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Escaping Route Method for a Trap Situation in Local Path Planning

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Abstract: This paper introduces a new framework for escaping from a local minimum in path planning based on artificial potential functions (APFs). In particular, this paper presents a set of analytical guidelines for designing potential functions to avoid local minima in a trap situation (in this case, the robot is trapped in a local minimum by the potential of obstacles). The virtual escaping route method is proposed to allow a robot to escape from a local minimum in a trap situation where the total forces are composed of repulsive forces by obstacles and attractive force by a goal are zero. The example results show that the proposed scheme can effectively construct a path planning system with the capability of reaching a goal and avoiding obstacles, despite a trapped situation under possible local minima.

Keywords: Local minimum, narrow passage, path planning, potential function.

1. INTRODUCTION

Compared with extensive studies focused on the derivation of optimal potential field functions and their applications, very few attempts have been made regarding the proposition of analytical design guidelines to identify a local minimum situation and have a robot escape from the local minimum. By such a motivation, our attention is focused on the escaping method that enables a robot to escape from such a local minimum in path planning problems. Differing from previous studies on local path planning based on APFs [1-4,18], the purpose of this study is to explore path planning design for identifying a local minima situation and then having a robot escape from the local minima.

Most artificial potential fields defined by different potential functions have a drawback called "local minima" which arise due to the special configuration of obstacles and the goal. This problem has been alleviated by: 1) the redefinition of potential functions with no or a few local minima; and 2) the utilization of efficient search techniques with the capability of escaping from a local minimum. The first class of treatment includes: repulsive potential functions with angle distributions [5], the navigation function [6,7] and harmonic potential field [8]. However, these solutions are limited to simple or conservatively bounded obstacles such that a considerable portion of the workspace might be ignored. Connoly *et al*. [9] and Akishita *et al.* [10] developed a global method based on harmonic functions for path planning to generate a smooth, collision-free path. It offers a complete path planning algorithm and paths derived from them are generally smooth. However, harmonic potential also has its drawbacks. The magnitude of grid division affects the precision of path planning directly. When grid size is large, planning time is decreased. When grid size is small, the capability of path finding is improved. However, the planning time is increased [8,11].

The second class of treatments employs a trap state detection and then an escaping method. In [12] we presented a comprehensive set of heuristic rules to recover from a different trap condition. However, it did not consider all trap conditions or the fact that a robot can be trapped in many different situations. When a robot is trapped in a local minimum, the simulated annealing is applied in order that the robot can escape from a local minimum [13]. In [13], in particular, the path planning methods that integrate the simulated annealing approach into artificial potential field path planning was proposed. This method provides the capability of escaping from any possible local minimum. However, the simulated annealing generally requires a large amount of running time, although this is no guarantee good results might will be obtained. Thus, it seems to be unsuitable for local path planning.

In this paper, as an extension of paper [14] by the same authors, we present a framework for path planning under a trap situation (in which the robot is trapped in a local minimum by the potential of obstacles). An attempt to deal with theoretical treatments for designing potential functions to avoid local minima in a trap situation is madden, which is the first analysis. The virtual escaping route method is proposed to overcome trap situations where the total forces composed of repulsive forces by obstacles and attractive force by a goal are zero.

2. PREVIOUS PROPOSED PATH PLANNING [14]

Before we describe artificial potential fields, a relative position vector between the robot and the goal is defined as

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$$\psi^g = \mathbf{P} - \mathbf{P}_{goal}, \tag{1}$$

where $\mathbf{P}$ and $\mathbf{P}_{goal}$ are the robot and goal positions. Attraction towards the goal is modeled by an attractive field, which in the absence of obstacles draws the charged robot towards the goal. The simple APFs for goal destination are modeled as follows.

$$U^g = c_g(1 - e^{-\frac{\|\psi^g\|^2}{l_g^2}}), \tag{2}$$

where c_g and l_g are the strength and correlation distance for goal destination. The first term c_g in the right side of (2) acts to make U^g zero when $\psi^g = 0$. Its corresponding force is then given by the negative gradient of (2).

$$F^g = -\nabla U^g = -\frac{2c_g\psi^g}{l_g^2} e^{-\frac{\|\psi^g\|^2}{l_g^2}}. \tag{3}$$

Relative position vectors between the robots and the obstacles are defined as

$$\psi_j^o = \mathbf{P} - \mathbf{O}_j, \tag{4}$$

where $\mathbf{O}_j$ is the position of obstacle j which is a neighbor of the robot. Collisions between the obstacles and the robot are avoided by the repulsive force between them, which is simply the negative gradient of the potential field. We employ the algorithm that prevents collisions with obstacles by calculating the repulsive potential, based on the shortest route to an object. The simple APFs for obstacle avoidance are modeled as follows.

$$U^o = \sum_{j \in N_o} \{c_o e^{-\frac{\|\psi_j^o\|^2}{l_o^2}}\}, \tag{5}$$

where c_o and l_o are the strength and correlation distance for obstacle avoidance. N_o denotes the set of indexes of those obstacles in the robot's vicinity. Its corresponding force is then given by the negative gradient of (5).

$$F^o = -\nabla U^o = \sum_{j \in N_o} \{\frac{2c_o\psi_j^o}{l_o^2} e^{-\frac{\|\psi_j^o\|^2}{l_o^2}}\}. \tag{6}$$

The following configuration for total potential is proposed to overcome such local minimum problems by the authors in [5] and, [14]. The total potential has a multiplicative and additive structure between the potential for goal destination and the potential for obstacle avoidance.

$$\begin{aligned} U^{ogg} &= \frac{1}{c_g} U^o \cdot U^g + U^g \\ &= \sum_{j \in N_o} \{c_o e^{-\frac{\|\psi_j^o\|^2}{l_o^2}}\}(1 - e^{-\frac{\|\psi^g\|^2}{l_g^2}}) - c_g e^{-\frac{\|\psi^g\|^2}{l_g^2}} + c_g. \end{aligned} \tag{7}$$

Its corresponding force is

$$\begin{aligned} F^{ogg} &= -\nabla U^{ogg} \\ &= \sum_{j \in N_o} \{\frac{2c_o\psi_j^o}{l_o^2} e^{-\frac{\|\psi_j^o\|^2}{l_o^2}}\}(1 - e^{-\frac{\|\psi^g\|^2}{l_g^2}}) \\ &+ \sum_{j \in N_o} \{c_o e^{-\frac{\|\psi_j^o\|^2}{l_o^2}}\}(-\frac{2\psi^g}{l_g^2} e^{-\frac{\|\psi^g\|^2}{l_g^2}}) \\ &- \frac{2c_g\psi^g}{l_g^2} e^{-\frac{\|\psi^g\|^2}{l_g^2}}. \end{aligned} \tag{8}$$

As for the mathematical analysis of the above case, see paper [14] proposed by the authors where it is proven that the proposed configuration of APFs is effective. Next, we consider a trap situation that can be caused in a narrow passage problem in [14] and other possible scenarios, and then analyze how to design APFs' parameters to overcome such problems.

The next section is the most contributive part in this paper where a local minimum is identified by specific conditions and a trapped robot can escape from it through a virtual escape route.

3. DESIGN OF APFS FOR A TRAP SITUATION

The proposed configuration for potential functions (7) alleviates the non-reachable or narrow passage region overwhelmed by the potential of obstacles to some extent as shown in [14]. However, a robot in the proposed configuration may get trapped in a local minimum (as is the case with other local path planners). While it is possible to devise a set of heuristic rules that would guide the robot out of trap situations and resolve *cyclic behavior* [12], the resulting path is still not satisfactory. In [15], it was reported that a sequence of basic behavior such as random wandering, obstacle avoidance and light following was able to coordinate a single robot to achieve more complicated behaviors using the potential function field of an oscillator.

However, these behavior-based computational organizations lack insightful comprehension of the problems and sometimes exhibit unpredicted and undesirable performances. It takes a great deal of time to train for the selection of proper parameter values in different working environments [15]. It seems neither approach presents a universal solution to ensure the robot can escape from trap situations.

To resolve the problem, we propose *the virtual escaping route* which allows a robot to escape from a local minimum in a trap situation where the total forces composed of repulsive forces by obstacles and attractive

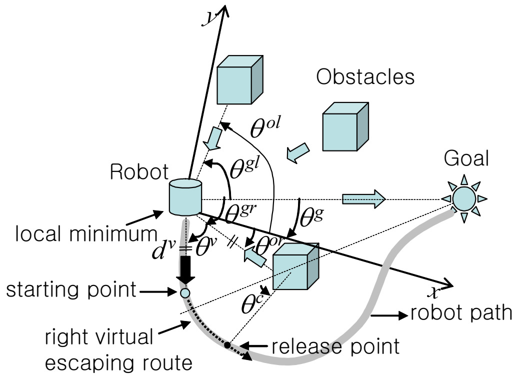

Fig. 1. virtual escaping route.

force by a goal are zero. Fig. 1 shows a situation where a robot is trapped in a local minimum by repulsive force from three obstacles and attractive force from the goal. A local minimum is identified when the following four conditions are satisfied;

$$
\begin{aligned}
&| F^{ogg} | < a_1, \\
&| \theta^g - \sum_{j \in N'_o} \theta_j^o | < a_2, \\
&| \psi^g | > a_3, \\
&| \mathbf{P}(k) - \mathbf{P}(k-1) | < a_4,
\end{aligned} \tag{9}
$$

where θ^g is the angle between a robot and a goal, and θ_j^o is the angle between a robot and each obstacle. N'_o denotes the set of indexes of those obstacles which trap the robot and can be identified as obstacles satisfying $|\psi_j^o| < a_5 l_o$ where a_5 is a positive constant. θ^{ol} and θ^{or} are angles between a robot and the nearest obstacle from the robot located in the left and right sides from the robot's view, respectively, as shown in Fig. 1. $\theta^{gl} = \theta_j^{ol} - \theta^g$, and $\theta^{gr} = \theta_j^{or} - \theta^g$.

The first condition of (9) is used for checking if the total forces (8) composed of repulsive forces by obstacles and an attractive force by a goal are zero. Thus, a_1 is chosen as a positive constant close to zero. In order to check whether a robot stays at a narrow passage occurred by two or more obstacles, the second condition of (9) is used. For that reason, a_2 is chosen as a positive degree close to zero. The third condition of (9) is used for checking if a robot arrives at a goal, since $|\psi^g|$ is a relative distance between the robot and goal. In order to check if a robot stays in the same place, the forth condition of (9) is used. Therefore, if the robot is trapped in a local minimum, $|\mathbf{P}(k) - \mathbf{P}(k-1)| = 0$. For this reason, a_3 and a_4 are chosen as positive constants close to zero. The reason why such parameters are not zeros but positive constants close to zero is due to the inaccuracy of numerical calculation. Note that a local minimum is identified when the above four conditions are all satisfied.

If a robot satisfies four of the conditions in (9), the robot chooses a left or right route according to $min(\psi^{gol}, \psi^{gor})$ where ψ^{gol} and ψ^{gor} are the distance between the goal and the nearest obstacle in the left and right sides from the robot's view, respectively. $\psi^{gol} = \sqrt{(\psi^g - \psi^{ol} cos\theta_j^o)^2 + (\psi^{ol} sin\theta_j^o)^2}$ and $\psi^{gor} = \sqrt{(\psi^g - \psi^{or} cos\theta_j^o)^2 + (\psi^{or} sin\theta_j^o)^2}$ where ψ^{ol} and ψ^{or} are the distance between a robot and the nearest obstacle in the left and right sides from a view of the robot, respectively. The obstacle chosen according to $min(\psi^{gol}, \psi^{gor})$ is denoted as $\mathbf{O}_e$. In Fig. 1, the robot chooses the right path due to $\psi^{gor} < \psi^{gol}$.

Before we describe a virtual escaping route, the relative position vector between a robot and the nearest obstacle that traps the robot is defined as

$$\psi_e^o = \mathbf{P} - \mathbf{O}_e, \tag{10}$$

where $\mathbf{O}_e$ is a position of the obstacle that traps the robot and is the closest to the goal. The simple APF for $\mathbf{O}_e$ is modeled as follows.

$$U^e = c_o e^{-\frac{\|\psi_e^o\|^2}{l_o^2}}. \tag{11}$$

Its corresponding force is then given by the negative gradient of (11).

$$F^e = -\nabla U^e = \frac{2 c_o \psi_e^o}{l_o^2} e^{-\frac{\|\psi_e^o\|^2}{l_o^2}}. \tag{12}$$

The relative position vector between a robot and a virtual point is defined as

$$\psi^v = \mathbf{P} - \mathbf{P}_v, \tag{13}$$

where $\mathbf{P}_v$ is a position of the virtual point.

$\mathbf{P}_v$ is at a distance of d^v from the robot with angle θ^v between the robot and the obstacle $\mathbf{O}_e$ as shown in Fig. 1. d^v is the distance of ψ_j^o when the robot is trapped by the obstacle and θ^v is an angle for the escaping route.

If the robot goes toward the virtual point, the position of the virtual point is updated on the basis so that the virtual point maintains the distance d^v from the robot and the angle θ^v between the robot and the obstacle $\mathbf{O}_e$, which makes the virtual escaping route.

The virtual point for the escaping route has the following attractive fields:

$$U^v = c_v (1 - e^{-\frac{\|\psi^v\|^2}{l_v^2}}), \tag{14}$$

where c_v and l_v are the strength and correlation distance for an escaping route. The first term c_v in the right side of (14) acts to make U^v zero when $\psi^v = 0$. Its corresponding force is then given by the negative gradient of (14).

$$F^v = -\nabla U^v = -\frac{2c_v\psi^v}{l_v^{\,2}} e^{-\frac{\|\psi^v\|^2}{l_v^{\,2}}}. \tag{15}$$

The total potential of the potential for the escaping route and the potential for obstacle avoidance are combined together is modeled as follows:

$$\begin{aligned} U^{vo} &= \frac{1}{c_v} U^e \cdot U^v + U^v \\ &= \{c_o e^{-\frac{\|\psi_e^o\|^2}{l_o^{\,2}}}\}(1 - e^{-\frac{\|\psi^v\|^2}{l_v^{\,2}}}) - c_v e^{-\frac{\|\psi^v\|^2}{l_v^{\,2}}} + c_v. \end{aligned} \tag{16}$$

Its corresponding force is

$$\begin{aligned} F^{vo} &= -\nabla U^{vo} \\ &= \{\frac{2c_o\psi_e^o}{l_o^{\,2}} e^{-\frac{\|\psi_e^o\|^2}{l_o^{\,2}}}\}(1 - e^{-\frac{\|\psi^v\|^2}{l_v^{\,2}}}) \\ &\quad + \{c_o e^{-\frac{\|\psi_e^o\|^2}{l_o^{\,2}}}\}(-\frac{2\psi^v}{l_v^{\,2}} e^{-\frac{\|\psi^v\|^2}{l_v^{\,2}}}) - \frac{2c_v\psi^v}{l_v^{\,2}} e^{-\frac{\|\psi^v\|^2}{l_v^{\,2}}}. \end{aligned} \tag{17}$$

Fig. 2 shows the scheme of an escaping route for trap situations. If a robot satisfies the four conditions in (9) while performing goal destination and obstacle avoidance, the robot follows the virtual escaping route using the force (17). The virtual escaping route is made in a curved line around the obstacle, which enables the trapped robot to turn the obstacle around. While the robot follows the virtual escaping route, the robot is released from the escaping route if it passes the point (called the *release point*) chosen by θ_c. θ_c is the angle between the robot and the obstacle on the basis of the axis that the robot, obstacle and goal are collinear with the robot lying on a different side of the goal as shown in Fig. 1. Then, the robot again performs goal destination and obstacle avoidance. In other words, the robot is affected by existing forces (8) to reach the goal.

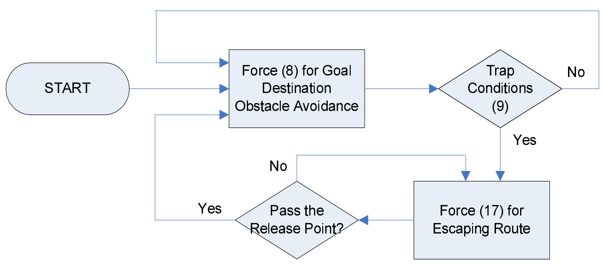

Fig. 2. Scheme of escaping route for trap situations.

4. SIMULATIONS

In this section, simulation results are given to illustrate the effectiveness of the algorithms discussed in the proceeding sections.

Fig. 3 presents an example of a trap situation with no passage using the proposed configuration where a robot starts from $(0,0)$. $a_1 = 0.001$, $a_2 = 10^o$, $a_3 = 0.1$, $a_4 = 0.02$, $\theta^v = 70^o$, $\theta_c = 10^o$, $c_v = 1$ and $l_v = 2$ are used. Small blank dots around the right obstacle mark the virtual escaping route.

If a robot meets another obstacle before it reaches the release point while escaping a local minimum, a new escaping route is created on the basis of a new neighboring obstacle. Then, the robot is affected by the potential fields exerted from the new neighboring obstacle and the virtual escaping route. If the robot passes the release point while following the virtual escaping route, then the robot goes toward the goal by existing potential fields (7). Fig. 4 presents a corresponding example with a series of two local minima where a robot starts from (1,0). Since the robot makes its way around the obstacles using the characteristics found

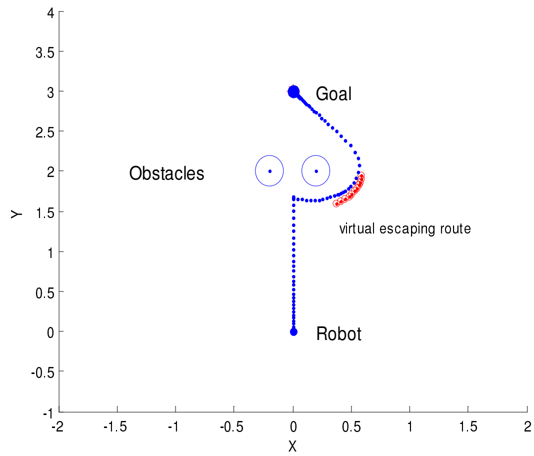

Fig. 3. Virtual escaping route at a local minimum.

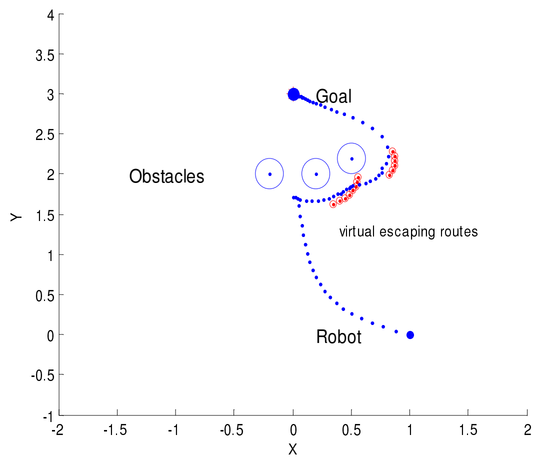

Fig. 4. Virtual escaping routes at a series of two local minima.

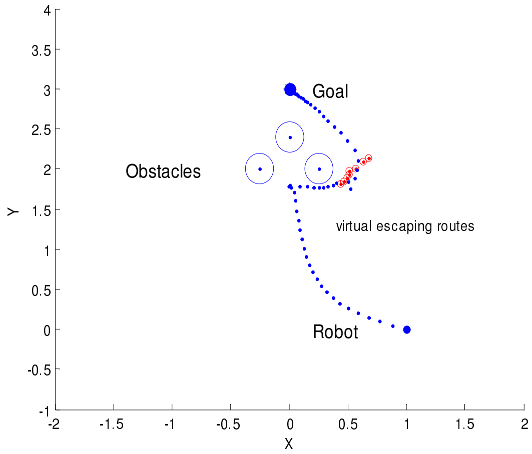

Fig. 5. Virtual escaping routes in a V-shape obstacles.

in the wall-following approach [16,17], the proposed approach can be considered as an obstacle-following strategy using a virtual escaping route based on APFs in order to escape from a local minimum.

In Fig. 5, the obstacles are arranged in a V-shape, which is the shape of a closed aisle. Therefore, the robot may be trapped in a local minimum created by a V-shape. However, in the proposed method, the robot detects a local minimum by calculating the distances and degrees between neighboring obstacles and the goal and, if the conditions meet, the virtual escaping route is generated. Fig. 5 shows that the robot escapes from the local minimum by using a virtual escaping route and successfully reaches its goal. This simulation shows that this method is also useful for a V-shape obstacle arrangement.

When a robot meets another obstacle before reaching the release point while escaping a local minimum, a new escaping route is created on the basis of a new neighboring obstacle. In such a case, a chattering phenomenon is not found, as shown in the trajectories of Fig. 3, 4. It makes no difference whether this occurs before or after the robot reaches the release point. The previous escaping route is ignored if a new escaping route is created under the local minimum identification condition (9), and a new escaping route is made in a curved line around another obstacle.

5. CONCLUSIONS

This paper presents a design framework based on APFs for local path planning under a local minimum situation. In order to distinct it from the previous studies on path planning, the paper presents a set of trapped conditions on APFs for the identification of local minima that may occur under a narrow passage or other possibly similar scenarios, and proposes a set of analytical guidelines for the APFs that enable a robot to escape from such a local minimum situation. The proposed virtual escaping route enables a robot to escape from possible local minima where the total forces are composed of repulsive forces by obstacles and attractive force by a goal are zero. For scaling parameters satisfying the proposition, the framework allows the robot to reach a goal through possible trap situations. Although, in this paper, we have focused on the analytical design of local path planning for a point robot, the underlying method should be tested using actual micro omni-directional mobile robots in the near future.

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