

Optimal path planning based on A* algorithm for submarine mining vehicle

Yuheng Chen^{1,*}, Hongyun Wu¹, Qiru Sui², Yinghao Chen³, Rongyao Wang¹, Bei Chen¹, Bingzheng Chen¹, Jingwei Li¹, Boling Yin¹, and Chunlai Wang²

¹Changsha Institute of Mining Research co. LTD, Changsha, Hunan, 410012, China

²School of Energy and Mining Engineering, China University of Mining and Technology Beijing, Beijing, 100083, China

³Central South University, Changsha, Hunan, 410083, China

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Abstract. Deep sea mining, as a frontier area in China, urgently needs to make progress in automatic navigation technology. In order to improve the operation efficiency of the seabed mining machine on the soft seabed, the submarine mining vehicle which complete the mining work in a certain mining area need to enter the next mining area quickly and economically. As a classical algorithm, the majority of scholars consider that A* algorithm is the most practical path planning search algorithm. Considering the limitation of operation conditions, the three-dimensional diagram is transformed into two-dimensional diagram by interpolation method when the seabed terrain conditions allow, and then the obstacles can be marked in two-dimensional diagram. A* algorithm was applied into the path planning of mining truck. The simulation results of the paper show that path cost, turning time and turning mode should be considered in the process of avoiding obstacles.

1 Introduction

The ocean, which accounts for about 71% of the earth's surface area, is rich in natural resources that has not yet been fully exploited and utilized by mankind. In addition to offshore oil, gas resources and coastal ore sands, metal mineral resources such as polymetallic nodules, cobalt-rich crusts and polymetallic sulfide are all deserved commercial exploitation. There are also more minerals, rich in nickel, cobalt, copper, manganese, gold and silver, than those on land. With the increasing demand for metal resources and the depletion of land-based mineral resources, seabed mineral resources tend to be alternative resources of mankind in the 21st century. The reason why these seabed mineral resources are called deep mineral resources is that they are produced in the seabed with a depth of several kilometers. Obviously, the exploitation of deep-sea mineral resources must rely on deep-sea mining equipment^[1].

* Corresponding author: 2018299266@qq.com

The carrier of seabed mining is the deep-sea polymetallic nodule mining vehicle, which is the most complex and critical part of the deep-sea seabed mining system^[2]. The technical problem faced by the mining vehicle is how to ensure that the mining vehicle can operate normally and reliably in the unknown environment of deep sea, and effectively collect nodules. If the mining vehicle can be driven to the next mining area in the shortest time, it can save costs and improve work efficiency.

Dr. Feng Chen of Central South University used Bessel curve to carry out local path planning, but did not involve global path planning^[2]. Dr. Jing-ni Yuan from Shanghai Jiao Tong University proposed an improved vehicle motion planning method combining RRT* and Bessel curve control point optimization, but it is not suitable for deep-sea environment^[3]. The Korean scholar Sup-hong et al. deduced that the angular velocity during turning should be limited to 0.043rad/s^[4,5,6,7]. Changsha Institute of Mining Research co. LTD., after the mining truck maritime test, concluded that the speed of the seabed mining truck should be controlled at 0.5m/s-1m/s. Considering that there is no sharp turn in obstacle avoidance, the actual turning distance is slightly larger than that of the idealized model. In order to simplify the simulation model, a penalty coefficient α is set for the turning distance. The determination of the parameters will be explained in detail in the following sections.

2 Kinematic model of deep-sea poly metallic nodule mining vehicle

Due to the complicated seabed topography of mining vehicles, the mining vehicles are prone to skidding and subsidence, etc. According to the existing track vehicle motion model and combined with the actual motion state of mining vehicles, a spatial kinematic model of mining vehicles with soft seabed is established, as shown in Fig. 1.

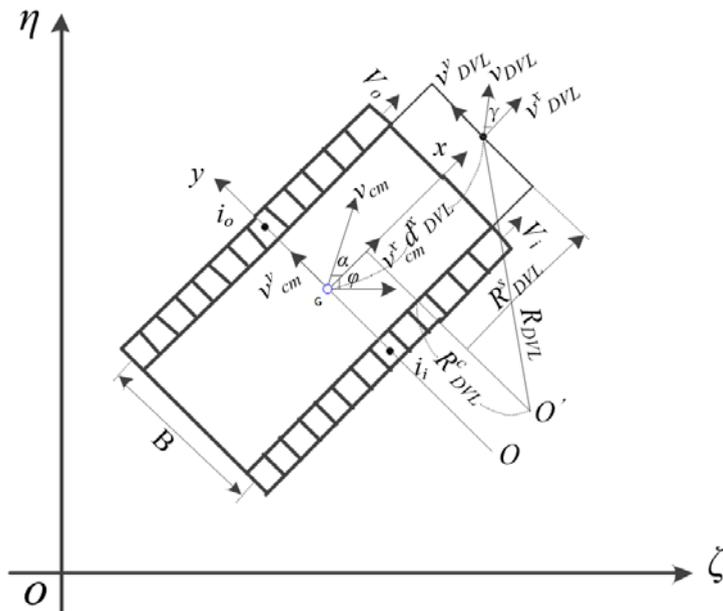


Fig. 1. The model of Submarine mining vehicle motion.

The mining vehicle model of deep sea poly metallic nodules is shown in the Fig.1. Northeast rectangular coordinate system $\zeta\eta$ is established. The carrier coordinate system of the mining vehicle xGy is established, in which G is the original and the instantaneous center

of its steering motion is O' . In order to obtain real-time motion information of the mining vehicle, the mining vehicle is equipped with sensors such as doppler velocimeter (DVL), fiber optic gyroscope (fog), crawler driven motor encoder, etc. The accurate heading Angle of the carrier φ is obtained by fiber-optic gyroscope, and the motion velocity V_o and V_i of the left and right crawler are obtained by track drive motor encoder. Doppler speedometer records the motion speed of mining vehicle V_{DVL} , V_{xDVL} and V_{yDVL} .

In Fig.1 , the center distance of seabed mining vehicle track is B . The motion angular speed of mining vehicle is ω . The real-time skidding rate of left and right tracks are i_o and i_i . The deviation Angle of mining vehicle is α . The kinematic equation of the mining truck is defined as Eq. 1, Eq. 2 and Eq. 3.

$$\dot{X}(t) = \frac{1}{2} \{V_{out}(t)(1-i_o(t)) + V_{in}(t)(1-i_i(t))\} \{\cos \varphi(t) - \sin \varphi(t) \tan \alpha(t)\} \quad (1)$$

$$\dot{Y}(t) = \frac{1}{2} \{V_{out}(t)(1-i_o(t)) + V_{in}(t)(1-i_i(t))\} \{\sin \varphi(t) + \cos \varphi(t) \tan \alpha(t)\} \quad (2)$$

$$\dot{\varphi}(t) = \frac{\{V_{out}(t)(1-i_o(t)) + V_{in}(t)(1-i_i(t))\}}{B} \quad (3)$$

In the steering motion of the mining truck, the instantaneous center of the steering motion changes from O to O' . By calculating the velocity of gravity center G and the deviation Angle of skidding rate of the real-time mining vehicle, the real-time position information of the mining vehicle can be calculated. The real-time position information and real-time speed information (V_{xDVL} , V_{yDVL}) of the mining vehicle are obtained by doppler velodrometer, where the track Angle of the mining vehicle $\gamma(t)$ is calculated as Eq. 4.

$$\gamma(t) = \arctan\left(\frac{V_{DVL}^x}{V_{DVL}^y}\right) \quad (4)$$

The distance between DVL and the instantaneous center O' of steering motion $RDVL(t)$ is defined as Eq 5. where the angular rate is $\dot{\varphi}(t)$.

$$R_{DVL} = \frac{V_{DVL}^y}{\dot{\varphi}(t)} \quad (5)$$

The moving speed of mining truck's center of gravity G is defined as Eq. 6 and Eq.7.

$$V_{CM}^x(t) = V_{DVL}^x(t) \quad (6)$$

$$V_{CM}^y(t) = (d_{DVL}^x - R_{DVL}^s) \dot{\varphi}(t) \quad (7)$$

According to the moving speed of the track and the mining vehicle, the actual slippage rate of the left and right track can be described as Eq. 8 and Eq. 9.

$$i_o(t) = \frac{V_o(t) - [V_{CM}^x(t) - \varphi(t)B]}{V_o(t)} \quad (8)$$

$$i_i(t) = \frac{V_o(t) - [V_{CM}^x(t) + \varphi(t)B]}{V_{in}(t)} \quad (9)$$

The deviation Angle α of mining vehicle is defined as Eq. 10

$$\alpha(t) = \arctan\left(\frac{V_{CM}^x(t)}{V_{CM}^y(t)}\right) \quad (10)$$

Therefore, the motion equation of mining truck in dilute soft substrate is defined as Eq. 11 and Eq. 12

$$X(t) = V_{CM}^x \{\cos \varphi(t) - \sin \varphi(t) \tan \alpha(t)\} \quad (11)$$

$$Y(t) = V_{CM}^y \{\cos \varphi(t) + \sin \varphi(t) \tan \alpha(t)\} \quad (12)$$

Based on studies and sea trials, the mining truck is about 8m long, 5m wide and 3m high. The minimum turning radius is 15m. The speed of straight line is between 0.5m/s and 1m/s, and the angular speed of turning is limited to 0.043rad/s.

3 Software simulation

3.1 A* algorithm

Path planning of A* algorithm is a classical path planning method at home and abroad, which is considered as the most practical search algorithm by great majority scholars, especially suitable for path planning. The cost function of A* algorithm is composed of two parts, which is defined as Eq. 13.

$$f(x) = g(x) + h(x) \quad (13)$$

where the cost of searching from the starting point to the current search point is defined as $g(x)$, and the cost of searching from the current search point to the end point is defined as $h(x)$. It is necessary to select the evaluation function reasonably, which affects the rationality of algorithm directly. The visited nodes which are the minimum cost of points in the OPEN queue are stored in CLOSED queues. The ordered set of points in the CLOSED queues is the coordinate value of the two-dimensional trajectory we seek. The improved A* algorithm^[8] is used in this paper. Search in the 2d equivalent digital graph which stores the obstacle information, saving passable points to the OPEN table. All the search points in the CLOSE table meet the constraints of the mining truck, and the point with the minimum value of the evaluation function is put in the OPEN table as the current point of the next search range, and then the specified search range is continued^[9]. The track is the optimal track of the mining truck. The specific steps of A* algorithm are as follows.

- (1) empty the OPEN queue and CLOSED queue;
- (2) put the starting point A of the mining truck path into the CLOSED queue as the current point, and put the satisfied feasible point into the OPEN queue;
- (3) calculate all the points in OPEN queue and find the minimum point;
- (4) put the point into the CLOSED queue as the current point, and judge whether the point is near the terminal; if so, turn (5); otherwise, turn to (2);
- (5) put terminal B into CLOSED queue and the algorithm terminates;

(6) The flow chart is shown in the Fig. 2.

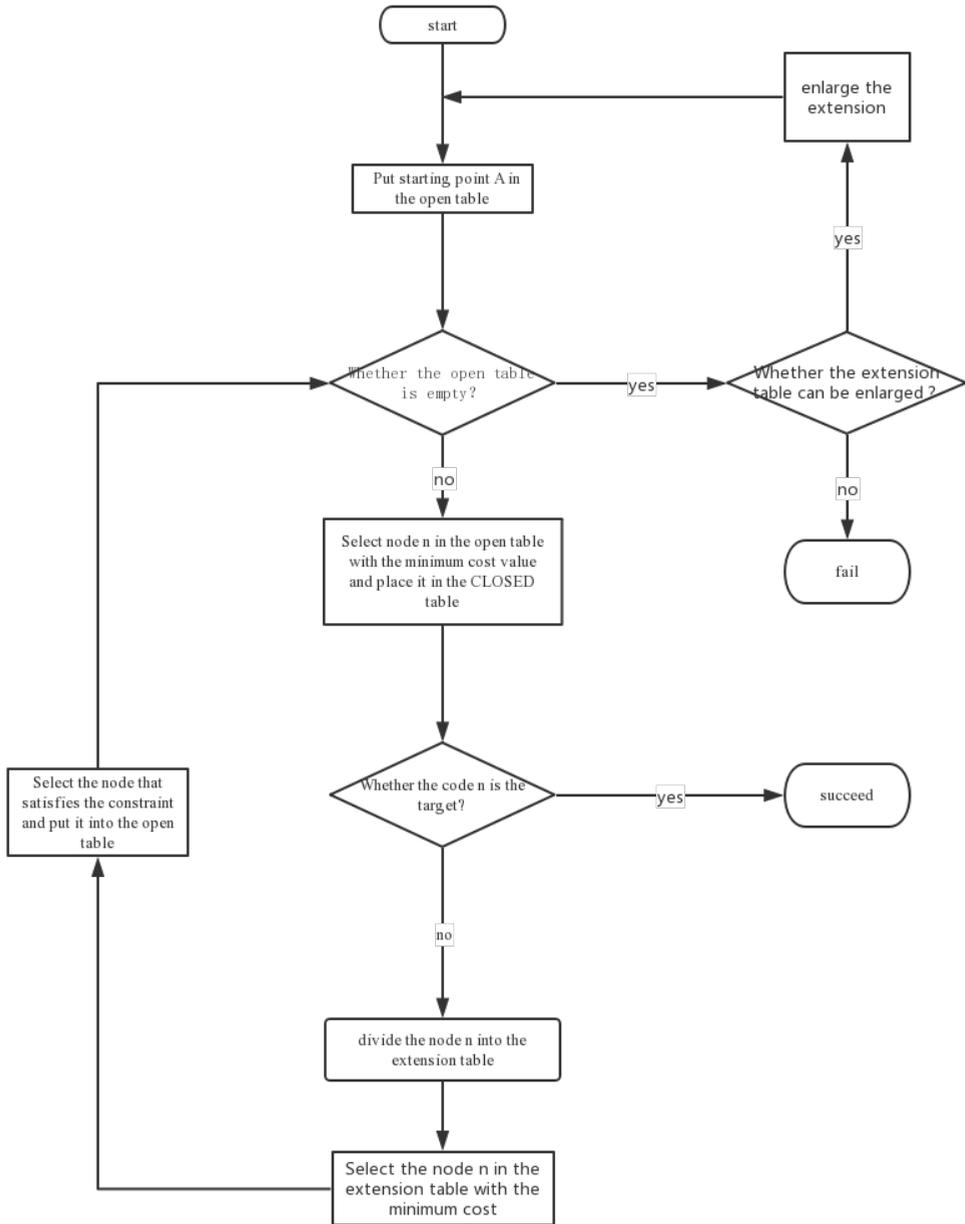


Fig. 2. The flow chart of A* algorithm.

3.2 Derivation of penalty coefficient α

After completing the turn, the mining truck starts to move in a smooth straight line at position P'_{i+1} , and the turning radius is R , as shown in Fig. 3. Penalty coefficient α is decided by Eq.13 and Eq.14.

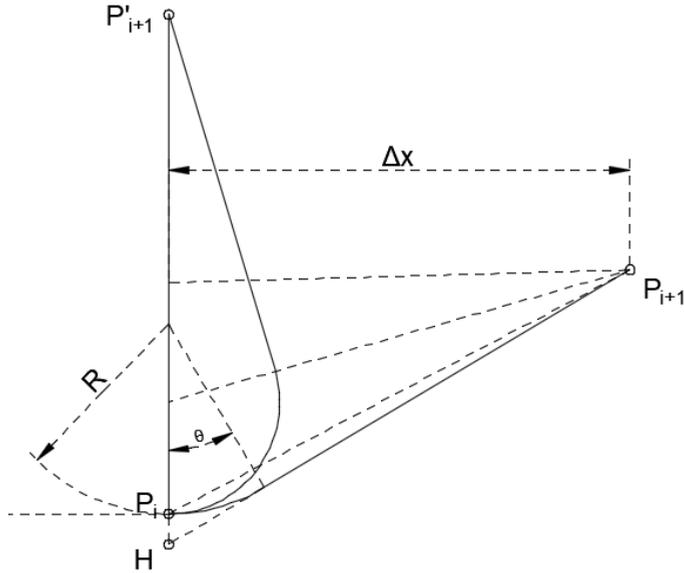


Fig. 3. Diagram of penalty coefficient.

$$\begin{cases} \cos \theta = \sin \angle H = \frac{\Delta x}{|P_{i+1}H|} \\ |P_iH| = \frac{R}{\cos \theta} - R \end{cases} \quad (14)$$

$$\alpha = \frac{|P'_{i+1}H|}{|P'_{i+1}P_i|} = 1 + \frac{|P_iH|}{|P'_{i+1}P_i|} = 1 + R \left| \frac{1 - \cos \theta}{P'_{i+1}P_i \cos \theta} \right| \quad (15)$$

where the coordinates of offset point H , start point \$P_i\$ and target point \$P_{i+1}\$ are known.

3.3 Simulation based on MATLAB platform

The maximum climbing gradient of the mining vehicle is \$10^\circ\$. The height of the obstacle that can be crossed is 0.5m. The width of the maximum gap that can be crossed is 1m.

A three-dimensional graph is projected into a two-dimensional graph by interpolation in this paper. The three-dimensional graph is shown in Fig .4. The Impassable area is defined by the constraints of the three dimensions. Several \$100 \times 100\$ m two-dimensional plans were used to simulate the seabed environment, in which the white area represents the impassable area and the black area represents the passable area. The algorithm is used to generate a path with the shortest walking distance, as shown in Fig .5. The actual turning is realized by differential steering, and the mining truck is prone to skidding , sinking in turn and being affected by the bottom flow , leading to path deviation, which may affect the safety and reliability of obstacle avoidance. Sharp turn will also influence the working condition.

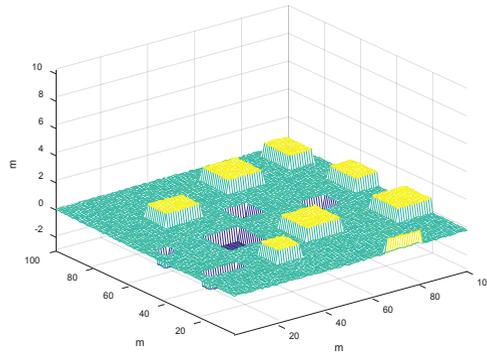


Fig. 4. 3d simulated seabed map.

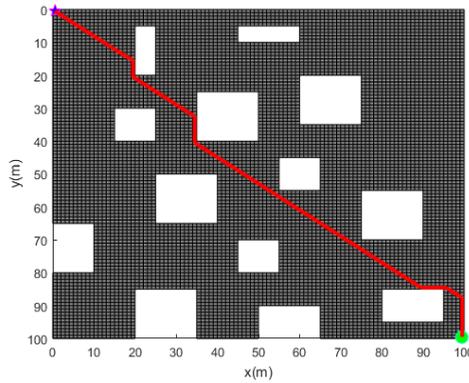


Fig. 5. The results of the first simulation.

Based on analysis above, the walking path time is affected by the walking distance and the number of turns. Then, a new seabed topography map is used in MATLAB simulation. The linear speed of the mining truck is set as 0.5m/s, the turning angular speed is set as 0.043rad/s, the penalty factor is set as 1.04, and the turning distance is multiplied by the penalty factor. The key to calculate the turn time is to ensure that any two adjacent nodes can be reached by the theory. It means that the two nodes conform to the minimum turning radius, then the distance between nodes is not less than that considering the minimum turning radius.

The second simulation results are shown in Fig. 6(a) and Fig. 6(b). The data is recorded in the Table. 1. According to the analysis in Table. 1, it can be seen that the time-cost of the minimum walking distance is nearly 50 seconds more than that of minimum number of turns. Obviously, we can find that the path planning of mining truck has to consider the number of turns, instead of only considering the shortest walking distance.

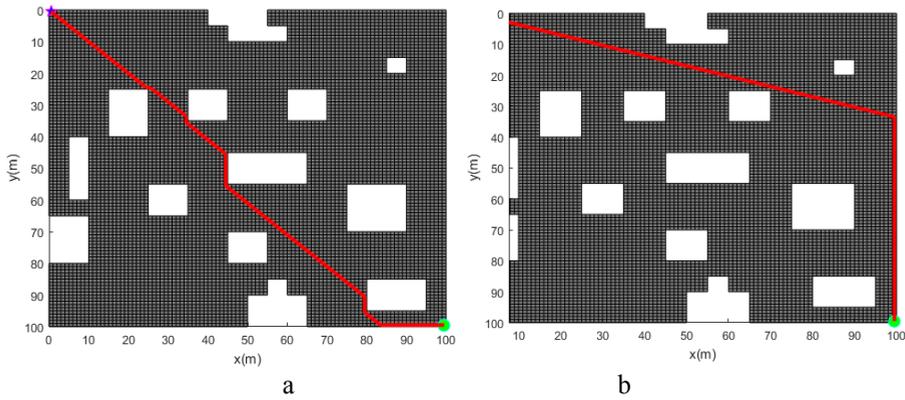
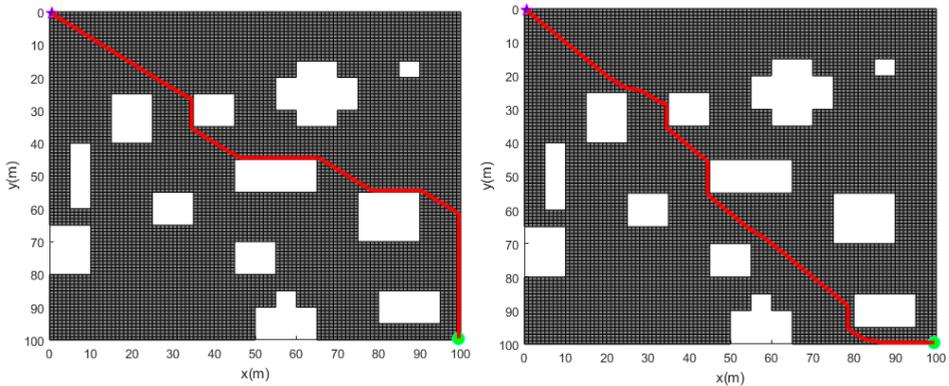


Fig. 6. (a). The result of the second simulation(a) (b).The result of the second simulation(b)

Table 1. The results of the second simulation.

Figure	The number of turning	Path cost	Time cost
Fig. 6(a)	7	149m	438.67s
Fig. 6(b)	1	170m	388.53s

The analysis of the second simulation is carried out considering two limitation states. It can be noticed that time-cost will drop when the number of turning is fewer, but path-cost will be higher. On the contrary, path-cost will drop when the number of turning is more, but time-cost will be high. In order to find out the impact of turning times and walking distance on the time-cost of mining vehicle dealers in path planning, another three MATLAB simulations were carried out in a new seabed topographic map. The third simulation results are shown in Fig. 7(a) Fig. 7(b) and Fig. 7(c). The data is recorded in Table. 2.



(a). The result of the third simulation(a) (b). The result of the third simulation(b)

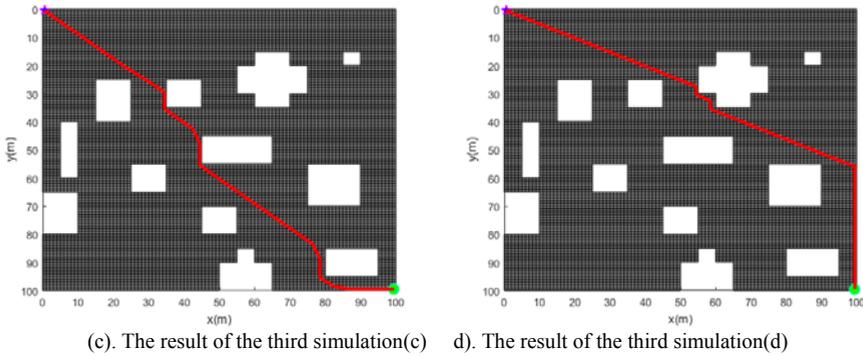


Fig. 7. The results.

Table 2. The results of the third simulation.

Figure	The number of turning	Path-cost	Time-cost
Fig. 7(a)	6	163.84m	439.67s
Fig. 7(b)	6	156.34m	417.25s
Fig. 7(c)	5	157.74m	413.37s
Fig. 7(d)	4	162.56m	416.28s

Compared with result(7a) and result(7b), it can be seen that turning in a smooth way will not only save time, but also reduce the time-cost. Compared with result(7a) result(7b) and result(7c), it can be seen that turning in a smooth way and reducing the number of turns will save time and reduce the time-cost, but it will not drop apparently when the number of turning is five. The path-cost adds a little. Compared with result(7c) and result(7d), if the number of turning is continuously reduced, both time-cost and path-cost will increase.

4 Summary

(1) The minimum turning radius should be taken into account, and measures should be taken to avoid sharp turning in path planning. Because Sharp turn will easily lead to unstable driving, affecting the safety and reliability of mining vehicle operation.

(2) The mining truck is prone to skidding and sinking on the seabed, especially in turn, and if the number of turns is too many, the walking distance will increase. So the number of turns should be reduced as far as possible, and smooth turns lead to better working conditions. However, if the number of turns is too small, such as one turn, time-cost being saved, path-cost will increase largely, undoubtedly increasing the risk due to there are many emergencies in submarine operations. Taking the simulation as example, the number of turning should be chosen as 5.

(3) A complete global algorithm includes path search and path smoothing. The main work of this paper is around the path search, and the following work can be combined with the motion constraints of mining vehicles such as the vibration frequency and the instantaneous velocity to optimize the path again in three-dimensional diagram.

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