Probe Point Selection Strategy for Lunar Rover Based on Particle Swarm Optimization

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Abstract. In order to successfully complete the exploration mission on moon surface, it’s necessary to choose a suitable probe point to plan a feasible path for lunar rover. In this paper, a probe point selection strategy is presented. The proposed strategy consists of the following three steps: Firstly, the feasible region on a given terrain map is generated by Breadth-first search algorithm based on rover travers ability; secondly, the evaluation cost of the probe point is constructed by geography information and light condition; finally, an optimal point that satisfies the constraint is selected by particle swarm optimization (PSO). In order to verify that the selected probe point can be safely arrived, the path of the rover is planned by A* algorithm. The experimental results show the correctness and feasibility of the proposed probe point selection strategy.

1. Introduction
The lunar rover is a spacecraft that can be applied to the lunar environment, moving on the lunar surface while carrying scientific instruments, and can complete tasks such as detecting soil, sampling, and carrying objects [1]. When using the lunar rover for lunar soil exploration mission, it is necessary to determine the probe point and plan path to that point for the lunar rover [2]. A suitable probe position and a safe path not only ensure the successful completion of the exploration mission, but also ensure the safety of the lunar rover. Hence, there is an urgent necessity to propose a probe point selection strategy and the motion planning method for lunar rover.

Probe point selection is the first step in the exploration mission. At present, there are few researches on the selection of probe points in the literature. Under normal circumstances, the probe point is selected by the operator by means of empirical knowledge in a three-dimensional terrain, which reconstructed by the vision system carried on the rover [2]. This does not take advantage of the rich three-dimensional information of the lunar surface and lacks scientific basis. Therefore, this paper proposes a probe point selection strategy by constructing the evaluation cost of the probe point. First of all, we obtain the feasible region of the rover on the lunar surface by constructing the lunar surface travers ability cost. Secondly, we construct the evaluation cost of the probe point by geography...
information and the light condition. Finally, the optimal probe point is selected based on the particle swarm optimization algorithm.

After obtaining the lunar probe point, path should be planned to enable the rover reach the probe point safely and efficiently. There are many path planning algorithms for lunar rovers, such as artificial potential field method [3], genetic algorithm [4], ant colony algorithm [5], neural network [6] and A* algorithm [7]. The A* algorithm is a heuristic algorithm, which is widely used in intelligent robots due to its search efficiency is relatively high and easy to implement. Because the lunar rover has the ability to cross obstacles, the path planning algorithm applied to the rover needs to be considered the rover’s mobility and terrain characteristics [8]. Therefore, this paper proposes a path planning algorithm of rover based on the combination of A* algorithm and travers ability of the lunar.

The remainder of this paper is follows: the probe point selection strategy is introduced in chapter 2; the path planning for lunar rover is studied in chapter 3; the feasibility of the proposed methods are verified by the simulation in chapter 4; finally, conclusions summarizes the paper in chapter 5.

2. The probe point selection strategy

2.1. The travers ability

The lunar surface DEM defines the position and height information of a series of discrete points on the lunar surface. Each point can be represented by a three-dimensional vector as follows.

\[ \{V_i = (x_i, y_i, z_i), i = 1, 2, \ldots, N\} \]  

(1)

In order to solve the feasible region of the lunar rover in the lunar surface, firstly, the DEM is divided into grids, each grid cell has a travers ability cost, which is defined by the lunar slope and flatness. And then the feasible region is obtained by breadth-first search algorithm. The size of the grid cell is determined according to the geometric characteristics of the lunar rover, as shown in Fig1.

![Fig. 1 dividing the grid according to the geometry of the lunar rover, enabling 9 grid cells to envelop the projection of the lunar rover in the horizontal plane](image)

For the definition of the travers ability, we consider the following two aspects:

(1) slope cost

The degree of inclination of the lunar surface relative to the horizontal plane can be described by the slope vector. The slope vector can be represented by two angle values as follow.

\[ V_p = (\theta, \varphi) \]  

(2)

Where \( \theta \) represents inclination angle, \( \varphi \) represents the direction of the vector in the horizontal projection.

For each grid cell, the tangent plane can be fitted by least square method through the elevation information in the surrounding nine grid cells. We assume that the tangent plane is \( z = ax + by + c \), then the value of \( a, b, c \) can be obtained by least square method.
Calculate the slope of lunar surface as shown in Fig 2. The normal vector of the tangent plane 
\( z = ax + by + c \) is \( n_1 = \{a, b, -1\} \) and the normal vector of the reference plane \( z = 0 \) is \( n_2 = \{0, 0, 1\} \)

\[
\begin{align*}
\cos \theta &= n_1 \cdot n_2 = \frac{1}{\sqrt{a^2 + b^2 + 1}} \\
\sin \varphi &= \frac{b}{\sqrt{a^2 + b^2}}
\end{align*}
\] 

(3)

According to the lunar rover motion constraint, when the lunar slope is greater than a certain angle, the rover will can’t pass. Therefore, the slope cost function of rover through a grid cell can be defined as follows:

\[
f_s(\theta) = \begin{cases} 
\frac{\theta}{\theta_{\text{max}}} & \text{if } \theta < \theta_{\text{max}} \\
\infty & \text{if } \theta \geq \theta_{\text{max}} 
\end{cases}
\] 

(4)

Where \( \theta \) is the slope of the grid cell, \( \theta_{\text{max}} \) is the maximum slope that the rover can pass. \( f_s(\theta) \) is the slope cost of the grid cell.

(2) Barrier cost

The barrier cost is described by the distance between the positive point and negative point of the grid cell that are furthest from the fitted plane, denoted by \( L = L_1 - L_2 \), as shown in Fig 3.

The distance \( L_i \) from any elevation point \((x_i, y_i, z_i)\) in the grids to the fitted plane is expressed as follows:

\[
L_i = \frac{|ax_i + by_i + c - z_i|}{\sqrt{a^2 + b^2 + (-1)^2}}
\] 

(5)
The lunar barrier cost function is defined as:

$$f_L(L) = \begin{cases} \frac{L}{L_{\text{max}}} & L < L_{\text{max}} \\ +\infty & L \geq L_{\text{max}} \end{cases}$$  \hspace{1cm} (6)$$

Where $L$ is the barrier description of the grid cell, $L_{\text{max}}$ is the maximum lunar barrier cost that can be accepted by a rover, $f_L(\theta)$ is the lunar barrier cost of grid.

According to equations (4) and (6), the travers ability cost of the lunar rover in a certain grid cell can be defined by Linear-weighted. The travers ability cost $f_e(e)$ of a grid cell $e$ is defined as follows:

$$f_e(e) = \alpha f_L(\theta_e) + (1-\alpha) f_L(L_e)$$  \hspace{1cm} (7)$$

Where $\alpha$ represents the weighting coefficient, and its value in the range of $[0,1]$.

2.2. Evaluation indicator of probe point

The lunar rover has certain requirements on the flatness and illumination conditions at the probe point when performing the exploration mission [9]. Therefore, we need to evaluate the flatness and illumination conditions of the area near the probe point.

(1) Probe point flatness evaluation

In this paper, the flatness of the terrain is represented by the average deviation of the area near the probe point. The average deviation is defined as:

$$\overline{D} = \frac{1}{N} \sum_{i=1}^{N} d_i$$  \hspace{1cm} (8)$$

Where $d_i$ represents the absolute distance from any elevation point $(x_i, y_i, z_i)$ in the area to the fitting plane, it is defined as follows

$$d_i = \frac{a x_i + b y_i + c - z_i}{\sqrt{a^2 + b^2 + (-1)^2}}$$  \hspace{1cm} (9)$$

According to formula (8), the flatness of the area near the probe point can be calculated. The size of the nearby area is determined by the circle centered on the probe point and $r$ is the radius. When the value of $\overline{D}$ is greater than the maximum allowable flatness $D_{\text{max}}$, it is considered that the probe point does not meet the flatness requirement. Otherwise, the probe point is considered to meet the requirement, but a certain flatness cost is required according to the value of the flatness $\overline{D}$. The flatness cost is defined as follows:

$$f_d(\overline{D}) = \begin{cases} \overline{D} & \overline{D} < D_{\text{max}} \\ \frac{\overline{D}}{D_{\text{max}}} & \overline{D} \geq D_{\text{max}} \end{cases}$$  \hspace{1cm} (10)$$
2) Probe point illumination evaluation
We use the angle between the reflected light of the sun and the axis of the detector to indicate the illumination evaluation of the point. The probe point lighting environment is as shown in Fig4.

![Probe Point Lighting Environment](image)

**Fig. 4** probe point lighting environment

The incident angle of the solar light can be obtained from the basic ephemeris, the normal of the fitting plane can be obtained by formula (3). Therefore, when the end position and posture of the arm is known, the axis of the spectrometer and the reflected light can be calculated. The angle is calculated as follows:

\[
\alpha = \theta + \theta_{\text{solar}} + \theta_{\text{robot}}
\]

(11)

Where \( \theta \) represents the angle between the fitting plane and the horizontal plane, which can be calculated by (5); \( \theta_{\text{solar}} \) represents the solar elevation angle, which can be calculated by the ephemeris; \( \theta_{\text{robot}} \) represents the angle between the axis of the detecting instrument and the horizontal plane, which is a known value. When \( \alpha \) is greater than a certain value \( \alpha_{\text{max}} \), it is considered that the probe point does not satisfy the illumination condition. Otherwise, the detection point satisfies the illumination constraint of the probe point, and a certain illumination cost is required. The illumination cost of the probe point is defined as follows:

\[
f_j(\alpha) = \begin{cases} 
\frac{\alpha}{\alpha_{\text{max}}} & \alpha < \alpha_{\text{max}} \\
+\infty & \alpha \geq \alpha_{\text{max}} 
\end{cases}
\]

(12)

2.3. Probe Point Selection Strategy Based on Particle Swarm Optimization
(1) Particle encoding
For the lunar surface DEM, since there is no overlapping data in the \( z \) direction, when determining the \( (x, y) \) coordinates of a point, its \( z \) coordinate is also determined by DEM. So the position vector of particle \( i \) is defined as \( \mathbf{x}_i = (x_{i1}, x_{i2}) \) (where \( x_{i1} \) corresponds to the \( x \) coordinate of the probe point, \( x_{i2} \) corresponds to the \( y \) coordinate of the probe point), and the velocity vector is defined as \( \mathbf{v}_i = (v_{i1}, v_{i2}) \).
(2) Particle initialization
The number of particles in a population used for optimization is denoted as $n$, and each particle of the population is encoded as described above, each particle representing a probe point. Before optimization, the initial value $x_i$ of each particle is randomly selected within the DEM range, and the velocity of each particle is also randomly selected within a limited range.

(3) Fitness function
The flatness cost and illumination cost of each particle can be solved by equations (10) and (12). The fitness function $f_i$ of particle $i$ is defined as follows:

$$f_i = \frac{1}{f_i + f_{i+1} + 1}$$  \hspace{1cm} (13)

(4) Update of velocity and position of the particles
Let $pbest_i$ be the optimal position searched by particle $i$, and $gbest$ is the optimal position searched for the whole particle population. The iteration equation for particles velocity and position are as follows:

$$v_i^{k+1} = wv_i^k + c_1r_1(pbest_i - x_i^k) + c_2r_2(gbest - x_i^k)$$  \hspace{1cm} (14)

$$x_i^{k+1} = x_i^k + v_i^{k+1}$$  \hspace{1cm} (15)

Where $i$ represents the serial number of particle; $k$ represents the number of iterations; $r_1$ and $r_2$ are random numbers, ranging from 0 ~ 1. $w$ represents the inertia factor. The constants $c_1$ and $c_2$ are called learning factors, which enable the particles to self-summary and learn from the best individuals in the population, thus constantly approaching their historical optimal position and the historical optimal position of the population.

3. Path planning based on A* algorithm

3.1. A* algorithm
In this paper, the A* algorithm is used to solve the path search problem of the rover. The main idea of this algorithm is to find the shortest path between the starting point and the destination point based on the cost function. The cost function is defined as follows:

$$f(n) = g(n) + h(n)$$  \hspace{1cm} (16)

Where $f(n)$ is the predicted value of the path cost of the starting point through node $n$ to the destination point; $g(n)$ is the actual value of the path cost from node to node $n$; $h(n)$ is an estimate of the path cost from node $n$ to the destination point.

3.2. Cost function definition
A* algorithm is based on a grid map. The grid cells are categorized into source cell, destination cell, free space cells and obstacle cells. We distinguish free space cells and obstacle cells by calculating the travers ability of the grid, is shown in Equation (7). When a grid cell is free, its travers ability has a value range of $[0, 1]$. Otherwise, its value is $+\infty$.

Therefore, for the A* algorithm applied to the rover, the cost function is defined as follows:
\[
\begin{aligned}
g(n) &= g(n-1) + c(n) + d(n) \\
h(n) &= d_i(n)
\end{aligned}
\]  \hspace{1cm} (17)

Where \( c(n) \) is the cost of the rover through the grid cell \( n \), and its value can be determined by the following optimization target; \( d(n) \) is the distance cost of the rover from grid cell \( n-1 \) to \( n \); \( d_i(n) \) is the Euclidean distance from point \( n \) to the destination point.

3.3. optimization goal

The difference in optimization goals determines the difference in the cost function of the path search. The optimization goal is a criterion for evaluating the pros and cons of search results. This paper designed two optimization goals to choose from, as follows:

1) Minimize distance

In this case, regardless of the impact of traversability on the path search results, only consider the effect of distance, so \( c(n) \) can be defined as follows:

\[ c(n) = 0 \]  \hspace{1cm} (18)

2) Minimize traversability

In this case, we need to minimize the traversability of the path, then

\[ c(n) = f_i(n) \]  \hspace{1cm} (19)

4. Simulation

In order to verify the feasibility of the probe point selection strategy and the path planning algorithm, this paper first gets a simulated lunar surface DEM through a stereo camera, as shown in Fig 6, and then the simulation experiment of the probe point selection and the path planning for rover are performed.

![Fig. 5 Lunar DEM. (a) is a point cloud obtained by a stereo camera (b) is a reconstructed simulated lunar surface DEM](image)

4.1. The lunar feasible region

The horizontal size of DEM is \( 10m \times 10m \). According to the size of the lunar rover (length equals \( 1.5m \), width equals \( 1m \)), set the grid cell size to \( 0.5m \times 0.5m \). We can calculate the traversability of each grid cell by formula (7), where sets \( \alpha = 0.5 \), the result is shown in Fig 7(a). The lunar feasible region is solved by the breadth-first search algorithm, where the starting point is set to \( (0,0) \), the result is shown in Fig 7(b).
Fig. 6 Schematic of feasible region of lunar surface. The traversability of each grid show in (a), the feasible region is show in (b), in which red labelled grid cell represents obstacles.

4.2. Probe point selection
The simulation experiment of the probe point selection strategy is carried out Based on the PSO algorithm.

| Table 1. | The specific parameters of the PSO algorithm are as follows: |
| Parameters                  | Value             |
| Number of population        | $N = 50$          |
| The maximum number of iterations | $ger = 100$     |
| Inertia factor              | $w = 0.8$        |
| Self-learning factor        | $c_1 = 0.5$      |
| Group learning factor       | $c_2 = 0.5$      |

The variation of the particle distribution is shown in the Fig8.
The particle optimal fitness curve in the iterative process of PSO is shown in the Fig. 7(c). Finally, all particles converge near a point whose coordinates are (904.0451, 862.8302), and the optimal fitness value is 0.84084. We have done a series of such simulation experiments by set different parameters. The experimental results show that the coordinates of the optimal particles are not much different.

4.3. Path planning based on A* algorithm
In order to verify the feasibility of path planning algorithm, we set the coordinates of the starting point to (0, 0), and the coordinates of the destination point are the coordinates of the optimal probe point, which has been obtained in the previous step. According to the task requirements, we perform path search with the minimum distance and the minimum traversability as optimization targets respectively, the experimental results are shown in Figure 10.
5. Conclusion

Based on PSO algorithm, this paper proposes a probe point selection strategy. By analyzing the influence of the lunar DEM on the probe point and the lunar rover, the strategy can realize the intelligent selection of the probe point, with which the autonomous navigation of the rover can be realized by using A* algorithm to reach the probe point. Then this paper performs the probe point selection experiment and the lunar rover path planning experiment based on the simulated lunar DEM. The experimental results show the correctness and feasibility of the proposed strategy.

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