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Obstacle Avoidance by a Hyperelliptic Potential and a Virtual Spring Method for Omnidirectional Cooperative Transportations

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Abstract—**Robots can be expected to make our work efficient by covering transportation tasks in factories and warehouses. However, it is not easy to transport a long object in a narrow space. In our previous research, an omnidirectional cooperative transportation system was developed to transport a long-sized object with two lift-up robots. Then, an obstacle avoidance method was implemented with a virtual spring method when passing through a narrow space, so as to realize transportation even though some uncertainties are included in the prior map and localization. However, the model of the repulsion acted between the robot and the obstacle is not considered the shape of the carrying object. If the shape of the transported object is can be represented by a simple mathematical formula, such as a point or a circle, the robot can easily calculate the distance of the transported object and obstacles. However, the long rectangular object can't be easily modeled. In this research, the shape of the transported object is modeled by the hyperellipsoidal approximation. Then, obstacle avoidances in the narrow space are realized by using repulsion with hyper-elliptic potential. The path to be followed is totally generated by the hyperelliptic potential and the virtual spring potential to obtain an efficient and shorter path. Finally, the usefulness of the proposed method is confirmed through some simulations by omnidirectional cooperative transportations of the long rectangular object in the narrow space.**

Index Terms—**Hyperelliptic potential, cooperative transportation, obstacle avoidance.**

I. INTRODUCTION

Introducing multiple robots in a transportation task in factories and warehouses can be expected to make our work efficient, because many objects can be transported simultaneously. Since there are various sizes of objects in factories and warehouses, a transportation robot is required to cope with any size of objects. One of the methods for solving this problem is to use a large-sized robot. Enlarging a transportation robot can deal with any objects in size. Note however that there arises the problem that the robot cannot run in a pathway narrower than its width. As an alternative solution, there exists a cooperative transportation in which one object is transported by multiple small-sized robots. It can cope with different-sized objects by changing the number of the transportation robots, depending on the size of the object. Because of making robots small-sized, it can run a narrower pathway. In addition, the work shared by multiple robots can be expected to shorten the working time because it can transport a number of objects at a time. Extensive environmental information can also be acquired by sharing the information on the sensors attached on each robot.

Fujii et al. [1] used a virtual spring method, among path optimization methods, for a nonholonomic mobile robot. After defining three virtual spring models in this method, the obstacle avoidance was realized by minimizing the total sum of potentials of these virtual springs. Motoyashiki et al. [2] built an omnidirectional cooperative transportation system that transports an object to a target position with two lift-up robots, without resorting to any human helps. This obstacle avoidance method extended the virtual spring method used in Fujii et al. to the omnidirectional cooperative transportation passing through a narrow space, when judging any collisions to obstacles due to some uncertainties included in the map and localization given in advance. However, a compression spring to split the robots from the obstacle did not considered the shape of a carried object.

If the carried object is assumed to be rectangular, then it can be approximated by a hyperelliptic curve [3]. Endo et al. [4] avoided the collision between robots by making a global path with a discretized Laplacian potential field and generating a repulsive potential field with a hyperelliptic curve for approximating the robot shape. In this paper, adjacent pathway points, generated by a global path planning in advance, are connected with flexible springs, according to the virtual spring method. In particular, a repulsive force from obstacles is modelled with a hyperelliptic potential, through approximating the shape of a carried object with a hyperelliptic curve. Then, an obstacle avoidance that takes into account the shape of the carried object is realized by a repulsive force is generated by a hyperelliptic potential, instead of using a compressive spring. The usefulness of the proposed method is also confirmed

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through simulations by the omnidirectional cooperative transportation of a rectangular object in a narrow space.

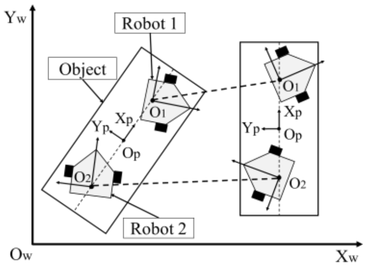


Fig. 1. Omnidirectional cooperative transportation

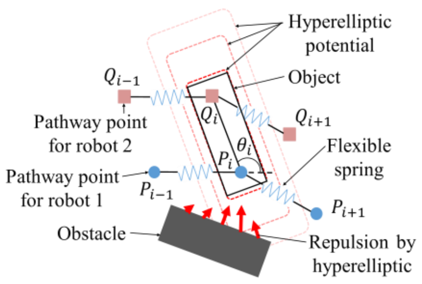


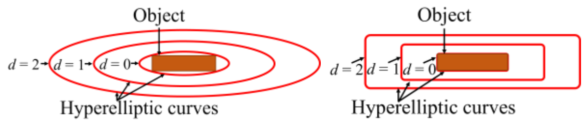
Fig. 2. Model of pathway optimization

II. Omnidirectional Cooperative Transportation

Fig.1 shows the movement of the omnidirectional cooperative transportation. Combining two transportation robots, one of which has an offset from the axel of driving wheels, performing a cooperative transportation that regards the support positions O1 and O2 as the controlled points, it can freely control two support positions of the object [5]. Therefore, two robots can arbitrarily decide the position and attitude of the object. When a moving path of the robot is set as the point sequence that is generated by a global path planned in advance, two robots can transport the object arbitrarily, deciding the position and attitude of the object during the transportation. However, the object may fall down from the robot, if the distance between the robots, which is determined by the supporting positions of the object, is changed greatly. Therefore, the distance between two robots has to be kept constant.

III. Obstacle Avoidance Method

When the robot transports the object by the path generated from the pre-map, the carried object may collide with an obstacle by the inaccurate localization, which is due to an inaccurate pre-map and the accumulation of the locomotion errors. In this research, the robots avoid obstacles by an obstacle avoidance method. This method adjusts the preplanned pathway points in accordance with the obstacles, so as to make a safe transportation without any collisions. Fig. 2 shows the schematic model of our proposed path optimization method, where the obstacle avoidance is performed by adjusting the pathway points using the hyperelliptic potential and the flexible spring potential.



(a) $n = 1$ (b) $n = 10$

Fig. 3. Effect of n in hyperelliptic curves

A. Calculation of Repulsion by Hyperelliptic Potential

The hyperelliptic potential is used to give the robots the repulsion acted between the robots and the obstacles, so that the initial path determined in advance is adjusted to a new path that does not collide with the obstacles.

1) *Distance Between Object and Obstacle:* The obstacle avoidance that takes into account the distance between the carried object and the obstacle is realized under considering the object shape. If the object shape can be represented by a simple equation, such as a circle, an ellipse, etc., then the robot can easily calculate the distance between the object and the obstacle. However, the distance between the object and the obstacle cannot be simply calculated because the rectangle to be considered is represented by multiple equations. Therefore, a hyperelliptic curve is adopted because it is approximately similar to a rectangle. The hyperelliptic curve is represented by:

$$\left(\frac{x}{a}\right)^{2n} + \left(\frac{y}{b}\right)^{2n} = 1 \tag{1}$$

with

$$a = \frac{L}{2}\left(2^{\frac{1}{2n}}\right),\ b = \frac{H}{2}\left(2^{\frac{1}{2n}}\right) \tag{2}$$

where (x, y) denotes the position of the obstacle obtained from the laser range scanners on the global coordinate system, L is the lateral length of a rectangle, H is the vertical length, and n is the coefficient to decide the shape of the hyperelliptic curve. Fig. 3 shows the various shapes of the hyperelliptic curve when the value of n is changed. Fig. 3(a) shows the shape of the hyperelliptic curve when $n = 1$, whereas Fig. 3(b) shows it when $n = 10$. The hyperelliptic curve approaches the shape of a rectangle with the increase in n. Therefore, considering the distance between the obstacle and the hyperelliptic curve that approximates the shape of a rectangular object, the distance d between the object and the obstacle can be represented by:

$$d = \left[\left(\frac{x}{a}\right)^{2n} + \left(\frac{y}{b}\right)^{2n}\right]^{\frac{1}{2n}} - 1 \tag{3}$$

2) *Strength of Hyperelliptic Potential:* As the distance between the object and the obstacle becomes shorter, the

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strength of the hyperelliptic potential becomes larger, whereas, as the distance between the object and the obstacle becomes

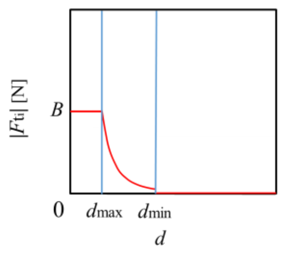

Fig. 4. Repulsion of the obstacle avoidance

longer, the strength of the hyperelliptic potential becomes smaller. The repulsion F_{ti} due to the strength of the hyperelliptic potential is represented by:

$$|F_{ti}| = \begin{cases} \dfrac{B}{d_{max}^3} & (d < d_{max}) \\ \dfrac{B}{d^3} & (d_{max} \le d \le d_{min}) \\ 0 & (d_{min} < d) \end{cases} \tag{4}$$

where B is the coefficient to control the maximum repulsion, d_{max} is the coefficient to determine the value of the distance d that makes F_{ti} a maximum value, and d_{min} is the coefficient to determine the value of the distance d that makes F_{ti} a minimum value, 0. The d_{max} is the upper bound of the range with a maximum repulsion, and the d_{min} is the lower bound of the range to remove an obstacle far from the repulsion F_{ti}. The relationship between the distance d and the repulsion F_{ti} is graphically shown in Fig. 4. Thus, if the distance between the carried objet and the obstacle becomes shorter than d_{min}, then the repulsion acts on the object.

3) *Direction of Hyperelliptic Potential:* The repulsion acting on the robot from the point sequence of the obstacle obtained with the laser range scanners is calculated by decomposing the repulsion acting toward the gradient of the hyperelliptic potential from the obstacle. The repulsion vector $\boldsymbol{F}_{\boldsymbol{d}i}$ acting toward the gradient of the hyperelliptic potential from the obstacle is represented by:

$$\boldsymbol{F}_{\boldsymbol{di}} = -\nabla \boldsymbol{F}(x, y)|F_{ti}| \tag{5}$$

where F (x, y) is given by the hyperelliptic curve in Eq. (1). Then, the repulsion acting toward the gradient of the hyperelliptic potential from the obstacle is decomposed into the direction of each robot. When multiple obstacles are measured and the number of the point sequences is biased, the robot behavior becomes large if the total sum of the repulsion is directly applied to the pathway points. The total sum of the repulsion is normalized by dividing it with the total number of the detected obstacle points. The normalized repulsion can overcome the collision of the robot to the obstacle, together with preventing the carried object from falling down.

B. Correction of Pathway Points by the Potential of Flexible Spring

The potential of the flexible spring, *Ui* to adjust the position of the pathway points is represented by:

$$U_i = \frac{1}{2} k_i (l_i - l_0) \tag{6}$$

where k_i is the spring constant for the pre- and post-pathway points, l_i is the distance between adjacent pathway points, and l_0 is the distance between adjacent pre-planned pathway points.

1) *Optimization by Newton's Method:* Each potential is described by a function of the pathway point. The path optimization can be dealt as a potential minimization problem, in which the start position and the goal position are set as the fixed ends. The Newton's method is used to obtain the correction amount of the pathway points that minimizes the flexible spring potential. Consider minimizing the potential U_i of a flexible spring between the i-th pathway point P_i and the (i+1)-th pathway point P_{i+1}. By substituting the distance l_i between two pathway points P_i and P_{i+1} for Eq. (6), the new pathway point P_{new} based on using the Newton's method is calculated by:

$$P_{new} = P_{old} - \boldsymbol{H}^{-1} \nabla \boldsymbol{U}_i + \boldsymbol{F}_{\boldsymbol{dt}} \tag{7}$$

where P_{old} is the coordinate vector at the pre-update pathway point P_i, $\boldsymbol{H}^{1}$ and $\nabla \boldsymbol{U}_i$ are the Hessian matrix and partial differentiation of U_i with respect to x_{pi} and y_{pi}, and $\boldsymbol{F}_{\boldsymbol{dt}}$ is the normalized repulsion. The new pathway point P_{new} that minimizes U_i is obtained from the repetitive calculation of Eq. (7).

2) *Application to Cooperative Transportations:* The cooperative transportation needs to keep the distance between the robots constant, to overcome a situation where the carried object falls down from the robots. Defining the pathway points of the first and second robots on the global coordinate are set as $P_i(x_{pi}, y_{pi})$ and $Q_i(x_{qi}, y_{qi})$ respectively, the positional relationship between both robots can be represented by:

$$\begin{aligned} x_{qi} &= x_{pi} + C\cos\theta \\ y_{qi} &= y_{pi} + C\sin\theta \end{aligned} \tag{8}$$

where C denotes the distance between the robots, and θ is the angle between the line parallel to the X-axis in the global coordinate system and the line connecting P_i and Q_i. Substituting the distance l_i between the pathway point Q_i and its next pathway point for Eq. (6), the new angle θ_{new} using the Newton's method is calculated by:

$$\theta_{new} = \theta_{old} - \frac{U_i'(\theta_{old})}{U_i''(\theta_{old})} \tag{9}$$

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where θ_{old} denotes the pre-update angle θ as used in Eq. (8). The new angle θ_{new} that minimizes U_i is obtained from the repetitive calculation of Eq. (9). The new pathway point for

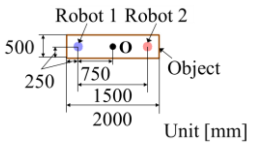


Fig. 5. Layout of a carried object and robots in simulation

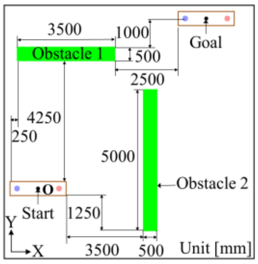
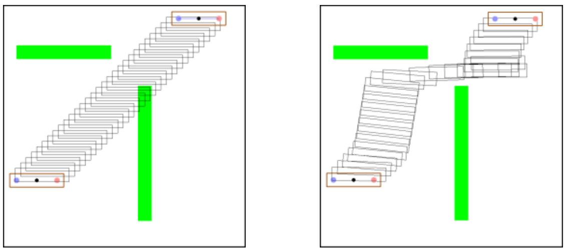


Fig. 6. Start, goal and obstacles in simulation



(a) Preplanned path (b) Planned path with the proposed method

Fig. 7. Simulation results of obstacle avoidance

the second robot is calculated by substituting the new angle θ_{new} for the angle θ in Eq. (8).

IV. Simulation Studies

The usefulness of the proposed obstacle avoidance method is confirmed through a simulation by conducting the omnidirectional cooperative transportation of a rectangular object at a narrow space.

A. Experimental Condition

In this simulation, a laser range scanner is mounted on the center of the robots, where the scanning angle is 360 [deg], the angular resolution is 0.36 [deg], and the maximum distance is 4000 [mm]. The working space of the simulation is 9000 [mm] in length and 9000 [mm] in width. The carried object and the robots are shown in Fig. 5. The environment for the simulation is shown in Fig. 6. The robot transports the object from the starting position (0 [mm], 0 [mm]) set as the origin O to the target position (6000 [mm], 6000 [mm]). It is known that in the simulation, the object collides with an obstacle during the transportation, if it is subjected to the preplanned pathway points. Therefore, the robots avoid an obstacle detected by a laser range finder using the proposed obstacle avoidance method, which is based on a hyperelliptic potential. The number of the pathway points is set to 30, and the number of iterations for the Newton's method is set to 30 per each pathway point. The coefficients of the hyperelliptic potential and the flexible spring potential are set to n=10, B= 20, d_{max} = 1, d_{min} = 1.25, and k_i = 3.

B. Simulation Results

Fig. 7(a) shows the trajectory associated to the carried object, without using any obstacle avoidance method. Fig. 7(b) shows the trajectory associated to the carried object, using the obstacle avoidance method proposed here. Comparing Fig. 7(a) with Fig. 7(b), it is found that the object can be transported from the initial position to the target position, without any collisions to the obstacles, by using the proposed obstacle avoidance method. This simulation proves that the proposed obstacle avoidance method is useful in the narrow space under the condition of suitable coefficients.

V. Conclusion

In this paper, a method has been described for the omnidirectional cooperative transportation, where two robots, each of which has an offset from the axel of driving wheels, were used. In addition, an obstacle avoidance method was proposed using the hyperelliptic potential and the flexible spring potential. A simulation experiment, in the case where the omnidirectional cooperative transportation was applied to a rectangular object at a narrow space, was conducted to check the usefulness of the proposed obstacle avoidance method due to a hyperelliptic potential. Simulation results showed that the proposed obstacle avoidances method was useful in the narrow space under the condition of suitable coefficients. Note however that it is not easy to determine a combination of suitable coefficients. Since the coefficients have many combinations, the robot collided with the obstacle, if unsuitable combinations were adopted. For future work, an obstacle avoidance system will be constructed so as to adjust each coefficient of the proposed obstacle avoidances method suitably, depending on the environment under transportation.

References

[1] A. Fujii, M. Tanaka, N. Nagasaka, Y. Takaoka, and T. Yamamoto, “Navigation in narrow spaces for human support robot,” Journal of the Robotics Society of Japan, vol. 32, no. 7, pp. 586–594, September 2014 (in Japanese).

[2] Y. Motoyashiki, S. Maeyama, and K. Watanabe, “Cooperative transportation by two mobile robots with lift-up mechanism,” in Proc. of The Japan Society of Mechanical Engineers Chugoku–Shikoku Branch, February 2015, 902(1)–(2) (in Japanese).

[3] J.–C. Latombe, "Potential field methods" in Robot Motion Planning, MA: Kluwer Academic Publishers, 1996, pp. 334–340.

[4] M. Endo, K. Hirose, K. Kosuge, K. Suzuki, K. Murakami, K. Nakamura, M. Nakanishi, and T. Kanbayashi, “A car transportation system using multiple coordinated robots: iCART (3rd Report, Trajectory generation for robots),” Trans. of The Japan Society of Mechanical Engineers, Series C, vol. 76, no. 763, pp. 627–634, March 2010 (in Japanese).

[5] M. Nukii, S. Maeyama, and K. Watanabe, “Cooperative transportation of large objects by multiple mobile robots with lift up mechanism,” in Proc. of The Japan Society of Mechanical Engineers Conference on Robotics and Mechatronics, May 2012, 1A2–T04(1)–(4) (in Japanes