Power-synchronized Path Planning for Mobile Robot in Rough Terrain

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ABSTRACT

This paper presents a path planning method for mobile robot that equips solar array panels (SAP) for its power supply. A new cost function is introduced for the path planning method which considers not only the terrain traversability, but also the power generated from the SAP mounted on the robot. The amount of power generation is calculated from the relative angle between the robot attitude and the time-dependent sun position. A simulation study of the proposed path planning is performed using a dynamics engine which calculates power generation from the SAP and power consumption of the robot while the robot following a given path. The simulation result confirms the usefulness of the proposed method over a classical one, typically in scenarios where the terrain is steep and the time window is in the morning or evening.

1 INTRODUCTION

In recent years, mobile robots in extreme environment, such as volcanoes and planetary bodies, are becoming indispensable for missions that human cannot carry out. The Mars exploration rovers, such as Spirit, Opportunity, and Curiosity have verified the effectiveness of the mobile robot in the precursor mission on the outer planet. These rovers need to possess an autonomous mobility system, enabling them to assess terrain traversability in unknown environment and to navigate itself during missions. Path planning is one of the key factors of the autonomous mobility system in order for the rover to achieve an efficient movement towards a location of interest. Despite the variety in researches on the technique of optimal path finding [1] - [5], there is little research focusing on the power management of the robot in the path planning.

In general for the planetary surface exploration, the rover equips solar array panels (SAP) and rechargeable batteries for its power source. Assuming a practical scenario in the above mentioned mission, unstable power supply may severely limit the rover activity. Therefore, stable power supply as well as less power consumption of the rover need to be sufficiently considered in the path planning phase. Also radioisotope thermal generator (RTG) has been often used for planetary exploration that provides stable power regardless of sunlight; but the power consumption of the rover should be as low as possible to secure its power margin.

Tompkins et al. [6] [7] developed a mission-level path planner called TEMPEST, in which the paths are optimized in combined terms of battery energy and path length. In a recent work Fallah et al. [8] presented a technique for path optimization problems to minimize the energy consumption of a rover with consideration of terrain geometry, and kinematic and dynamic constraints of the robot. A hardware-in-the-loop simulation is developed for the rover's power flow. Sutoh et al. [9] [10] conducted a path planning simulation with a constraint on the power limitation of the mobile robot. The power limitation was determined by the power consumed and generated, which were estimated from the terrain inclination and the shadow observed at the corresponding terrain. The above mentioned studies, however, have been numerically or experimentally tested in a limited number of scenarios and implicitly discussed the effectiveness of the path planner on different types of terrain features.

This paper proposes a path planning method that employs a cost function of the terrain geometry and the power generated by the solar array panels fixed on the rover. A path is basically generated using terrain geometry data. The terrain is modeled as a digital elevation map. A cost function used for the path planning is composed of terrain roughness, terrain inclination, path length, and power generated by the SAP mounted on the rover. The first three indices are directly calculated from the terrain geometry. The last index is given from the area of SAP and the rover orientation relative to the sun position. In this work, path planning simulations are conducted under various terrain features and diurnal variation of the sun direction.

The proposed planning method is compared to a classical planning one. For this comparison, a dynamics simulation of the rover is employed to obtain the power aspect and dynamics aspect of the rover as evaluation metrics. The driving or steering torques that act on the actuators can be calculated from the simulation and used to derive the power consumption of the rover. Also the rover orientation can be useful to obtain the accurate amount of power generation. Such evaluation is performed in cases of different path generation on different types of terrain features.

The rest of this paper is organized as follows: Section 2 present the path planning algorithm proposed in this paper, Section 3 introduces the dynamic simulation model and evaluation metric used for the simulation study. Section 4 describes the simulation study of the path planning and dynamic simulation, and highlights the usefulness of the proposed method.

2 PATH PLANNING METHOD

For the path planning of a mobile robot in rough terrain, the terrain feature is generally discretized into a number of grid-patterned shape (lattice shape), and each intersection of the grid-patterned shape (node) has a certain amount of elevation. The edge of the node defines a cost to travel between adjacent nodes. A path from a start to a goal is then obtained by finding minimum values of the summation of the costs on the path. Hence the definition of the cost is a key aspect in the path planning.

2.1 Terrain Map

Geometric information of terrain, such as obstacle size, slope angle, or roughness is essential for the path planning process. As a major technique to create a terrain map, a LIDAR (light detection and ranging) or LRF (laser range finder) sensor provides point cloud data of the terrain geometry: each point is expressed by three dimensional distance from the sensor to the object. Usually, the point cloud data is converted to a digital elevation map (DEM) in order to reduce the memory space as well as to increase the computational efficiency in the path planning phase. The DEM represents terrain elevations for ground positions at regularly spaced intervals.

In this paper, a DEM in the cylindrical coordinate [11] is used for path planning since such map well represents the characteristic of the LIDAR: variable density of the point cloud data depending on distance from the sensor. The distance interval and the angle interval as seen in Fig. 1 are adjustable: the number of nodes (the circle in Fig. 1) depends on the value of each interval. One node connects with eight edges, allowing the rover to move in eight possible direction from its current node. This paper focuses on the usefulness of the proposed cost function, thus the possibility of the rover staying at the same node is not considered. However, such time-domain planning (motion planning, trajectory planning) will be effective to recharge the battery using a power margin when the battery level becomes low.

2.2 Cost Function

In the path planning, given paths may depend on the components of the cost function. Ishigami et al. [11] proposed a cost function derived from terrain geometry, as follows:

$$E_{ij}=\frac{W_L L_{ij}}{N_L}+\frac{W_B B_{ij}}{N_B}+\frac{W_{\theta_x}\theta_{x_{ij}}}{N_{\theta_x}}+\frac{W_{\theta_y}\theta_{y_{ij}}}{N_{\theta_y}} \tag{1}$$

where E_{ij} represents the cost when a rover moves from node n_i to node n_j, L_{ij} is the distance, B_{ij} is the terrain roughness, $\theta_{x_{ij}}$ is the rover's roll angle, and $\theta_{y_{ij}}$ is the rover's pitch angle. W_L, W_B, W_{θ_x}, and W_{θ_y} are the weighting factors and their values are determined relative to one another. N_L, N_B, N_{θ_x}, and N_{θ_y} are the normalization factors. Here the terrain roughness is calculated as follows. First, the nodes inside the projection area of the rover $\mathbf{R_{ij}}$ are rotated to the local terrain coordinate from the inertial coordinate. Then the roughness is calculated from the standard deviation of the local elevation z' by the following equation [12]:

$$B_{ij}=\sqrt{\frac{I}{N}\sum_{n_k\in\mathbf{R_{ij}}}\left[z_k'-\bar{z}'(\mathbf{R_{ij}})\right]^2} \tag{2}$$

where N is the number of nodes in the region, $\bar{z}'$ is the average elevation in the region, respectively. The cost function tends to create a shorter and lower mobility hazard levels on path.

In the proposed planning method, a new index, power generation, is added to the classical cost function to take account of power status of a rover:

$$E'_{ij}=E_{ij}+W_G\left(1-\frac{G_{ij}}{N_G}\right) \tag{3}$$

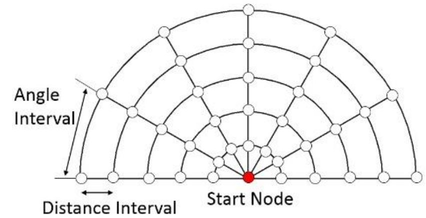


Fig.1. Cylindrical Coordinate DEM

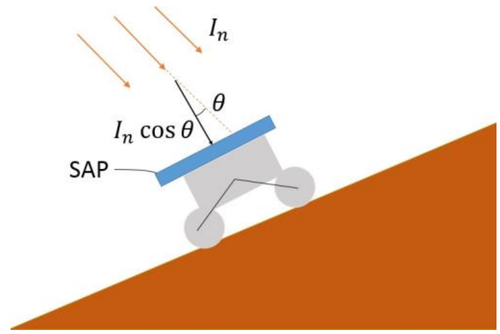
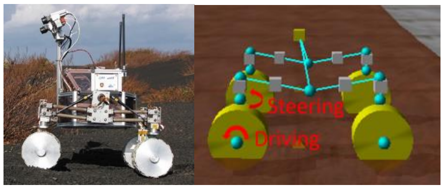


Fig.2. Robot geometry relative to sun/slope



(a) Rover test bed (b) Dynamics model

Fig. 3. Rover test bed and dynamics model

Table 1: Test bed specification

Weight [kg]	36.5
Wheelbase [m]	0.60
Wheeltread [m]	0.50
Constant Power Consumption [W]	66.2
Desired Velocity [m/s]	10.0
Nominal Voltage [V]	12.0

here G_{ij} is the value of power generation, G_L is the weighting factor for power generation, and N_G is the normalization factor, the value of which is assumed as the solar constant in this paper (as described in below).

In the case that solar array panels are fixed on the top surface of the rover being parallel to the horizontal surface, the power generated G, by the solar panel can be calculated by the following equation (Fig. 2):

$$G = \eta A I_n \cos\theta \tag{4}$$

η denotes the conversion efficiency of the solar cells, A denotes the panel area, and I_n denotes the solar constant, respectively. The solar constant is the total radiation energy received from the sun on a surface perpendicular to the sun ray, and its unit is W/m^2. θ is the relative angle composed of the vector of the sun ray and the normal vector of the solar array panel. Measuring the rover orientation from the dynamics simulation note in Section 3, the accurate power generation is calculated using (4).

The 1st term of (3) related to the terrain geometry is assumed as a pseudo power consumption index since steep, long, or, bumpy path requires more power to be traveled. The 2nd term in (3) is inverse proportion to the power generated: large amount of the power generation leads to small value of the index. Therefore the minimization of the total cost will produce an optimal path that modestly considers the power margin of the rover.

There are research working on changing the angle of the SAP with reference to the sun elevation angle. Both method, fixing the SAP or making it movable, have advantages and disadvantages. Fixing the SAP will be hard to earn high power generation, but it does not require any actuators which would be often favorable for a rover on planetary exploration. Moving the SAP generates more power, but will require an actuator(s) to continuously point the SAP to the sun which will lead to constant power consumption. In addition, a typical risk of this approach is that a malfunction of the actuator would occur and the SAP faces towards unexpected direction, resulting in a less power generation. Either approach can be selected through trade-off studies for a target rover mission. Here, in our work, a fixed SAP is selected as a standard approach for planetary exploration mission.

3 DYNAMICS SIMULATION MODEL AND EVALUATION METRIC

Dynamics simulation can be used to quantify travel time, rover state, power generation and consumption. In this section the dynamics simulation model is explained. The rover in the simulation is referred to the rover test bed developed in the authors' group, and the dynamic model is shown in Fig. 3(b). The basic specification is shown in Table. 1. The parameters for each link and the constraint condition for each joint is precisely set based on the CAD data of the test bed.

The contact mechanism between the ground and the wheel is modeled as the spring-mass-damper system. An open source library, the Open Dynamics Engine [13], is employed to solve the rigid body dynamics and to detect the collision between the ground and the wheel.

The path given from (3) is represented by a number of consecutive nodes, and the rover in the simulation is required to follow the nodes. A path following control in the simulation is based on the method proposed by Ishigami et al. [14]. Applying a feedback control to obtain the desired wheel velocity and steering angle, the torque τ on each actuators can be calculated from the simulation.

The values of the joint torque are then used to estimate the variable power consumption of the rover using the following equation:

$$W_{motor} = V \frac{\tau}{i k_i \eta_h} \tag{5}$$

where V is the nominal voltage induced to the motors, i is the gear ratio, k_i is the torque constant (motor constant), η_h is the transmission efficiency of the gear train of the motor head.

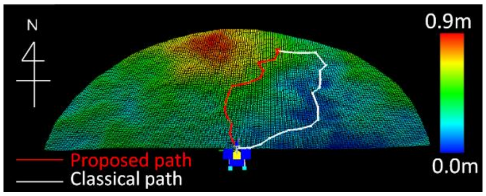
The power consumed by the rover, C, is divided into two factors:

$$C = C_{const} + C_{unconst} \tag{6}$$

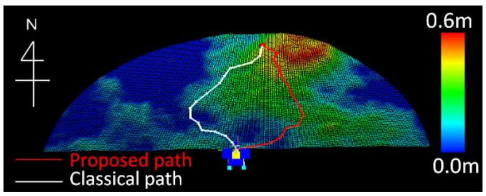
C_{const} is the constant power, regardless to the path. For instance, C_{const} includes the power consumed by the rover components such as camera, on board PC, and IMU. The other factor $C_{unconst}$ is the power consumed by the driving and steering actuators of the rover calculated from (5). Then the power margin is calculated, which is the difference of the power generation and the power consumption.

The energy used for the path traverse is then calculated as the time integral of the power profile.

One remarkable advantage of the use of the



(a) Case1



(b) Case2

Fig. 4. Examples of path planning with classical/proposed method

Table 2: Simulation Condition

Gravity [m/s^2]	3.71
Solar Constant [W/m^2]	600
SAP area [m^2]	1.00
SAP efficiency [-]	0.25

dynamics simulation is to obtain such energy-based quantitative result that is useful to discuss a feasibility of the paths generated.

4 SIMULATION STUDY

The simulation study is performed to discuss the usefulness of the proposed method.

In this simulation, two different paths are generated on a given terrain map: one is based on the proposed method (3) and the other is from a classical method (1) that does not consider the power generation index. The results are examined from the qualitative point of the path difference between the classical and the proposed methods.

First, the path planning method is evaluated by an amount of power generation and a simplified power margin derived from terrain geometry.

Subsequently a dynamics simulation of the path traverse of the rover provides power consumption as well as the dynamic behavior of the rover. These profiles are used for the path evaluation. The parameters used for the simulation study are summarized in Table. 2. Here, the Martian condition is assumed such that the solar constant and gravity become smaller than those on the Earth.

4.1 Path Planning Simulation

In the simulation study, 63 cases of different paths have been generated under 20 sets of the terrain maps by selecting different goal nodes. Paths were generated on a terrain geometrical map expressed with the cylindrical DEM. The goal node is assigned about 8～9 meters from the start position, and optimized paths were obtained using the dijkstra algorithm. The weighting factors were chosen equally: 0.25 for each index in (1), and 0.2 for each index in (3). The virtual terrain map created from the MATLAB code was used in 38 of 63 cases, and the rest of them were in the real map obtained from volcanic field. The threshold angles for the roll and pitch are set as 7.5 degrees for nominal case and 15 degrees for challenging scenario. When the values of the roll and pitch exceed this threshold a feasible path is not generated. These values of the threshold were derived by a mobility test using the corresponding rover test bed. Once a path is generated, the power margin can be roughly estimated. The power consumption is predicted from geometrical features: traction load due to the gravity and steering angle between nodes. To evaluate the difference between the classical path and the proposed path, we focused on the percentage increase. Note that the positive value of the percentage indicates that the proposed method provides more power-efficient path as compared to the classical method does.

Typical examples between the simulation results is shown in Fig. 4. The white line shows the path generated by the classical method, and the red line shows the one from the proposed method. It is clearly seen from Fig. 4 that these two paths are different: the path with the classical method passes almost smooth surface to let the rover avoid from a mobility hazard such as vehicle rollover. Meanwhile, the path generated by the proposed method is drawn such that the rover is exposed under larger amount of the sunlight. It should be noted that not all the cases show remarkable difference between the two paths as seen in Fig. 4. This was due to the sun position, terrain feature characteristics, or the values of the weighting factors. Given larger value of the weighting for the power generation in (3) as compared to the other indices, much difference path may be generated. However, in this simulation, equivalent weighting factors were given for fair comparison between the paths generated by the classical/proposed methods. For practical scenario, the values of weighing factors should be carefully selected under a trade-off: shorter path length, larger power generation, or smooth terrain. Such trade-off is related to multi-objective optimization problems [15] [16], which is out of scope of this paper and remains as a future work.

The rate of increase on the power generation becomes positive in most cases: 49 paths out of 63 trials are positive. Other cases in which the rate of increase becomes negative are 14 cases with respect to 63 cases, but the average value of the rate is negligible (about -0.22 %). The result basically depends on the terrain inclination since the power generation index defined in (4) includes the terrain angle. The rate of increase on the power margin was positive in 45 paths out of 63 trials. Fig. 5 shows

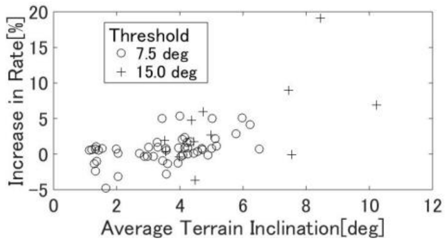


Fig. 5. Correlation between terrain inclination and power margin

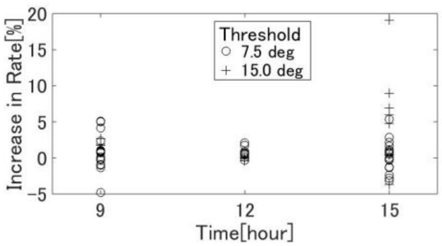


Fig. 6. Relationship on time and power margin

the relationship between the rate of increase of the power margin and the average terrain inclination.

It is clearly seen that the increase has a positive correlation (correlation factor is 0.61) in accordance with the terrain inclination. Fig. 6 indicates different rates of increase with respect to the local time. The figures show that the proposed method is more effective when the terrain inclination is high, and has more positive influence at the morning and evening. As the terrain inclination gets higher the rover can tilt the solar panel such that the solar array panel faces as perpendicular as possible relative to the sun ray. The explicit deviations are seen in the morning and evening, while they are negligible in the midday since the power generation at that time would not diverge at each node.

The following subsection addresses dynamics simulation which enables accurately calculating the power consumption of the rover, dynamic behavior of the rover, and path traversability.

4.2 Dynamics Evaluation

As described above, the dynamics simulation provides motion profiles of the rover while traveling on a given path. Here, two paths, one of which is generated based on the classical method and the other is by the proposed method, are evaluated from the motion profiles. In the simulation, the rover orientation and the torque consumed at each motor were acquired in 10 millisecond interval.

When the rover testbed following the two paths in Fig. 4, typical results of the dynamics simulation was obtained. Table. 3 summarizes the simulation result related to the power and energy of the rover.

The elapsed time is the duration that the rover spends to follow the given path from the start to goal. The amount of the power generation is basically calculated from (4) but the rover orientation for the equation is assigned as the one given from the simulation. The power consumption is calculated from (5) and (6).

As summarized in Table. 3 case 1 and case 2, the path created by the proposed method enables the rover to generate more power than the classical method: in the case of Table 3 case 1, the new cost function increased the power generation and margin of 2.2 % and 10.2 %, respectively. The average power consumption between two paths are almost equivalent. The total energy margin on the path differs according to the traveling time: the longer the more energy margin earned.

These results could be explained by the time profile of the rover orientation and power indices, which are shown in Fig. 7 and Fig. 8, respectively. From the figures, it is clearly seen that both power generation and power consumption have relationships with the rover orientation. Again, the relevance between the power generation and the rover orientation can be explained from (3) and (4): because of the 2nd term, the proposed method tries to maintain a constant power income, whereas the classical method does not have such constrains so that the path is selectable from a wide range from the given map. The jaggy profiles are observed from the power consumption (Fig. 8): this seems to be caused by the vibration of the rover orientation. The peak power consumption is detected when all three orientation, the roll, pitch, and yaw are changing drastically. The roll and pitch profile of the rover in both paths are within the range of ± 10 degrees, and therefore, the average power consumption between two paths did not show remarkable difference.

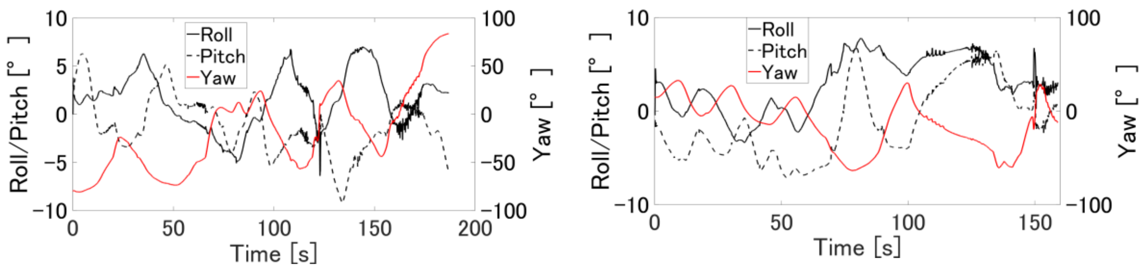
Also the dynamics simulation can be used to judge whether the rover can overcome challenging conditions: mainly high inclination areas. As the proposed path planning algorithm seeks an area where higher sunlight is available, some nodes on the path may include regions where the rover cannot traverse further. These circumstances could lead to mission failure.In this study, the dynamics simulation was performed in order to evaluate the usefulness of the proposed path planning method by comparing the path generated from the classical method, but the dynamics simulation is also useful to double check the path traversability.

4.3 Discussion

The results in the path planning and the dynamics simulation showed that the new cost function has a positive impact on the power generation and margin of the rover. The usefulness of the proposed method increases when the rover traverses terrain where a diversity of sun ray could be observed. The dynamics simulation can be conducted under the condition of bumpy terrains and low battery charge situations. It is difficult to observe the continuous

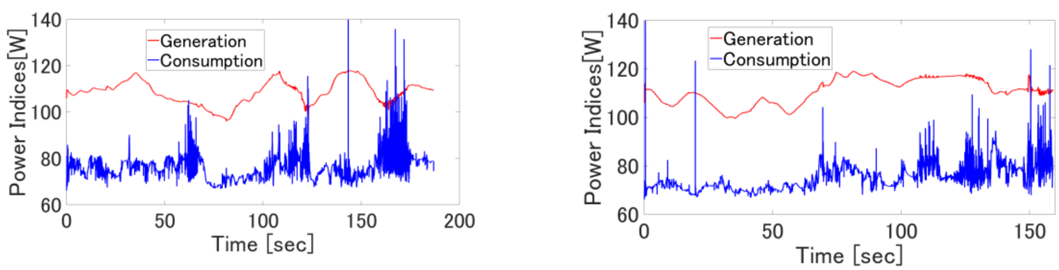
Table 3: Summary of power indices for Fig. 3

	Case 1		Case 2	
	classical	proposed	classical	proposed
Time [s]	187	159	166	161
Average Income [W]	108.5	110.9	96.6	103.1
Average Outcome [W]	76.2	75.1	76.3	76.1
Power Margin [W]	32.3	35.8	20.3	27.0
Total Income [kJ]	20.3	17.6	16.1	16.6
Total Outcome [kJ]	14.2	12.0	12.7	12.2
Energy Margin [kJ]	6.1	5.6	3.4	4.4



(a)classical (b) proposed

Fig. 7. Time profile of rover orientation



(a)classical (b) proposed

Fig. 8. Time profile of power indices

change in the rover orientation from the geometric-based path planning as defined in (3).Thus to calculate accurate power indices the dynamics simulation is essential. The proposed method provides a power efficient path, but it is not always an energy-efficient path. Therefore, a dynamics simulation has to be carried out to elaborate a hazard-free and energy-efficient path for a rover.

The proposed path planning algorithm would be practical at regions where a diversity of sun ray could be observed: scenarios where the terrain is steep or time windows in the morning/evening. The dynamics simulation should be carried out under conditions when the terrain has a wide variety of altitude.

5 CONCLUSION

The main contribution of this paper was to propose a cost function that generates a power efficient path compared to the classical method, and to find out what scenario in which this method was most useful. A new cost function has been proposed by considering the terrain geometry and the power generation of a rover. To evaluate the proposed method from path traversability and power/energy conditions, we conducted a dynamics simulation based on a rover test bed model.

The path planning simulations have been performed under 20 different sets of terrain. From the path planning simulation results, it can be concluded that the proposed method has achieved to generate a path that can increase the amount of the power margin. This improvement is more remarkable in steeper terrain feature and in the morning/evening time window.

From the dynamics simulation results, the new cost function has a positive impact on the power generation and margin of the rover. Also a relation between the rover orientation and power consumption were observed: this could help the power management of a rover, since varied power supply is not favored. It should be noted that the dynamics simulation was performed not for all the cases presented in Section 4.1, and therefore more simulation scenarios should be examined in order to highlight the applicability of the proposed path planning method.

In the path planning simulation, the weighting factors was kept constant and a multi-objective optimization problem remained as a future work. It would be necessary to solve this problem to generalize a power efficient path: it could be dynamically adjusted during the dynamics simulation. Also accurate wheel contact model (terramechanics) could be injected which will improve the quantitative aspect of the dynamics simulation result. This would be helpful to investigate whether pivotal turn or continuous steering consumes more energy.

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