrix} = \frac{1}{n_l+1}\begin{bmatrix} (n_l-k+1)x_2^{head} + kx_1^{head} \\ (n_l-k+1)y_2^{head} + ky_1^{head} \end{bmatrix} \quad (14)$$

where (x_1^{head}, y_1^{head}) and (x_2^{head}, y_2^{head}) are the positions of head robots, respectively. The controller of k^{th} leader robot is $u_{l,k}(x,y) = f_{l,k}^{att}(x,y) + f_{l,k}^{rep}(x,y)$. Finally, we repeat above processes until all objects are located in the goal.

V. Simulation Results

We conducted simulations to verify the proposed technique. Our simulation tool is MATLAB 2013a with Intel Core-i5 processor. The proposed multi-robot team consists of 18 guide robots, two leader robots, and two pusher robots. All robots have identical radii, which is 10 cm. The radii of two objects which were manipulated by the multi-robot team are 30 cm and 10 cm, respectively. The velocities of pusher and guide robots are 13 cm/s and 50 cm/s, respectively. Fig. 6 shows simulation results of proposed technique. When static obstacles are obstructing the path of guide robots, the leader robots order the head robots to create a modified vector field which is generated by considering the static obstacles. By applying the field generation, the tail robots could avoid upper obstacle at 13 seconds. Two pusher robots pushed the objects from behind by keeping step with the movement of guide robots. Total travelled time was 45 seconds, and two objects were successfully manipulated by the proposed technique without collision.

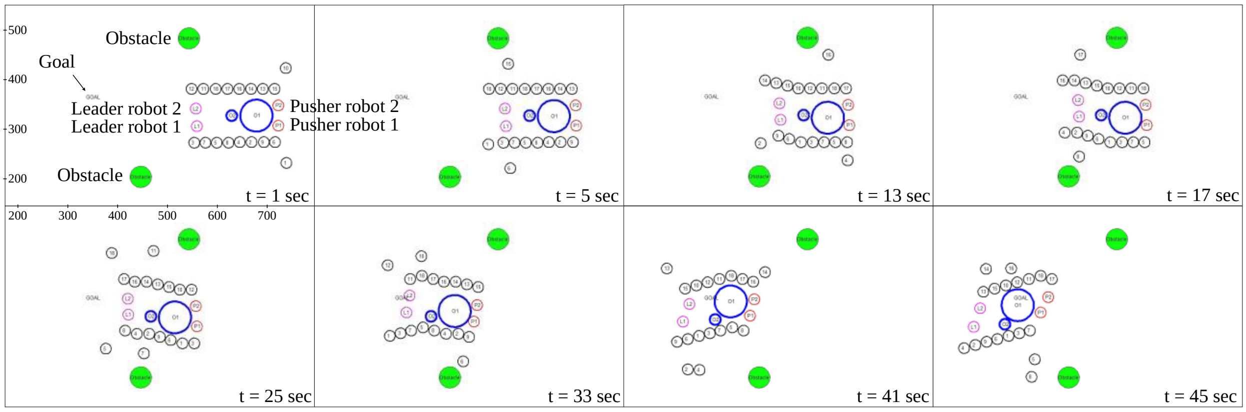

Figure 6. Simulation results of proposed technique

VI. CONCLUSIONS

This paper proposed a cooperative multi-object transportation technique with obstacle avoidance. The geometrical information of objects, e.g., shape or position, is unnecessary in the proposed technique. Also, the equipped tools for transporting the objects, e.g., a manipulator or a rope, are unnecessary. Two different sized objects are manipulated to a goal successfully by the coordination of multiple robots. The proposed technique can be applied to diverse areas, such as foraging and automatic transportation system.

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