Vision Based Behavior Planning for Planetary Exploration Rover

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Abstract

In recent years, many researchers have studied and developed unmanned mobile robots for lunar or planetary surface exploration. Rovers need to move autonomously, because there is communication delay between the earth and the moon or planets. This paper describes how a lunar or planetary rover can plan its behavior autonomously and efficiently. This paper proposes a method to know the surroundings of a rover with one gray-level image obtained from a payload camera. This paper also proposes a method to plan a rough route to the given goal and follow the route. The effectiveness of the proposed methods is shown by computer simulations.

1 Introduction

In space missions, exploration rovers have especially attracted the attention of scientists and engineers. Rovers can move widely on the surface of the moon or planets searching for minerals and other scientific materials. Therefore rovers are expected to make an important role for the near future missions of lunar or planetary exploration. One of the essential functions for rovers is that they can reach the area exactly, where scientists would like to investigate. And also rovers need the ability to move autonomously. Because there is some communication delay between the earth and the moon or the planet.

The planetary exploration rover : Sojourner, which was operated by NASA/JPL, succeeded in exploring on the Mars in 1997[1]. Recently many researchers have earnestly studied and developed rovers with higher performance than Sojourner. Rovers have the following restrictions:

- Power consumption is limited.
- Only electronic machines, which are available in space environment, can be used.
- The lighter rovers are better, because the payload of the rocket is limited.
- Rovers are expected to have ability to explore as widely as possible during the limited exploration period.
- There is communication delay.
- Rovers have to recognize unknown environment and move on the rough surface.

Therefore exploration rovers need the ability to process sensing data as fast as possible and to navigate themselves efficiently.

Conventional behavior planning methods are as follows:

- The sensing data from LRF (Laser Range Finder) or stereo vision are processed and transformed to DEMs (Digital Elevation Maps), and the path is planned based on DEMs[2]-[4].
- The fuzzy rules are used for environment recognition and path planning based on the range information obtained from LRF or stereo vision[5][6].
- The steering control to avoid obstacles is done based on the rage information obtained from stereo vision[7].

With those methods, rovers can avoid obstacles exactly. However those methods have the following problems. Therefore rovers cannot travel over long distance at once.

(1) Rovers cannot get the information about far environment.
(2) Rovers have to stop each time, because sensing and processing time is so long.
(3) Rovers have to repeat the same processing and navigate themselves even when there is no obstacles in front of them.

A method to plan behavior with using a single camera was proposed for reduction of computation time[8]. The proposed system consists of three independent vision modules for obstacle detection. Each of vision modules is computationally simple and uses a different criterion depending on the purpose of detection. These criteria are based on brightness gradients, RGB (Red, Green, Blue) color, and HSV (Hue, Saturation, Value) color, respectively. However, the sensing area of the system is not so wide. Therefore the proposed method also has the problems (2)(3).

The environment such as the moon and planets have the flat surface and a few obstacles for rovers on the surface. In order to move efficiently and without stopping for sensing, therefore, it is necessary that rovers recognize the environment widely, from the near-area to the far-area.

This paper describes an efficient scheme to plan travel behavior for lunar or planetary exploration rovers. Here planning travel behavior consists of rough route planner and sensing strategy planner. This paper proposes a method to recognize wide area based on the image and a method to plan rovers' behavior based on environment recognition.

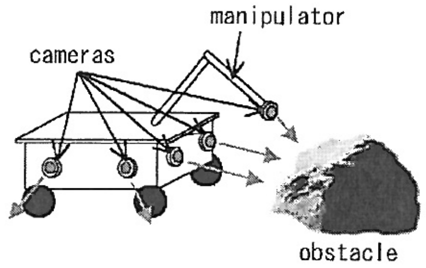


Figure 1: Exploration Rover with Cameras

2 Behavior Strategy

2.1 Navigation Ability

First of all, let's discuss how people go to their destination for developing the navigation ability rovers should have. People usually recognize their environment with their eyes. After the recognition,

- if there are any obstacles in front of them, they find the path they can avoid obstacles and proceed paying attention to them.
- if there is no obstacles in front of them, they proceed as fast as they like.

Therefore, people seem to change the processing information in their brain according to the environment. Hence autonomous rovers requires the following abilities:

- the ability to know generally the far information and the near information at the same time
- the ability to change the environment recognition schemes depending on their situation

2.2 Navigation Sensor

A camera is used as a navigation sensor, because rovers can get the environment information including far and near area. Moreover rovers usually carry cameras for scientific observation. And recently the weight of camera becomes lighter and the size becomes smaller. So it is possible for rovers to carry a lot of cameras. Many cameras make the view of rovers wide. Figure 1 shows the illustration of the rover with cameras. For example, when rovers can carry cameras on four sides; front, rear, left and right, they can make panorama images and recognize wide area around them. The manipulator system with a camera gives the ability to look at the same environment from the different direction. Therefore, cameras are suitable sensors for navigation.

2.3 Behavior Strategy

Images obtained from a single camera have a lot of environment information from the area near rovers to the skyline. However, it is difficult to go to the destination with only gray-level images, because information on the farther area is more ambiguous.

Accordingly, the authors propose a method to know the situation around the rover and plan the behavior based on gray-level images. Figure 2 shows the flowchart of the proposed strategy. Firstly the rover turns to the direction of the given goal at Start Point (SP) and then recognizes the environment. The rover plans a rough route and sensing strategy based on recognition results. In the safe-area, the rover recognizes the environment locally with gray-level images. When a rover is close to the dangerous-area, the rover changes the navigation method and avoid the dangerous area correctly. And then the rover updates the environment data by local sensing to reduce uncertainty.

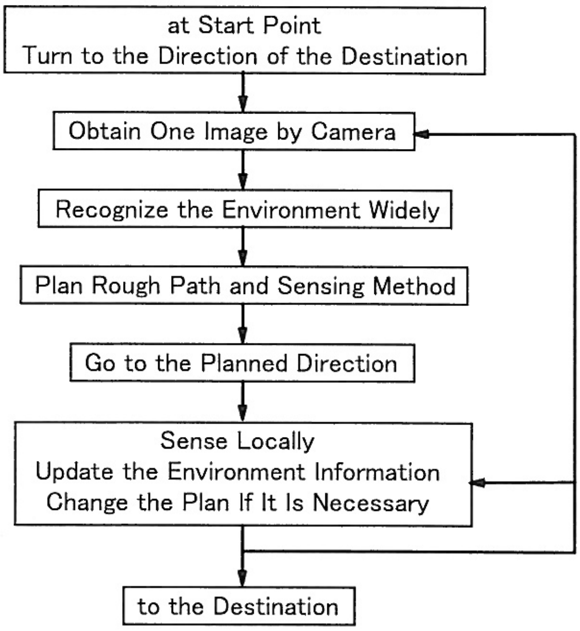


Figure 2: Behavior Strategy

3 Environment Recognition

3.1 Extraction of dangerous-area

When people see the gray-level images of lunar surface, they judge as follows:

- white areas are "safe areas"
- areas with a lot of shade change are "rough areas"

Hence the safe-areas for rovers are the whiter area with little shades change. In the gray-level image, shades indicate the rate of white and variances indicate changes of shades.

For the extraction of dangerous-area, the gray-level image is meshed. Each mesh is called "Window". From the result of calculation for the shades average and the variance in each Window created on the image, dangerous-areas are extracted. Figure 3 shows the coordinate system of the image. Only part of the ground on the image, $0 \leq y \leq y_h$ (y_h is the height of the horizon), is used for the extraction.

The following assumption for the lunar exploration rovers is introduced as follows :

- rover moves on the flat ground
- rover has a single camera, an inclinometer and the sun sensor
- rover has exact time clock

The inclinometer is the sensor which shows the inclination of rovers' body on the ground. When rovers run on the rock etc., the error which appear in the image can be corrected from the inclinometer data. The time and the inclinometer data and the sun sensor data give rovers the information about their direction.

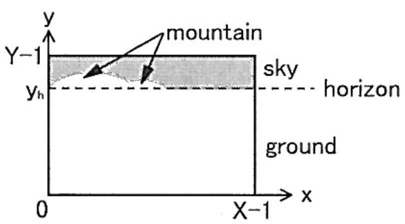


Figure 3: Image Coordinate System

3.2 Window Width

Rocks near rovers look bigger and rocks far from rovers look smaller on the ground. Therefore an obtained image is not meshed evenly. For the bigger y, the image is meshed in a smaller Window. The width of each Window, w_{gk} [pixel] (k = 0,1,2,) (for the shades average) and w_{vk} [pixel] (k = 0,1,2,) (for the variance) are determined as shown in Figure 4. In Figure 4, the angle of the direction of the equipped camera is α[°], the angle of camera's view is β [°], the height of camera is H [m] |the diameter of rovers' wheel is T [m] and the length of rovers' diagonal is R [m]. And d [m] indicates the base length to decide each Windows ($d = R$ at the calculation of the shades average, $d = T$ at the calculation of the variance; the shades average should be calculated from the area rovers can go into, and

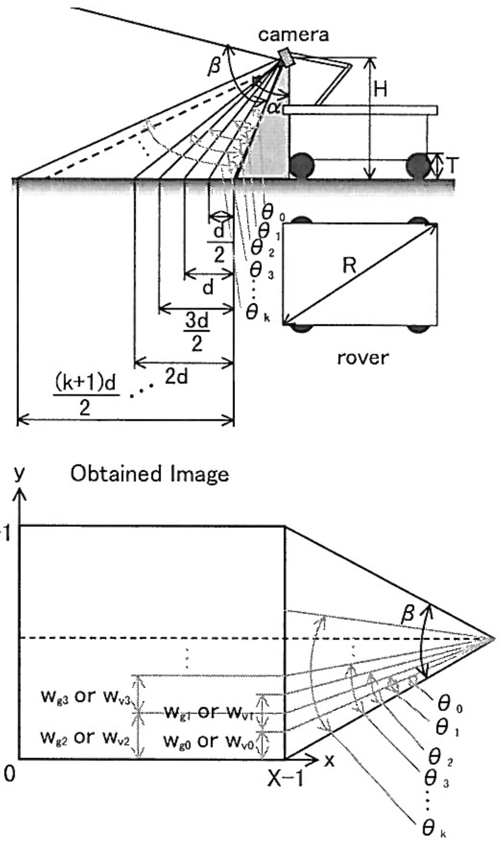


Figure 4: Parameters for Calculation of Window

the variance should be calculated from the height rovers can go over). Each Window is overlapped as shown in Figure 4. Because it happens that the result for the extraction of dangerous-area is biased depending on the position of set Window.

With these parameters, each θ_k's tangent is given from the following equation;

$$\tan\theta_k = \frac{(k+1)d}{2H + \{(k+1)d + 2H\tan(\alpha - \frac{\beta}{2})\}\tan(\alpha - \frac{\beta}{2})} \tag{1}$$

And the width of each Window, w_{gk} or w_{vk}, is given from the following equation;

$$\begin{array}{c} w_{gk} \\ \text{or} \\ w_{vk} \end{array} = \begin{cases} \dfrac{Y(1+\tan^2\frac{\beta}{2})}{2\tan\frac{\beta}{2}} \cdot \dfrac{\tan\theta_k}{1+\tan\frac{\beta}{2}\tan\theta_k} & (k = 0, 1) \\ \dfrac{Y}{2\tan\frac{\beta}{2}}\{\tan(\frac{\beta}{2} - \theta_{k-2}) - \tan(\frac{\beta}{2} - \theta_k)\} & (k \geq 2) \end{cases} \tag{2}$$

The Window size is more than 3 [pixel]. Because it is meaningless that the shades average or the variance is calculated in Window, whose size is 2 [pixel] or 1 [pixel]. $y = y_g$ when the Window size w_{gk} becomes 2 [pixel], and $y = y_v$ when the Window size w_{vk} becomes 2 [pixel]. At $y_h \leq y \leq y_g$, the shades average is calculated with w_{gk} = 3 [pixel]. At $y > y_v$, the variance is not calculated. Therefore, each calculation is done like the following:

- $0 \le y < y_v$
  the shades average and the variance (the value of w_{gk} or w_{vk} changes) are calculated
- $y_v \le y < y_g$:
  only the shades average is calculated (the value of w_{gk} changes)
- $y_g \le y \le y_h$:
  only the shades average is calculated ($w_{gk} = 3$ [pixel])

The reason why the variance is not calculated at $y > y_v$ is that rough area far from rovers can be looked differently from the actual shape.

3.3 Degree of Danger

The degree of danger, $D(x, y)$, to each pixel is calculated based on the image, according to the following sequence;

1) The shades average or the variance to each Window is calculated with w_{gk} or w_{vk} (k = 0,1,2,). Each pixel (x, y) (x,y = 0,1,2,) memorizes the sum of the shades average or the variance, and the number of calibration.
2) From the average of the shades average calculated at each pixel (x, y), the gray-level value $G(x, y)$ is obtained. From the average of the variance calculated at each pixel (x, y), the variance value $V(x, y)$ is also obtained.
3) The degree of danger $D(x, y)$ to each of pixels is calculated from the following equation;

$$D(x,y) = 1 - f_0(V(x,y), B) \cdot \frac{G(x,y)}{N} \quad (3)$$

B is experimentally determined as the threshold of the variance, N is determined as the maximum of brightness, and $f_0(V(x,y), B)$ is calculated from the following equation;

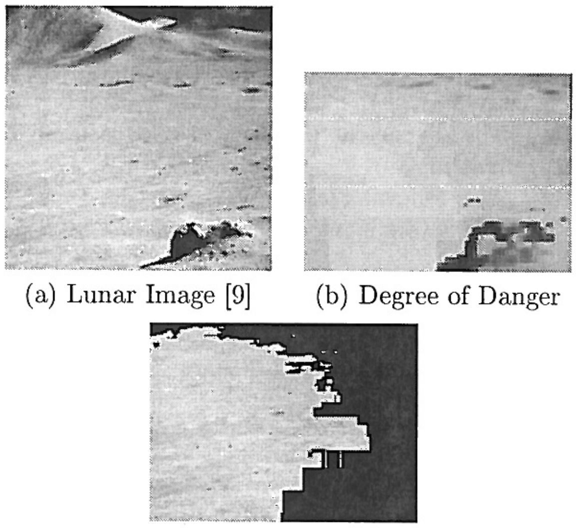
$$f_0(V(x,y),B) = \begin{cases} 1 & \left(\begin{array}{c} y \ge y_v \\ y < y_v : V(x,y) \le B \end{array} \right) \\ \dfrac{B}{V(x,y)} & \left(\begin{array}{c} y < y_v : \\ V(x,y) > B \end{array} \right) \end{cases} \quad (4)$$

The range of the degree of danger $D(x, y)$ is $0 \le D(x, y) \le 1$. And the bigger the degree of danger $D(x, y)$ is, the harder area rovers travel over.

3.4 Simulation Study

To examine the validity of the proposed recognition method, the simulations were performed by using lunar images, which were obtained in the Apollo Mission[9], and the Mars Image, which were obtained at the Mars Pathfinder Mission[1]. Figure 5 shows an example of the simulation results. Figure 5(a) shows the lunar image, (b) shows the simulation result that the degree of danger $D(x, y)$ is expressed by 256 phases, and (c) shows how the environment recognition works by determining the pixels which degree of danger is bigger than the threshold as dangerous area (black area in the image). Compared with Figure 5(a) and (b)(c), it is shown that the dangerous areas for rovers could be extracted by the proposed method.

The other lunar images and the Mars images were also examined, and the same results were obtained.



(a) Lunar Image [9] (b) Degree of Danger

(c) Simulation Result

Figure 5: Simulation Results (Lunar Image)

4 Behavior Planning

4.1 Rough Route Planning

It is difficult for rovers to plan the detailed path based on the gray-level image, because the image contains ambiguous information. Therefore, rovers do not need to trace the planned route exactly, but they turn to the planned direction and follow the planned route. Furthermore, they change their route, when they judge the necessity of changing it from the sensing result on progress.

In planning rough paths on the image, the area "Way Area (WA)", where rovers change their course, is introduced. The threshold for judging whether it is dangerous or not, is decided based the average of the whole shades on the image, the environment and the characteristics of the reflection rate. Because shades on the image depend on the sun light's condition and the reflection rate at the same environment.

On the image, the rough route is planned with the straight routes. The straight route is searched by checking whether any dangerous-areas exist or not. If dangerous-areas exists on the route, it's judged that rovers turn to left or to right. The turning direction is decided by the following two parameters;

- degree of danger $D(x, y)$
- the maximum distance a rover has to leave from the straight route

The area a rover leaves from the straight route maximally on the planned route is defined as a new Way Area, WA_i. According to the dangerous-area searching and the definition of WA_i, the rough route is determined.

Moreover, the start area (SA) on the image, where a rover goes into from the start point, is the square whose Window size is w_{g1} [pixel] (as shown in Figure 6). The position of SA showed in Figure 6 is the initial start position. If the initial start position is judged as a dangerous-area, the new SA is created in the safe area, rovers turn to the direction of the new SA, and move to the new SA. Besides the destination area (DA) on the image is the square whose Window size is 3 [pixel] (as shown in Figure 6). The position of DA showed in Figure 6 is the initial destination position. If the initial destination position is judged as a dangerous-area or the initial destination position should change because of determined WA_i or new SA, the new DA is created.

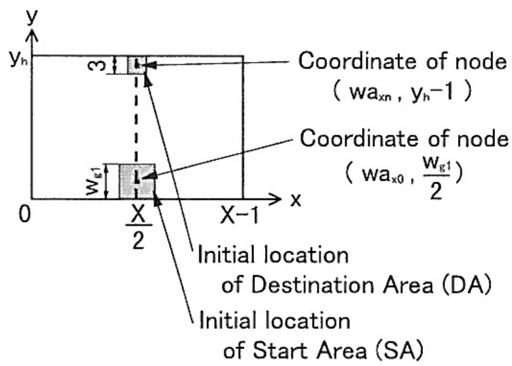


Figure 6: Start Area and Destination Area

4.2 Sensing Strategy Planning

In the environment recognition, the image is divided into three parts (cf. 3.2). According to this division, three parts on the image are defined as follows:

- $y_g \leq y \leq y_l$: Long-distance Area
- $y_v \leq y < y_g$: Middle-distance Area
- $0 \leq y < y_v$: Short-distance Area

Moreover, five-phase Safe Rate is defined on the planned route with the threshold determined at 4.1, as follows:

- safe
- a little safe
- a little attention
- attention
- special attention

Sensing strategy is planned with Safe Rate on the planned route. The list of sensing strategy is as follows:

A move without sensing
B obtain gray-level image locally in progress and confirm the safety in front
C sense the distance between rovers and dangerous areas with LRF or stereo vision in progress
D make a detailed map with LRF or stereo vision and avoid dangerous areas exactly
E do the environment recognition and the behavior planning based obtained image, following the planned route
F turn to the destination and do the environment recognition and the behavior planning based obtained image

The reason why sensing strategy is planned depending on three parts of image is that the ambiguous information on the image is variable according as how the Window size is determined. It is obvious that the 1-pixel's information about the environment and the ambiguous is different comparing between Long-distance Area and Short-distance Area.

4.3 Simulation Study

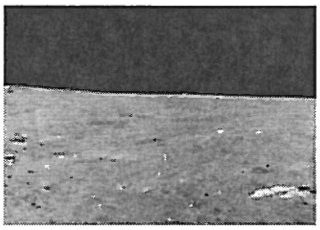
To investigate the validity of the proposed behavior planning method, computer simulations were performed by using the lunar image obtained at the Apollo[9]. Figure 7 shows an example of the simulation results. Figure 7(a) shows the lunar image, Figure 7(b) - (f) show each step of planning rough route respectively. Figure 7(g) shows the result of planning rough route and the area for planning how to sense and Figure 7(h) shows the result of planning how to sense. Two white lines on Figure 7(h) are the border lines between Short-distance and Middle-distance Area, or Middle-distance and Long-distance Area.

The steps of planning rough route are performed as follows:

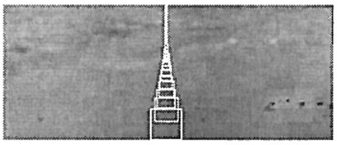
1) search on the straight route as shown in (b)
2) judge whether a rover turns to left or right with two areas, and leave the straight route maximally as shown in (c), because there are dangerous-areas on the straight route
3) determine that the direction of turning is left and the WAs as shown in (d), and change the position of SA, because the initial SA position is in dangerous-area.
4) search on the straight route as shown in (e) and judge there is no dangerous-area on it
5) search on the straight route as shown in (f) and judge there is also no dangerous-area on it
6) therefore, determine the rough route as shown in (g)

The following results of sensing strategy planning are obtained:

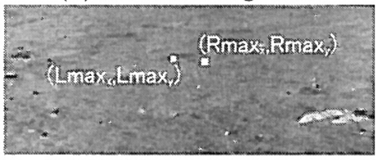
1) at Start Point, "F:turn to the destination and do the environment recognition and the behavior planning based obtained image"



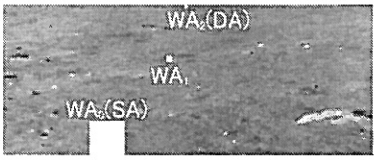
(a) Lunar Image [9]



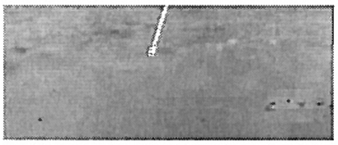
(b) 1st Searching Area



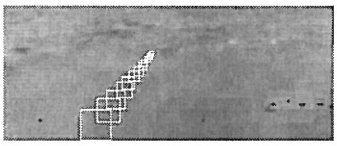
(c) Selection of WA_1



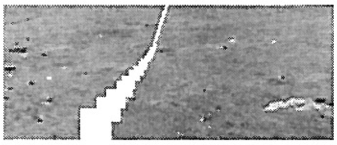
(d) List of WA_i



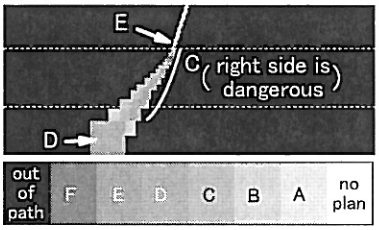
(e) 2nd Searching Area



(f) 3rd Searching Area



(g) Rough Route Planning Result



(h) Sensing Planning Result

Figure 7: Behavior Planning

2) after passing Start Area, "C:sense the distance between rovers and dangerous areas with LR-F or stereo vision in progress" provided that there are dangerous-areas on the right

3) at the border line between Middle-distance and Long-distance Are, "E:do the environment recognition and the behavior planning based obtained image, following to the planned route"

As a result, the reasonable rough route and sensing strategy were planned. The other lunar images were also examined and good results were obtained.

5 Conclusion

This paper has presented a vision based method to plan travel behavior for lunar exploration rovers. In the proposed method, travel behavior was planned by judging whether it is safe or danger at the area, based on gray-level image obtained from a payload camera. The shades average and the variance at each pixel were calculated to recognize the environment widely. Computer simulations showed that a reasonable rough path and sensing strategy were planned by the proposed method.

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