Efficient Motion Planning for Mobile Robots Dealing with Changes in Rough Terrain

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Abstract: This paper proposes a novel motion planning method that can deal with changes in rough terrain efficiently. Previous studies on motion planning in rough terrain did not consider significant changes in the environment. To solve this problem, we propose an efficient re-planning method. The re-planning method is characterized by using search tree repeatedly as long as it is still valid. Reusing search tree enables limiting the re-planning region, which leads to the shorter planning time. After re-planning, the re-planned path is deformed to shorten the length of the path. Experimental results show that the proposed method can generate a collision-free path against a significant environmental change and perform the re-planning within a short time.

Keywords: Mobile robots, Rough terrain, Motion planning, Path planning, Autonomous navigation

1. INTRODUCTION

In recent years, the importance of mobile robot operation is increasing in rough terrain such as disaster sites. In rough terrain, teleoperated robots are often used. However, there is a problem that the efficiency of teleoperation is low because of limitation of the information available. Therefore, as few operations by human as possible are desirable. Thus, the ability to generate a safe and reliable path with sensing surrounding environment is needed for mobile robots in rough terrain.

Ji et al. proposed a path planning method for mobile robots traveling on rough terrain (Ji et al. (2019)). In this method, the feasibility of specific pose of robot is evaluated by considering not only position but also orientation, which enables generation of traversable path under 3D uneven environment. However, the path planning is implemented under the assumption that the map information of a target environment is pre-given and not changeable. Therefore, this method cannot be applied directly to a motion planning dealing with environmental changes.

Doi et al. proposed a path planning method which considers pose errors of a mobile robot in rough terrain (Doi et al. (2018)). This method guarantees safety of the mobile robot against the uncertainty of the environment. However, it cannot handle a significant change in the environment. To best of our knowledge, a motion planning method which can deal with significant changes in rough terrain does not exist.

Apparently, it seems that mobile robots can handle changes by simply using the method (Ji et al. (2019)) whenever a significant change is detected. However, this causes a problem that the execution time gets longer. This is because a lot of new nodes should be generated from zero in the method which uses no prior information every re-planning. As a solution to this problem, D* algorithm which can modify only obstructed parts of the initial path is widely known (Stentz (1994)). However, in order to use this algorithm, graph structure for all search space must be prepared. Therefore, this method is not applicable to 3D rough terrain in this research because much computation time is needed to generate graph structure for 3D search space.

For the reasons above, the purpose of this study is defined as establishing an efficient motion planning method which can handle changes in rough terrain. In order to achieve this purpose, we propose a novel motion planning method which is efficient in terms of both re-planning time and length of re-planned path. Regarding the re-planning time, we realize a shortcut of re-planning time by reusing search tree repeatedly as long as it is still valid. With regards to the length of the re-planned path, we get a shorter path by deforming the re-planned path. Although Yoshida et al. proposed a path deformation method for mobile robots (Yoshida et al. (2011)), it cannot be applied to the case of rough terrain because it does not consider an orientation of a mobile robot. Thus, we propose a path deformation method suitable for rough terrain by considering an orientation of a mobile robots.

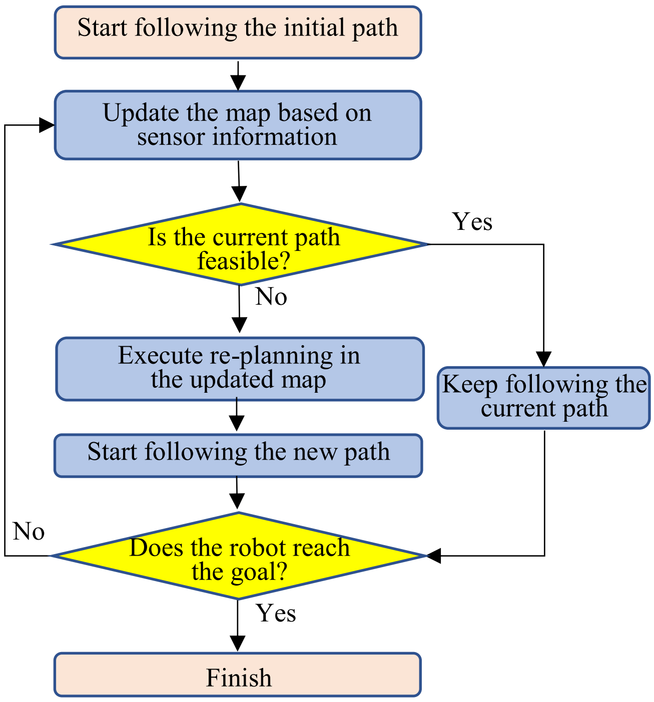

Fig. 1 Flowchart of motion planning.

2. MOTION PLANNING DEALING WITH CHANGES

2.1 Problem Settings

In this study, we propose a motion planning method for mobile robots travelling on rough terrain. An environment map, an initial path generated by offline search in the map, and search tree obtained as a result of the offline search are given to the mobile robot. The mobile robot starts following the initial path and collects sensor information of surrounding environment, while the map is updated based on the sensor information. Here, we assume that the parts where no sensor information exists is not updated. Under this assumption, re-planning is executed when the current path is not feasible in the updated map. In order to evaluate the feasibility of the current path, we use the method proposed in (Ji et al. (2019)), which is suitable for rough terrain.

2.2 Overall Process of Motion Planning

The overall process of the proposed motion planning is illustrated in Fig. 1. First, a mobile robot starts following the initial path and updates the map by utilizing sensor information. Next, the robot judges whether the current path is feasible or not based on the updated map. Only when the robot cannot follow the current path due to a new obstacle, re-planning is executed from the current position to the target position. An example of a re-planned path generated by the proposed method is illustrated in Fig. 2. A yellow path represents the initial path, and a red path represents the re-planned path. A Green circle represents an environmental change. This process is repeated until the mobile robot reaches the target position.

2.3 Efficient Re-planning Method

Figure 3 is a conceptual image that shows the re-planning method in the proposed motion planning. A green object in Figure 3 (a) represents a mobile robot, and it is assumed that a new obstacle is detected when the mobile robot reaches the position shown in the figure. At this time, a search tree obtained as a result of the offline search is updated. In updating the search tree, the parts colliding with the new obstacle are removed from the original tree. In Fig. 3(a), dotted lines mean removed parts and solid lines mean reused parts. This updated search tree is employed for re-planning. By using it, the number of nodes generated in the re-planning can be reduced.

Re-planning process using the updated search tree is shown in Fig. 3(b). In this process, as a first step, the nearest node of the updated search tree is identified. Next, the search tree is extended from the nearest node to the target node in order to generate a new safe path. Once the search tree reaches the target node, the states connected from the current node to the target node are returned as a re-planned path. A blue line in Fig. 3(c) shows the re-planned path. The merit of this re-planning process is that it enables limiting the re-planning region to the smaller region like a red circle shown in Fig. 3(b), which in turn leads to shorter planning time.

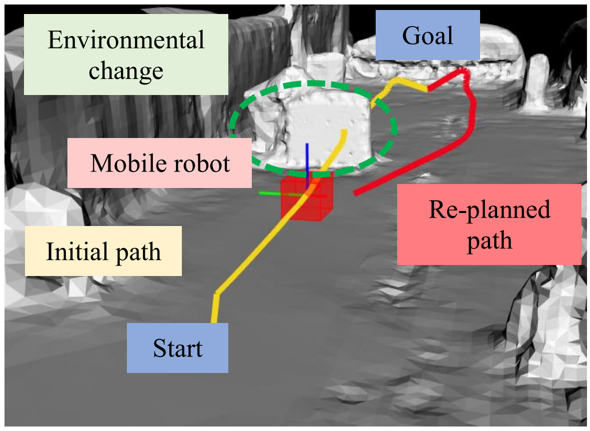

Fig. 2 Re-planned path generated by proposed method.

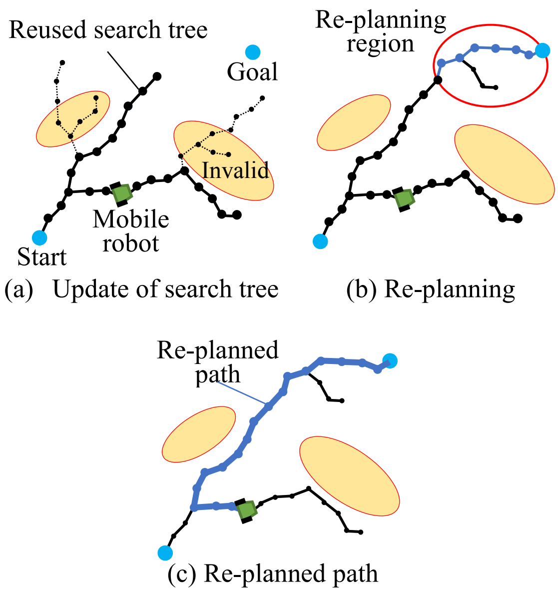

Fig. 3 Conceptual image of re-planning method.

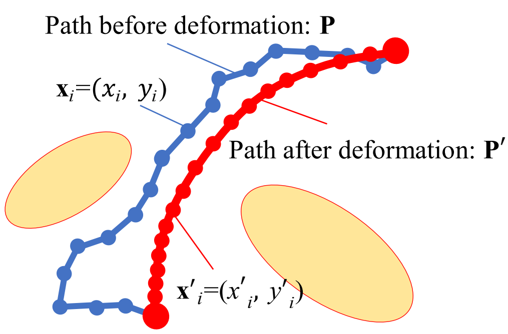

Fig. 4 Definition of path.

However, the path obtained by this re-planning process may result in a detour. In the case of Fig. 3(c), for example, the mobile robot must go backward in order to follow the re-planned path. It takes long time for the mobile robot to reach the target position. Therefore, in case of using the method described above, total time to travel from the initial position to the target position may get longer although it is able to shorten the re-planning time. To solve this problem, we add a path deformation step after the re-planning in the proposed method.

2.4 Path Deformation Method

Figure 4 shows a definition of path generated by the proposed method. A path consists of positions that a mobile robot should follow. Here, path deformation is carried out by manipulating each point of positions (i.e., nodes) on the path. From this definition, path deformation is formulated as an optimization problem. Let f($\mathbf{P}'$) be an objective function, then the optimization problem is defined as follows:

$$\widehat{\mathbf{P}'} = \arg\min_{\mathbf{P}'} f(\mathbf{P}') = \alpha \sum_{i=1}^{n-1} \|\mathbf{x}'_{i+1} - \mathbf{x}'_i\|^2 + \beta \|\mathbf{P}' - \mathbf{P}\|^2 + D(\mathbf{P}') \quad (1)$$

where $\mathbf{P}=\{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n\}$ denotes the path before deformation, $\mathbf{P}'=\{\mathbf{x}'_1, \mathbf{x}'_2, \dots, \mathbf{x}'_n\}$ denotes the path after deformation, and $\mathbf{x}_i$ denotes the position (x_i, y_i) on the path. α and β are the weight parameters. Since $\sum_{i=1}^{n-1}\|\mathbf{x}'_{i+1}-\mathbf{x}'_i\|^2$ means the length of the path after deformation, the path is deformed in the direction in which the length of the path gets shorter by (1). Moreover, the distance $\|\mathbf{P}'-\mathbf{P}\|^2 = \sum_{i=1}^{n}\|\mathbf{x}'_i-\mathbf{x}_i\|^2$ between the paths before deformation and after deformation is added to the objective function. The aim of this is to shorten the time to calculate by minimizing the deformation of the path. Finally, a risk function D($\mathbf{P}'$) is added to the objective function in order not to manipulate each point of positions on the path to the region the mobile robot cannot enter. The risk function is defined as follows:

$$D(\mathbf{P}') = \begin{cases} 0, & \text{if } \mathbf{P}' \text{ is feasible} \\ \infty, & \text{if } \mathbf{P}' \text{ is not feasible} \end{cases} \quad (2)$$

In (2), the path $\mathbf{P}'$ is judged not feasible if it includes any positions, even just one position, which the mobile robot cannot realize. Here, the method introduced in (Ji et al. (2019)) is utilized for judging the validity of each position. Since D($\mathbf{P}'$) returns infinity in case that $\mathbf{P}'$ is not feasible, the path is deformed into one which the robot can travel by (1).

The optimization process (1) is executed for the objective function described above. For this calculation, Levenberg-Marquardt method is adopted for the reason that it is suited to solve a nonlinear least squares problem like (1). The solution path $\widehat{\mathbf{P}'}$ is the final output in the proposed method.

Fig. 5 Experimental condition.

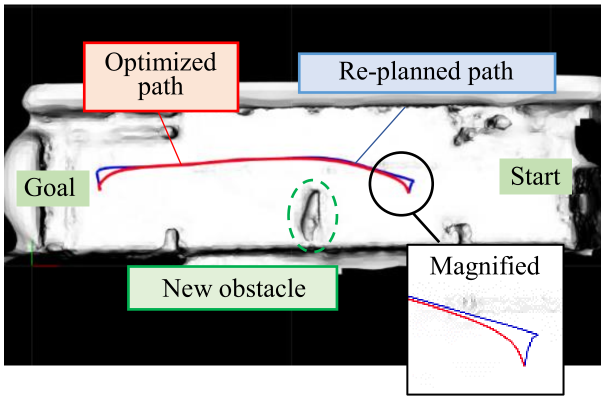

Fig. 6 Simulation result.

3. SIMULATION EXPERIMENT

3.1 Experimental Setting and Procedure

In order to verify the effectiveness of the proposed motion planning method, we conducted a simulation experiment. The simulation experiment is carried out by using maps of a real outdoor site. The experimental site is shown in Fig. 5. In this experiment, we made an artificial change by setting a 1.4 m × 1.0 m blue board in 7 m × 28 m outdoor experimental site. A re-planned path is generated against this change in the environment. Then, we applied the proposed path deformation method for the re-planned path. In this experiment, we measure the re-planning time and the length of the path. In the experiment, we set the weight parameter α and β to 1.0 and 0.1, respectively.

3.2 Experimental Result

Figure 6 shows the result of the simulation experiment. In the figure, the experimental site is depicted from the top view. An object surrounded by green dotted line represents the new obstacle. A blue path represents the re-planned path. A red line represents the optimized path after deformation. The result shows that the proposed motion planning method was able to generate a collision-free path by re-planning. Figure 7 shows the re-planning time in case of applying the method proposed in (Ji et al. (2019)) to the re-planning and in case of using the proposed method. The proposed method was able to shorten the re-planning time by 83 %. Furthermore, as shown in the

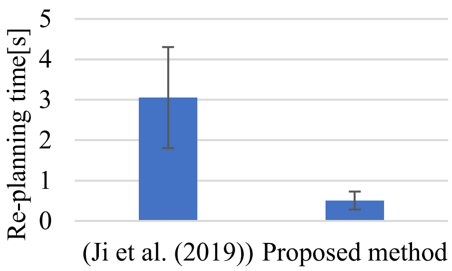

Fig. 7 Re-planning time.

Table 1 Path length.

	Length [m]
Before	18.1
After	17.2

magnified part of Fig. 6, the optimized path is deformed so that the mobile robot can go directly to the goal with avoiding the obstacle. Table 1 shows a change of the length of the path. From the table, we can find out that the length of the path changed from 18.1 m to 17.2 m. Therefore, we confirmed that the proposed deformation method was able to shorten the length of the path.

4. FIELD EXPERIMENT

4.1 Experimental Setting and Procedure

In order to verify the validity of the re-planned path in a real environment, we conducted a field experiment using a real mobile robot. The experimental site is shown in Fig. 8. In this experiment, we made an artificial change by setting a slope whose inclination angle is 56.4° in 7 m × 28 m outdoor environment. Figure 9 shows a re-planned path generated for this environment. A red line represents the re-planed path. As shown in the figure, the proposed re-planning method generated a collision-free path, and it is given to a mobile robot. PIONEER 3-AT was used in this experiment as a mobile robot.

4.2 Experimental Result

Figure 10 shows the result of the field experiment. The mobile robot travelled in order of Fig. 10(a) to Fig. 10(d). The robot was able to travel safely along the re-planned path without colliding with the obstacle. Thus, we confirmed that the proposed re-planning method was able to generate a safe path in real environments.

5. CONCLUSIONS

This paper proposed an efficient motion planning method dealing with changes in rough terrain. The proposed motion planning method has two strong points. One is that it can generate a re-planned path within short planning time by reusing search tree repeatedly. The other is that the length of the re-planned path is short because it performs a path deformation after re-planning, which can shorten the length of the re-planned path by solving an optimization problem. A simulation experiment and a field experiment verified the validity of the proposed method. For future works, we should conduct an experiment under more difficult condition.

Fig. 8 Experimental condition.

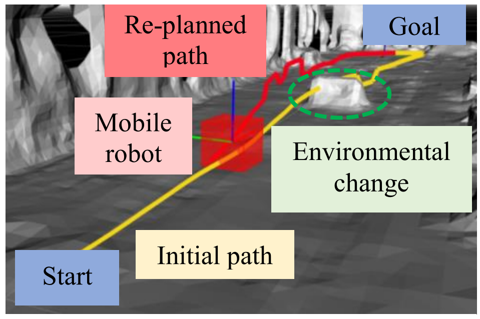

Fig. 9 Re-planned path.

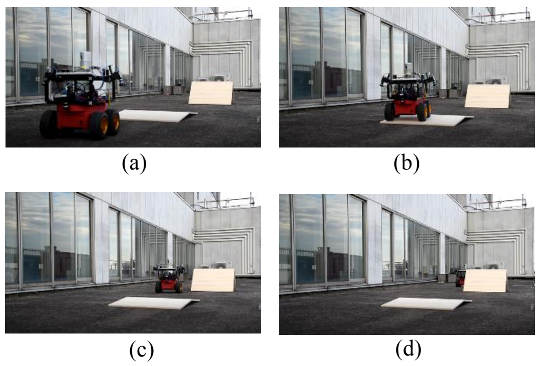

Fig. 10 Mobile robot used in the field experiment.

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