ABSTRACT: This paper describes a path planning method for planetary rover to search for a path on planetary surface. Planetary rover is required to travel safely over a long distance for many days in unfamiliar terrain. Hence it is very important how planetary rover processes sensory information to understand the environment and to make decisions. As a new data structure for a map information, an extended elevation map (EEM) has been newly introduced, which includes the effect of the size of the rover. The proposed path planning can be conducted in such a way as if the rover were a point while the size of the rover is automatically taken into account. The validity of the proposed method is verified by computer simulations.

KEY WORDS AND PHRASES
Path planning, planetary rover, elevation map.

INTRODUCTION

In recent years many researchers have extensively studied and developed mobile robots (planetary rovers) for unmanned surface exploration of planets[1][2][3]. Planetary rover is required to travel safely over a long distance for many days in unknown terrain. Due to the communication delay between the earth and the rover, round trip propagation time, and bandwidth limitation, autonomous capability of rover is essential.

One of the important functions for a planetary rover is to plan a path from a start point to a goal without hitting obstacles. Path searching in a structured world with polygonal obstacles has received considerable attention as part of the general problem of robot motion planning, and various algorithms have been proposed [4][5][6][7]. However, there are few outdoor guidance systems that can create a path plan in such unknown and unstructured environment as planetary surface[8][9]. There have also been proposed only few practical path planning methods that consider the size of the robot.

This paper describes a path planning method for planetary rover to search for a path on planetary surface. The model of a rover is introduced to consider the size of planetary rover. This model can be easily modified into any other rover architecture. A planetary rover makes an elevation map by observing the environment. The conventional elevation map was based on the implicit assumption that a rover can be described as a point[10]. We have newly introduced an extended elevation map, which includes the effect of the size of the rover. By using an extended elevation map, path planning can be conducted in such a way as if the rover were a point while the size of the rover is automatically taken into account. The difference of the height in accordance with the different rover orientation is also taken into consideration. The proposed path planning algorithm is based on grid search method.

This paper is structured as follows. In 2nd Section, modeling of the planetary rover is discussed. Then a method to make an extended elevation map is explained in 3rd Section. In 4th Section, a path planning algorithm based on extended elevation map is proposed. Computer simulations are given in 5th Section. Final Section is for discussion, conclusion, and future work of the research.
ROVER GEOMETRY

The performance of a rover moving in unstructured environment depends upon the geometry, such as suspension, size, the number of wheels etc. To consider the size of a planetary rover, a model of the rover is introduced as shown in Fig. 1. Rover geometry is expressed by three parameters, roll angle criterion, pitch angle criterion, and height criterion.

The maximum roll angle $\alpha_{max}$ corresponds to the capability to clear obstacles. The maximum pitch angle $\beta_{max}$ means the maximum angle of inclination for a rover to go over. The height $h_{min}$ means the minimum distance between the body of a rover and the ground to avoid hitting the ground. Though this model shows the case for a four wheel rover, it is easy to adapt such a modeling to any other rover with different geometry.

EXTENDED ELEVATION MAP

Map Data Structure

The planetary rover plans a path based on an elevation map which consists of many square grids. Each grid $G(x,y)$ has the height information $z$ of that point $(x,y)$.

$$z = h(G) = h(x,y)$$  \hspace{1cm} (1)

An elevation map shows the terrain data in front of the rover detected by a sensor. The conventional elevation map is based on the implicit assumption that a rover can be described as a point. Here a new map concept is proposed to include the effect of the size of the rover as shown in Fig.2. A rover actually occupies some grids on the elevation map. So virtual map with the information on the position and the attitude of a rover is proposed. The authors call this map an Extended Elevation Map (EEM). The information about the traversability is added to each grid on EEM. By using EEM, path planning can be conducted in such a way as if the rover were a point while the size of the rover is automatically taken into account.

Figure 1. Model of a rover

Figure 2. Extended elevation map
Judgment of Traversable Area

Traversable area means the area where a rover can stay stably. Now suppose that the position of four wheels of a rover are FR, FL, RR, and RL respectively. And then the position of the center of gravity and the orientation (azimuth angle) of a rover on EEM is to be expressed by \((x, y, \theta)\) respectively. The stability conditions for a rover roll angle and pitch angles are,

\[
\frac{|h(FR) - h(FL)|}{l_w} \leq \tan(\alpha_{\text{max}}) \quad (2)
\]

\[
\frac{|h(RR) - h(RL)|}{l_w} \leq \tan(\alpha_{\text{max}}) \quad (3)
\]

\[
\frac{|h(FR) - h(RR)|}{l_s} \leq \tan(\beta_{\text{max}}) \quad (4)
\]

\[
\frac{|h(FL) - h(RL)|}{l_s} \leq \tan(\beta_{\text{max}}) \quad (5)
\]

The condition for the rover body to avoid hitting the surface of the ground is

\[
h(G_i) < P(G_i) \quad (\forall i=1, \ldots, N) \quad (6),
\]

where \(P\) denotes the plane constructed by the contact points of the wheels with the ground. \(N\) is the number of grids occupied by the rover. If all the conditions from (2) through (6) are satisfied, that area is defined as traversable one. Otherwise such a area means non-traversable one.

The height \(H\) of a rover on EEM is expressed as follows.

\[
H(x, y, \theta) = \frac{1}{4} \left[ h(FR) + h(FL) + h(RR) + h(RL) \right] \quad (7).
\]

**PATH PLANNING**

Extended grids on EEM are searched in the proposed path planning algorithm. Here suppose that the rover can move in eight kinds of directions \((\theta = \frac{\pi}{8} \cdot j \quad (j = 0, \ldots, 7))\). The following two action patterns for the rover are selected.

**Action_1**: move to the neighboring grid without turning
**Action_2**: turn to a different direction at the same place

In the case of a 2-1/2 dimensional environment like the surface of Mars, simple distance does not provide a correct required traverse time since the slope of the terrain can drastically affect the time. A cost function is required for estimating the time and power of motion over a 2-1/2 dimensional terrain. So the path from a start point to a goal is determined in such a way as the following cost function be minimized. The cost function \(E\) consists of two energy functions, the motion energy \(E_{\text{hor}}\) for horizontal movement and the potential energy \(E_{\text{ver}}\) for vertical movement.

\[
E = E_{\text{hor}} + E_{\text{ver}} \quad (8)
\]

where

\[
E_{\text{hor}} = K_1 \cdot \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (9),
\]

\[
E_{\text{hor}} = K_1 \cdot \frac{\pi}{8} \sqrt{l_w^2 + l_s^2} \quad (10),
\]

\[
E_{\text{ver}} = K_2 \cdot \left| H(x_1,y_1,\theta_1) - H(x_2,y_2,\theta_2) \right| \quad (11),
\]

\(K_1, K_2\) : constant.

**SIMULATION RESULTS**

In order to investigate the validity of the proposed method, path planning in a terrain environment shown in Fig.3 is simulated. Table 1 shows the parameters for this simulation. Traversable areas and untraversable areas are obtained as shown in Fig.4. White regions mean traversable areas, and black regions mean non-traversable areas. Gray regions show the areas where a rover can stay stably or not depending upon the orientation of the rover. Figure 5 shows that a reasonable path can be planned by the proposed algorithm. Calculation time is about 3.0[s] (CPU: SPARC IU/FPU 40MHz).

<table>
<thead>
<tr>
<th>Table 1. Parameters for a rover</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>map size</strong></td>
</tr>
<tr>
<td><strong>grid size</strong></td>
</tr>
<tr>
<td><strong>width of rover</strong></td>
</tr>
<tr>
<td><strong>length of rover</strong></td>
</tr>
<tr>
<td><strong>wheel base</strong></td>
</tr>
<tr>
<td><strong>distance between right wheel</strong></td>
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<tr>
<td><strong>distance between left wheel</strong></td>
</tr>
<tr>
<td><strong>start point</strong></td>
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<tr>
<td><strong>goal point</strong></td>
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<td><strong>K_1, K_2</strong></td>
</tr>
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</table>
CONCLUSION

A new path planning for a planetary rover has been presented in this paper. The validity of the proposed method is confirmed by computer simulations. Experiments of mobile robot in an outdoor environment are under planning.

REFERENCES


