Safety Path Planning for Mobile Robot on Rough Terrain Considering Instability of Attitude Maneuver

Takeshi OHKI, Keiji NAGATANI and Kazuya YOSHIDA

***Abstract*—In disaster scenarios, mobile robots that have the capability to explore in dangerous environments can offer significant assistance in search and rescue missions instead of rescue crews. The realization of such robot systems is depending on many technologies. One important future technology is autonomous navigation to replace the currently used teleoperation technology. To develop a 3-D path planning method, we focused that how to evaluate environment by skilled operators of rescue robots. From the observations of maneuvers made by skilled operators, it was found that attitude maneuvers that are turning/rolling maneuvers, are minimized on rough terrain. Therefore, in this research, we propose a path-planning method for autonomous mobile robot considering the instability of attitude maneuvers on rough terrain. The proposed method consists of three steps: "gradient calculation," "nodes detection," and "path evaluation." In the gradient calculation step, the gradients of terrain are calculated. Next, in the nodes detection step, the terrain is divided into flat regions and rough regions, and the center positions of each flat regions are identified; this is called the "node." Finally, in the path evaluation step, the best path from current position to the target destination via nodes is planned using the proposed evaluation method. The proposed method has been implemented in our simulator, and some simulation experiments were conducted to demonstrate a validity of our method.**

I. INTRODUCTION

A. Background

In disaster scenarios, such as that during and after earthquakes or nuclear/biological/chemical (NBC) terrorist attacks, it becomes very dangerous for rescue crews to search for victims at disaster sites, that there is a possibility that a secondary disasters might occur. In such a situation, remote-controlled mobile robots, called "rescue robots" can be of great help when searching inside collapsed buildings, taking the place of the rescue crews. In light of such social demands for rescue robots, research and development activities on rescue robots have increased world wide [1][2]. One of the most important technologies in this regard is autonomous navigation because skilled operators of teleoperated mobile robots may be in short supply in the case of a wide-spread disaster.

Our research group has been developing rescue robots, called "Kenaf" (Fig. 1), to explore underground malls in an NBC terrorist attack scenario [3]. To undertake search missions in the above scenario, we are currently researching teleoperation methods, communications, locomotion methods on rough terrains [4], 3-D mapping technologies, and autonomous navigation methods [5], using the Kenaf as a research platform.

Fig. 1. Rescue robot "Kenaf"

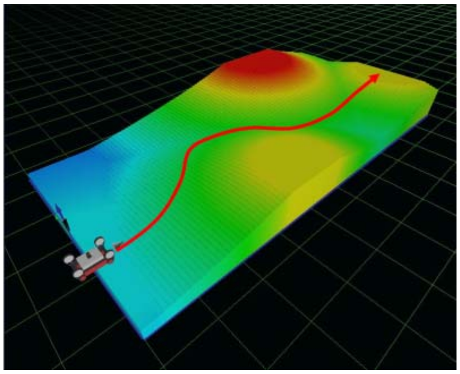

Fig. 2. Example of planned path by conventional method on rough terrain (red region: high altitude, blue region: low altitude)

In a disaster area, a robot must plan a path that has a small risk of stuck and slip of the robot on the rough terrain. In this problem, we value the safety over the speed of the robot on the planned path.

One of the basic methods for solving the above path-planning problem is to plan the shortest path that avoids high-gradient regions of the terrain [6].

Fig. 2 is one example of the above strategy. However, skilled operators of the rescue robots said that it was not a reasonable path because it requires too many operations of steering maneuver, and actually they performed path planning and navigation in different manner. This research was started from this point.

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B. Research Purpose

Our aim was to plan a path on rough terrain as done by skilled operators, and to determine the difference between conventional methods and those used by skilled operators. Though it seems that there are a number of rules that skilled operators used to determine the desired path, we consider that the experimental rule that turning and rolling maneuvers should be avoided on rough terrain is particularly important. This rule is based on the experimental fact that turning or rolling maneuvers on rough terrain cause slip and stuck; in particular, the maneuver of rolling with turning can considerably increase the risk of slip and stuck. In this research, we introduce our path-planning method considering attitude maneuver instability on rough terrain rule, and we show a simulation result.

C. Related Works

There are some previous reports of path planning on rough terrain.

Bapna, et al. [7] reported their mobile robot traversed long distance in Atacama desert. To traverse rough terrain automatically, their robot had a stereo camera to gather information of the terrain. They planned radial eleven paths as candidates and evaluated them on the basis of the attitudinal stability of the robot. This method is the same in the aspect of focusing the stability of the robot. However, the strategy of this method does not treat the turning maneuver on rough terrain as unstable in essentials. In this point, our strategy is different from their one.

Ishigami, et al [8] proposed a path-planning method and its evaluation method that pay attention to wheel slip dynamics of lunar/planetary exploration rovers. They implemented their method on their simulator and showed the usefulness of their method. This method also considered slip of the mobile robot; however, the planned path by this method is the same as the conventional method that avoid high-gradient region in essentials.

II. PROPOSED METHOD

A. Overview

First, we introduce an overview of our novel path-planning method for mobile robots on rough terrain considering the instability of attitude maneuver. We make the following assumptions in this research.

1) The target environment is a square region that consists of flat and rough terrain.
2) The start and the goal position are located on the flat region.
3) A 3-D LIDAR (laser intensity direction and ranging) is assumed as a sensor on the robot.
4) The robot obtains complete environment by using a 3-D LIDAR, and occluded areas are not considered.
5) The locomotions of the robot consist of pivot turn and going straight.

On the basis of the above assumptions, we propose a path-planning method that consists of three steps: "gradient calculation," "nodes detection" and "path evaluation."

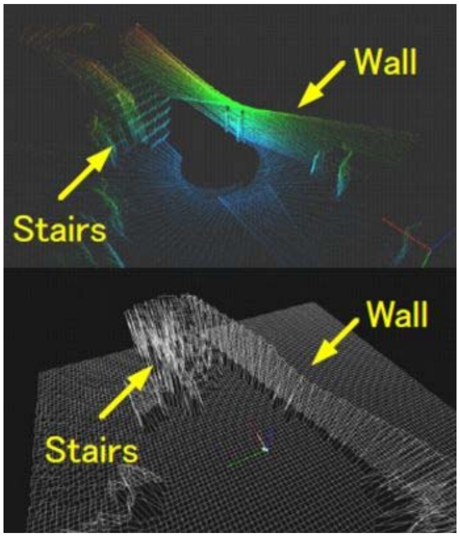


Fig. 3. Environment expression by point cloud (upper) and DEM (lower)

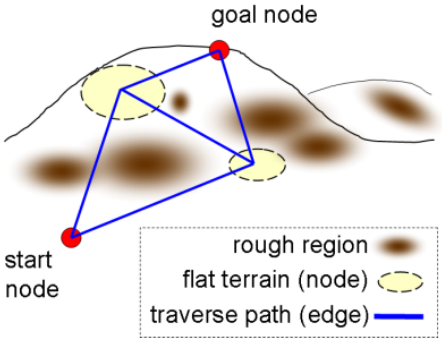


Fig. 4. Nodes and edges

The first step, gradient calculation gathers environment information by using 3-D LIDAR, and it expresses the information as a digital elevation map (DEM) representation [9]. Fig. 3 shows an example of environment expression by point cloud and DEM. Next, a gradient of each grid is calculated as a maximum height difference between the grid and the adjacent grids. This calculation is performed in all grids on the DEM and the calculated values are registered to a grid based map, called a digital gradient map (DGM).

The second step, nodes detection finds flat region from the information in the DGM, and define *node* grids as the center positions of each flat region. In addition, the node pair defines an *edge* as a straight traverse line. The nodes and edges construct a graph, as shown in Fig. 4, and this graph will be used to plan a path in the next step.

In the third step, path evaluation, a path via nodes and edges is planned and evaluated. This planning is performed by a general graph search algorithm. To evaluate the path, the costs of the path candidates from the start position to the destination are calculated as the integral of the attitude swing on the path and the distance.

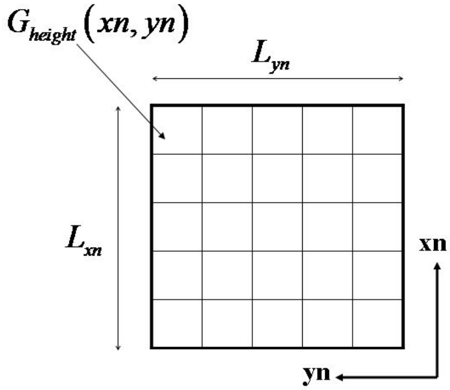


Fig. 5. Definitions of DEM

In the next subsections, we introduce the above steps in details.

B. Gradient Calculation

In the first step, our method calculates the gradients of terrain by using DEM representation.

Our method gathers environment information by using the 3-D LIDAR, and it expresses the information as a DEM representation. DEM is a grid-based expression of environment and its data size relays on the resolution of its grid. A grid in the DEM is called $G_{height}(xn,yn)$, where xn and yn are parameters that decide a position on the plane of X-Y coordinates (Fig. 5). The value of $G_{height}(xn,yn)$ means the maximum height that is included in the region of the grid.

Now, we generate a new map, called a digital gradient map (DGM), to express the gradient of each grid regions in the DEM. The L_{xn}, L_{yn} of G-DEM are the same as those of the DEM. A grid in DGM is expressed as $G_{grad}(xn,yn)$ in the same way. The value of $G_{grad}(xn,yn)$ has an absolute value of a maximum difference in height between the $G_{height}(xn,yn)$ and the adjacent grids. By using the above definition, all grids DGM are calculated from the DEM.

C. Nodes Detection

In the second step, our method calculates flat regions from the DGM and assume the regions as special areas that a robot can turn on it easily.

Flat regions are detected by using a threshold $H_{threshold}$. If a value of $G_{grad}(xn,yn) \geq H_{threshold}$, the $G_{height}(xn,yn)$ is detected as a grid on flat terrain. The center position of the flat region is called a*node*, as a symbol of a flat region. In addition, the nodes pair is defined as an *edge* that is a straight traverse line. A graph is constructed by the nodes and the edges and is used for path planning.

D. Path Evaluation

In the third step, a 3-D path via nodes and edges is planned. This planning is similar to general graph search algorithm.

At the beginning, the most closest node to a start position is searched, and named $node_{start}$, and in the same way, $node_{goal}$ is also searched. Then we generate candidates of path from $node_{start}$ to $node_{goal}$ via other nodes.

Now, we define evaluation function to evaluate the candidates of the path. The function is as follows;

$$\begin{aligned} Cost &= \sum_{path} \{ (k_{pos} * \Delta roll * \Delta yaw) + \\ &\quad (k_{roll} * \Delta roll) + \Delta move \} \end{aligned} \tag{1}$$

where, $\Delta roll(deg)$ is the roll angle from the horizontal plane and $\Delta yaw(deg)$ is the swing of the yaw angle of the robot at each positions on the path. $\Delta move(mm)$ is a distance of each segments of the path, and k_{pos}, k_{roll} are coefficients.

The cost calculated by the $(k_{pos} * \Delta roll * \Delta yaw)$ term is called *roll-yaw swing cost*, the cost calculated by the $(k_{roll} * \Delta roll)$ term is called *roll swing term*, and $\Delta move$ is called *distance term*.

The first term means the cost of the maneuver of turning with its rolling angle that has a high risk of slip, and the second term means the cost of rolling maneuver, and the third term means the cost of the path redundancy.

III. IMPLEMENTATION AND EVALUATION

In this section, we implement the proposed method on our mobile robot simulator and evaluate the planned paths. In addition, the conventional method is implemented in the same manner to compare with the proposed method.

A. Mobile Robot Simulator

To confirm the applicability of the proposed method, we use an improved version of our rescue robot simulator [5]. Fig. 6 shows an example of the simulator.

A feature of the simulator is to generate arbitrary virtual rough terrains. A number of user programs to control a virtual rescue robot can be executed on the simulator, and the result of execution of the user programs is visualized.

In this research, we implemented our path-planning method as a user program of this simulator, and checked the behavior of our method by visualized results. The simulator does not guarantee the same motion in the real world because it does not consider the dynamics of mobile robots. However, it is enough to confirm a validity of the path-planning method.

B. Implementation of Our Method

In the gradient calculation step, each grid size of the DEM is 100 (mm) square, L_{xn} and L_{yn} are 10 (m) and 5 (m), respectively. Thus, the total number of grids in the DEM is 5000. In the detection step, $H_{threshold}$ is set to 5 (mm), and L_{max} is set to infinity. In the planning step, for simplicity, each coefficients is set as $k_{pos} = 10$, $k_{roll} = 10$, $k_{dist} = 1$, and $\Delta move$ is set as 3 by using heuristics.

Fig. 7 shows a virtual environment for this simulation. The color of Fig. 7 refers to the height of the each grids: the red area signifies high altitude, and the blue area signifies

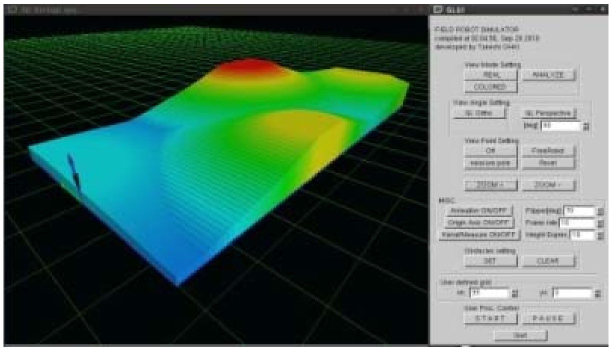


Fig. 6. Field simulator

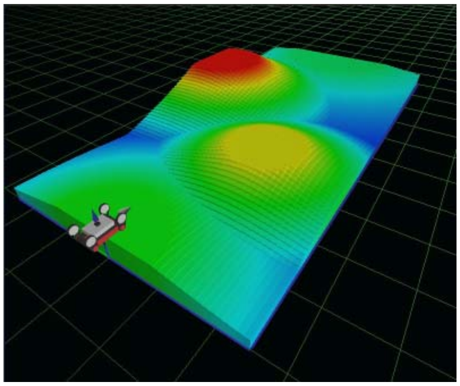


Fig. 7. Virtual DEM

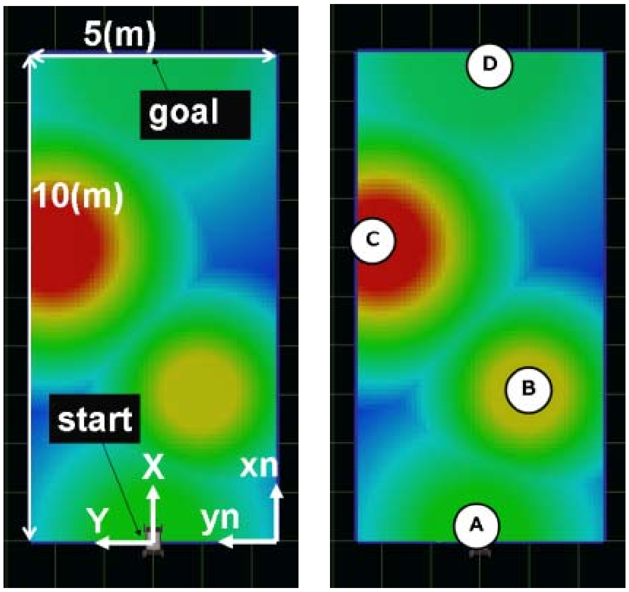
low altitude. The coordinates are set as shown in Fig. 8-(a). There are two coordinates; one is defined to express the 2-D position by using (x, y), and the other is defined to express the grid $G(xn, yn)$ of the DEM.

In this simulation, we set four hills named hill A, B, C, and D, as shown in Fig. 8-(b). The height of the hills A, B, C, and D are 0.5 (m), 0.75 (m), 1.0 (m), and 0.4 (m) respectively. The start position is set to the node position that is most close to the position (0, 1) (m), and the goal position is also set to the node position that is most closest to the position (10, -1) (m) for simplicity.

We conducted several path planning in different virtual environments. We present one example of the planning results. Fig. 9-(a) is a generated DGM by the first step. In Fig. 9-(a), the heights of each grids are extended ten times.

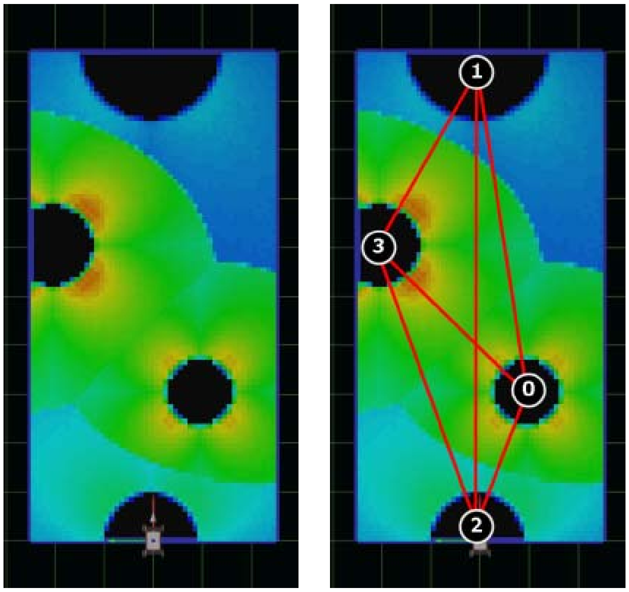
The generated nodes and edges in the nodes detection phase are shown in Fig. 9-(b). The nodes are expressed as circles with the number of the node, and the edges are expressed as red straight lines. Finally, the best evaluated path is planned that is from the $node2$ to $node1$ via $node0$ on the basis of the evaluation function shown in equation (1).

The calculated costs of the path candidates by our method are the paths from A to E, and the cost of the path by the conventional method is path R, as shown in Table I. The values of the costs in the table are expressed as integer with rounding off.



(a) Coordinates definitions (b) Four hills

Fig. 8. Implementation condition



(a) Calculated DGM (b) Nodes and edges

Fig. 9. Result of first and second step of our method

The best path that has the lowest cost is path C. The planned path by our method does not contain the maneuver of turning with rolling on rough terrain. Therefore, the roll-yaw swing cost of path A to E are always zero.

C. Implementation of Conventional Method

To compare our method with conventional methods, we implemented a conventional method. This method consists of three steps; gradient calculation, obstacles detection, and path planning.

In the first step, this method is completely the same as ours. The DEM representation is used to express the terrain, and the gradients of the each grid of the DEM are registered to a DGM.

In the second step, this method imports a height threshold $H_{threshold}$ to divide the grids of the DGM to the grids in free space and in obstacle space. The grids that have the higher value than the $H_{threshold}$ are identified as the grids in obstacle space. In other words, this phase converts the 3-D path-planning problem on rough terrain to the 2-D path-planning problem with obstacle avoidance.

In the final step, simple shortest path search algorithm is applied to plan a shortest path in the free space. The planned path relays on the threshold $H_{threshold}$ of the DGM in the second step.

In this implementation, the condition is the same as the condition in section III-B with out path planning part. We set the height threshold $H_{threshold}$ as 48 (mm). Fig. 10-(a) shows the obstacle space that consists of the grids that has the higher value than $H_{threshold}$ on the DGM, and in this figure, the red line is the shortest path that avoids the obstacle spaces. Fig. 10-(b) shows the same red path on the DEM, and Fig. 10-(c) is a 3-D view of Fig. 10-(b).

D. Discussion

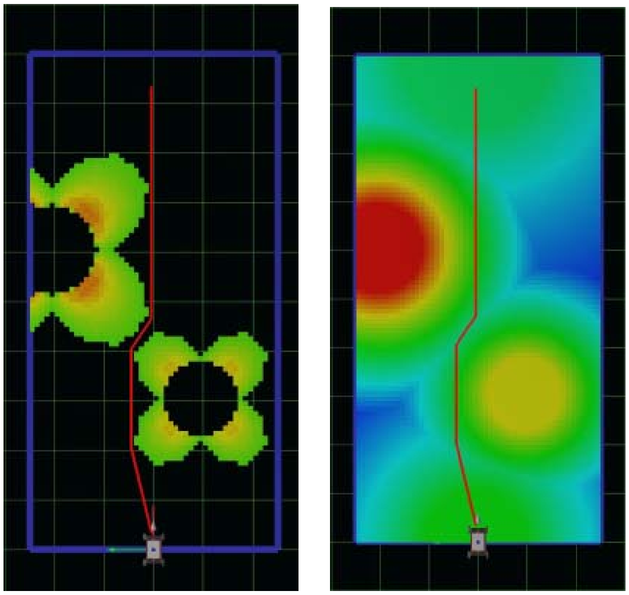
The path evaluated as the best among in the path candidates planned by our method is path C, shown in Table I. Though the shortest path in the path candidates is path E, the roll cost of the path C is much smaller than that of path E. While the difference of the distance costs between path C and path E is almost 3 (%) of the distance cost of path C, the difference of the roll cost is almost 57 (%) of the roll cost of path C. Therefore, the difference of the roll cost is more prominence than the distance cost in the above comparison.

The path R planned by the conventional method has a large roll-yaw cost as shown in Table I. Though the distance cost of path R is more or less the same as path C by our method, the roll and roll-yaw swing cost is much larger than that of path C. This is because the conventional method forces the robot to pose rolling attitude during traversing and turning on the path, as Fig. 10-(c) indicates.

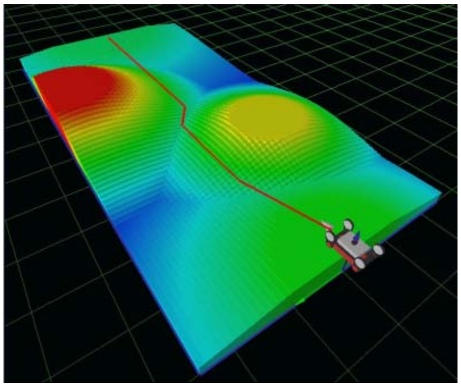
IV. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

We have proposed a path-planning method for a mobile robot on rough terrain. This method evaluates the terrain on the basis of the experimental rule that roll and yaw swing maneuver is unstable for a mobile robot on rough terrain. A simulation result showed the difference in the roll-yaw swing cost between our method and a conventional method. Finally, this result demonstrates the effectiveness of our method.



(a) Path on the DGM (b) Path on the DEM



(c) Path on the DEM (3-D view)

Fig. 10. Results of the conventional method

TABLE I

COSTS OF THE PATHS

path	passing nodes	roll swing cost	roll-yaw swing cost	dist. cost	total cost
A	2 → 3 → 1	2567	0	10521	13088
B	2 → 3 → 0 → 1	3395	0	17435	20830
C	2 → 0 → 1	2214	0	9376	11590
D	2 → 0 → 3 → 1	2228	0	11596	13823
E	2 → 1	3474	0	9096	12570
R	path is shown in Fig. 10	3710	4895	9258	17862

B. Future Works

1) Advanced algorithm for node detection to enable detection of node on complex terrain.
2) Consideration of the occlusion of a 3-D LIDAR sensor.
3) Implementation of our path-planning method on a real machine.

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