The Research on Path Planning of Wall Climbing Robot based on Ant Colony Algorithm and Minimum Gravity Consumption Algorithm

Jun Liu\textsuperscript{1,a}, Jun Xiao\textsuperscript{2,3,b} and Xianzheng Sha\textsuperscript{1,c}

\textsuperscript{1}College of Basic Medical Science, China Medical University, Shenyang, 110001, China
\textsuperscript{2}College of Information Science and Engineering, Northeastern University, Shenyang, 110819, China
\textsuperscript{3}State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, 110016, China
\textsuperscript{a}highbaby21cen@163.com, \textsuperscript{b}xiaojun@ise.neu.edu.cn, \textsuperscript{c}xzsha@mail.cmu.edu.cn

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Abstract. Wall climbing robot is widely studied and used in a lot of industries such as cleaning, nuclear industry, construction industry and fire department due to the character of working on vertical wall. It is adopted because it can work in the dangerous space instead of people. The paper mainly studies path planning of wall climbing robot. Firstly, the paper demonstrates path planning of wall climbing robot on the plane conditions using basic ant colony algorithm and improved ant colony algorithm. Secondly, the paper proposes the minimum gravity consumption algorithm to execute path planning on the vertical wall. At last, the paper makes path planning with the fusion of ant colony algorithm and the minimum gravity consumption algorithm. The simulation shows that the algorithms are effective.

Introduction

In the construction industry, the cleaning of high building is still done by workers taking the baskets. However, the work is very dangerous. The costs are extremely expensive. It is necessary to develop a robot to work in the dangerous places instead of people. In the task of terrorism, wall climbing robot can insure the safety of the staff and improve the success rate of operation. Therefore, it is significant to study wall climbing robot.

Path planning is an important direction among the technologies of wall climbing robot [1]. At present, there are few studies on path planning of wall climbing robot. It needs a concrete analysis of specific issues because of the complexity of operating environment. The goal of path planning of wall climbing robot is to search an optimal path from the start point to the destination point in the environment of static obstacles. This paper is based on the platform of national program funded by 863 projects “studying of wall climbing robot for detecting”. Wall climbing robot prototype is shown in Figure 1. In the plane environment, the paper completes path planning with improved ant colony algorithm and compares the corresponding results with basic ant colony algorithm. On the vertical wall surface, the paper proposes a minimum gravity consumption algorithm. The paper also integrates this algorithm with ant colony algorithm for path planning on the vertical wall surface.

Fig. 1 The Wall climbing robot prototype
Model of Wall Climbing Robot’s Path Environment

One key issue is model of path environment about path planning of wall climbing robot. Establishing the appropriate environment model is helpful to the solution of path planning. In this paper, an improved grid method is adopted to model the path environment [2].

In this paper, wall climbing robot environment is two-dimensional plane space. The paper takes wall climbing robot as a particle, assuming all the obstacles in the environment are stationary. It is useful to simplify the analysis. In this article, it is set that the grid granularity is 1X1. If there are not any obstacles in the range of the grid, it is claimed that the grid is for free with the white; the other grid is referred to as barriers to express by black. Suppose wall climbing robot’s operating environment as the CRA. Take the lower left corner as the coordinate origin, the right direction for the x-axis and vertical upward direction for the y-axis, the model can make the establishment of system Cartesian coordinates Z. Suppose maximum of the CRA in the x-axis and y axis respectively as $X_{\text{max}}$ and $Y_{\text{max}}$. Set walking step of wall climbing robot to $\lambda = 1$. Divide the CRA with $\lambda$ at x-axis and y-axis respectively to form many grids. Number of each row is $\frac{X_{\text{max}}}{\lambda}$, and the number of each column of the grids is $\frac{Y_{\text{max}}}{\lambda}$. Grid environment model diagram is shown in Figure 2.

In order to express the path easily, the paper introduces the following concepts to establish a link between the grid map and matrix [3].

1. Coordinate matrix. The matrix named C is consisted of all the coordinates of the grids in the path environment. The number of grid is n, and then this matrix is one of n rows and 2 columns.

2. Distance matrix. The matrix D is made of the distances of different grids in the path environment. In order to differentiate different nature of the grids, the paper sets that the distances from the free grid to barrier grid are infinite.

3. Grid matrix. It is arranged that the information of the grid obstacles and free space in the path is stated in a matrix called GRID. The number of rows and columns is related to the shape of the grid [4].

![Fig. 2 The diagram of grid environment model](image)

As the path grid environment is shown in Figure 2, the number of grid division is 100. The distribution grid is 10 rows and 10 columns, so the corresponding grid matrix is a matrix of 10 rows and 10 columns, expressed with GRID. The matrix is shown in equation 1.
In order to distinguish the conditions of plane environment and the vertical wall surface, the paper takes method of increasing the vertical distances of the grids to represent the situations. Specific distance value is set to 1000. The vertical wall of the grid environment is shown in figure 3.

![Fig. 3 The grid environment of vertical wall surface](image)

As is shown in figure 3 about the vertical wall surface of the grid environment, grid 3 to 13, grid 4 to 14 and grid 14 to 24, all the distances between the grids are set to 1000. The other distances are set in accordance with the above modeling.

### Path Planning based on Improved Ant Colony Algorithm of Wall Climbing Robot on the Plane Environment

The application of ant colony algorithm on path planning of wall climbing robot can be described briefly as follows: in order to simulate the foraging behavior of ants, set the starting point of the robot S for the nest and the final point E for food sources. The process of ants foraging is to start from S to food sources in the scope of RCA. Put m ants on the starting point S. Each ant utilizes the current node as the center, and goes to the next node according to a certain degree of selection strategy. The ants update pheromone of the following path according to the pheromone updating method. After wandering across the RCA repeatedly, the ants will eventually find the shortest path bypassing all obstacles for the positive feedback of ant pheromones. Path planning of wall climbing robot based on Ant colony algorithm is actually the process that the ants find the optimal path from the starting point to the destination to avoid all obstacles through the interaction and mutual cooperation [5].

The flow chart of path planning of wall climbing robot based on basic ant colony algorithm in the plane environment is shown in Figure 4.
For the basic ant colony algorithm, the paper proposes the following improved methods.

1. **Deadlock easing method.** In this improved method, fix the directions of ants using purposeful and selective way. The direction of the ants is changed from eight directions to three directions which are determined by the location of the starting point and destination point in the process. Ants like this are called artificial intelligence ones. The great advantage of this set is to avoid the ants emerging to the ring in the path search and to improve the algorithm stagnation.

2. **Double pheromone updating strategy.** In every searching iteration process, each ant updates the pheromone on the traveling path. By drawing on the theory of elite ants, select the global optimal ant after the completion of a circle and update the global pheromone again on its path again. Thus, update pheromones of the global ant constantly in the global process, and enhance the positive feedback mechanism to improve the convergence rate of ant colony algorithm. At the same time, the paper takes the method of updating pheromone of each ant on the path and the global updating pheromone on the path. This method increases the diversity of the answers and avoids premature convergence [6].

3. **Two strategies of random.** For ant colony algorithm is easy to fall into local optimal solution, the first random strategy is to propose the parameter random q0. when ant k move to j grid from i grid, the first step is to produce a random number q. Then calculate the probability of selecting the next grid of the ants according to the size of q and q0. According to this configuration, the corresponding formula for calculating the probability is improved to as follows.
Add the perturbation parameter $q_0$. Then the ants choose the next grid according to visibility between regular intervals. After that, ant colony algorithm can avoid greater uncertainty because of too much positive feedback. This method can expand range of the search and effectively avoid the ant falling into local optimal solution [7].

If $q$ is less than or equal to $q_0$, the first step is to calculate the probability of the allowing selecting grids in accordance with the given formula. The next step is to select the next grids following the second random strategy (comparing the size). Assume that the grids allowed to choose are $(a, b, c)$. The probabilities are calculated according to a formula. The probabilities meet the rules $0 < \mu_1, \mu_2, \mu_3 < 1$ and $\mu_1 + \mu_2 + \mu_3 = 1$. The implementation process of second random selection strategy is as follows. Among the three probabilities $(\mu_1, \mu_2, \mu_3)$, select randomly two of the three probabilities. Compare the size of the two probabilities, and then choose the probability of the larger grid as the next mobile grid.

If $q$ is larger than $q_0$, the first step is to calculate the probability of the allowing selecting grids in accordance with the given formula. The next step is to select the next grids following the second random strategy (the roulette method). Assume that the grids allowed to choose are $(a, b, c)$. The probabilities are calculated according to a formula. The probabilities meet the rules $0 < \mu_1, \mu_2, \mu_3 < 1$ and $\mu_1 + \mu_2 + \mu_3 = 1$. The implementation process of second random selection strategy is as follows. Firstly, get the cumulative probability of the transition probability $(\mu_1, \mu_1 + \mu_2, \mu_1 + \mu_2 + \mu_3)$, and then generates a random number called rand between 0 and 1. If the rand is between 0 and $\mu_1$, choose grid a for the transfer one; if the rand is between $\mu_1$ to $\mu_1 + \mu_2$, choose grid b for the transfer one; if the rand is between $\mu_1 + \mu_2$ to 1, choose grid c for the transfer one. The flow chart of two strategies of random is shown in Figure 5.

\[
\begin{align*}
P^k_j(t) = \begin{cases} 
\frac{\tau^a_j(t)\eta^b_j(t)}{\sum_{s \in \text{allowed}_j} \tau^a_j(t)\eta^b_s(t)}, & j \in \text{allowed}_k, \; q > q_0 \\
\frac{\eta^a_j(t)}{\sum_{s \in \text{allowed}_j} \eta^a_s(t)}, & j \in \text{allowed}_k, \; q \leq q_0 \\
0, & \text{otherwise}
\end{cases} 
\end{align*}
\]
Path Planning of Wall Climbing Robot based on the Minimum Gravity Consumption Algorithm on the Vertical Wall Environment

There are other path planning requirements in addition to a shorter path when wall climbing robot crawls on the surface of vertical wall. Wall climbing robot at a certain height has certain gravity as it climbs up from the ground. Wall climbing robot is able to stay on the vertical wall surface relying on the negative pressure suction. The effect of the gravity will cause some wear and consumption to wall climbing robot's suction device. The effect will increase wear and consumption when wall climbing robot works at a high wall for extended periods. This will inevitably reduce the life of wall climbing robot. In order to alleviate this problem, in the design of mechanical hardware parts of wall climbing robot, it ought to low the quality of wall climbing robot body to the great extent on the base of the normal work. It can reduce the wear and consumption of the suction device at the same high wall because of smaller gravity. When the quality of wall climbing robot is fixed, it needs to find other ways to reduce the wear and consumption of wall climbing robot in the path planning.

In order to quantitatively describe wear and consumption of wall climbing robot, the paper defines a parameter to characterize the amount that wall climbing robot for gravity consumption of C. In the path of the environment in this article, the definition of the gravity consumption of the wall-climbing robot is

$$C = mg \cdot h \cdot t \cdot \frac{v}{h}$$

In the definition, mg stands for gravity of wall climbing robot, h stands for the height of wall position, t stands for the time interval during which wall climbing robot experienced in the location. This article assumes that wall climbing robot's speed is constant.

![Fig. 6 One kind of vertical wall surfaces](image)

Fig. 6 One kind of vertical wall surfaces

In Figure 6, assume wall climbing robot runs on the vertical surface. Grids 7, 8, 9 are on the low position of the vertical wall, and grids 17, 18, 19 are on the high position of the walls. Wall climbing robot starts from a starting point grid 7 to reach the target point grid 19. The middle 13 grid is an obstacle and it is insurmountable. Therefore, the lines of wall climbing robot have two options of line 1 (7, 8, 9, 14, 19) and line 2 (7, 12, 17, 18, 19). In the two lines, there are the same lengths, and the same running time. Because of different heights and different positions in the two lines, wear and consumption of wall climbing robot are different. The specific parameters are calculated as follows: suppose the quality of wall climbing robot is m, the speed is v, the grid height is h, the starting grid in which the height is x, and all are shown in Figure 6. The gravity consumption of walling climbing robot can be calculated under the two paths[8].

Line 1

$$C_1 = mg \cdot x + \int_0^{2h/v} mg (x + vt) dt$$

$$= mg \cdot x + mg \left( \frac{1}{2} \cdot \frac{4h^2}{v^2} + \frac{8h^3}{3v^2} \right)$$

$$= mg \cdot x + mg \left( \frac{1}{2} \cdot \frac{4h^2}{v^2} + \frac{1}{3} \cdot \frac{8h^3}{v^2} \right)$$
Line 2

\[ C_2 = mg(x + 2h)\left(\frac{2h}{v}\right) + \int_0^{\frac{2h}{v}} mg(x + vt)tdt \]

\[ = mg(x + 2h)\left(\frac{2h}{v}\right) + mg\left(\frac{1}{2}x^2\frac{4h^2}{v^2} + \frac{1}{3}\frac{8h^3}{v^2}\right) \]  

(5)

Among the sections [9, 14, 19] and [7, 12, 17] of the two routes, the height of wall climbing robot and the running time are the same. So the gravity consumption of wall climbing robot is the same. However, in the sections [7, 8, 9] and [17, 18, 19] of the two routes, it is clear that the gravity consumption of wall climbing robot on [17, 18, 19] is larger than that on [7, 8, 9]. The calculations above can verify this conclusion. To reduce the consumption of wall climbing robot in the path planning, it is obvious that the route 1 should be selected.

There is a need to consider the other situations in the vertical wall surface, and the grid environment is shown in Figure 7. From grid 1 to grid 7, there are three paths, named path 1 (1, 2, 7), path 2 (1, 6, 7) and path 3 (1, 7). In the three paths, the gravity consumption is different. It is evident that the gravity consumption of path 2 is the largest, so the path 2 is not commendable. There is a need to determine which path has less gravity consumption between path 1 and path 3 by calculating. Suppose the quality of wall climbing robot is m, the speed is v, the grid height is h, the time consume is t from the starting point 1 to the destination point 7, and the height of the grid 1 and grid 2 is x, which are all shown in Figure 7. The gravity consumption situation of wall climbing robot can be calculated under the two paths,

Fig. 7 The other kind of vertical wall surfaces

Line 1

\[ C_1 = mgx\frac{h}{v} + \int_0^{\frac{h}{v}} mg(x + vt)\cdot tdt \]

\[ = mg\frac{h}{v^2}\left[xv + \frac{1}{6}h(3x + 2h)\right] \]  

(6)

Line 2

\[ C_2 = mg(x + h)\frac{h}{v} + \int_0^{\frac{h}{v}} mg(x + vt)\cdot tdt \]

\[ = mg\frac{h}{v^2}\left[xv + \frac{1}{6}h(3x + 2h) + vh\right] \]  

(7)

Line 3

\[ C_3 = \int_0^{\frac{h}{v}} mg(x + vt\sqrt{\frac{2}{2}})\cdot tdt \]

\[ = mg\frac{h}{v^2}\left[xh + \frac{2}{3}h^2\right] \]

(8)
Among them, the path 2 has the largest consumption of gravity. A comparison of gravity consumption can be done between path 1 and path 3. The following results can be obtained.

\[
\Delta C = C_3 - C_1 = mg \frac{h}{v^2} (xh + \frac{2}{3} h^2) - mg \frac{h}{v^2} (xv + \frac{1}{6} h(3x + 2h))
\]

\[
= mg \frac{h}{v^2} (x(x - 2)v + \frac{1}{3} h^2)
\]

(9)

There are the discussions about the three paths.

1. When wall climbing robot moves slowly, the results are \( \Delta C > 0 \). The gravity consumption of path 3 is larger than the path 1. So, when taking into account the minimum gravity consumption, the algorithm should give priority to path 1.

2. When wall climbing robot moves faster and climbs up to higher height, the results are \( \Delta C < 0 \). The gravity consumption of path 1 is larger than the path 3. So when considering the minimum gravity consumption, the algorithm should give priority to path 3.

When wall climbing robot runs on vertical wall, in order to consume the minimum gravity, it should be made to move to the target point below in the initial stage of path planning, and then crawls to the target point of the vertical surface along the wall. In the path planning, route selection should be combined with the specific route of the above two [9].

**Path Planning of Wall Climbing Robot based on the Fusion of Ant Colony Algorithm and the Minimum Gravity Consumption on the Vertical Wall Environment**

On the vertical wall, it needs to take into account of several aspects of path planning on some occasions (a shorter path, a shorter running time and less gravity consuming). The paper presents an algorithm based on the fusion of minimum gravity consumption and ant colony algorithm. The algorithm combines the minimum gravity consumption and ant colony algorithm. The algorithm uses the iterative optimization methods to search for the shortest path and uses the minimum gravity consumption to reduce the mechanical loss of wall climbing robot. The fusion of the two algorithms determines the moving trend of the wall climbing robot in the path of the search. And in the end the algorithm will find the optimal path which meets the evaluation function. In this paper the evaluation function of path planning is set like this.

\[
\min[F] = k_1 L + k_2 C
\]

(10)

L stands for the length of the path, C stands for gravity consumption, and \( k_1, k_2 \) are the weighting coefficients with the satisfaction of \( k_1 + k_2 = 1, k_1, k_2 \in [0,1] \). The optimal path planning can adjust the size of the weighting coefficients according to the requests. The attention is attached to the path length in the path planning, and \( k_1 \) should choose the larger value; the attention is attached to gravity consumption in the path planning, and then \( k_2 \) should take the larger value. In this article, \( k_1 \) and \( k_2 \) has a value of \( k_1 = 0.7, k_2 = 0.3 \).

The steps of the algorithm are explained as follows. Wall climbing robot tries to move to the horizontal position below the target point from the starting point in the initial stages of the path planning. And in the second stage of path planning, it moves to the target position. In the second stage, the gravity consumption and the length of the path should be all considered. According to the size of weighting coefficients the algorithm considers the impacts of two aspects. The algorithm should ensure both the length of path and gravity consumption in the course of the path planning of wall climbing robot [10].
Simulation and Analysis

In order to measure the overall performance of the improved ant colony algorithm, compare the results of the improved algorithm and the basic algorithm in 2 different grid environments respectively. The diagrams are 5X5 and 10X10 grid environment. The white part stands for the freedom grid, the black part stands for the barrier grid, S stands for the starting point, and E stands for the target point. In the program the algorithm can calculate the length of the shortest path of wall climbing robot. In each grid environment the obstacles can be set up freely. In order to ensure the randomness of simulation, the simulation results were the average of 10 simulation experiments.

1) Path planning of wall climbing robot on the plane environment based on basic ant colony algorithm and improved ant colony algorithm

Fig. 8 5X5 plane grid environments

In the 5X5 plane grid environment, the red lines stand for the shortest path on the left of the figure through the iteration in the path planning. The red lines stand for the average path length in the right side of the figure, and the right blue lines stand for the shortest path length. The shortest path is 8 based on basic ant colony algorithm, and the shortest path is 6.8084 based on improved ant colony algorithm. The iteration time is 5.147s based on basic ant colony algorithm, and the iteration time is 1.9872 s based on improved ant colony algorithm.

Table 1 Contrast of two Parameters

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<th>[Relative error E0]</th>
<th>[Robust performance ER]</th>
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<tbody>
<tr>
<td>basic ant colony algorithm</td>
<td>[0.171]</td>
<td>[0.171]</td>
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<tr>
<td>improved ant colony algorithm</td>
<td>[0]</td>
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Fig. 9 10X10 plane grid environments
In the 10X10 plane grid environment the red lines stand for the shortest path on the left of the figure through the iteration in the path planning. The red lines stand for the average path length in the right side of the figure, and the right blue lines stand for the shortest path length. The shortest path is 18 based on basic ant colony algorithm, and the shortest path is 16.8284 based on improved ant colony algorithm. The iteration time is 15.234s based on basic ant colony algorithm, and the iteration time is 7.2374 s based on improved ant colony algorithm.

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<th>[Relative error E0]</th>
<th>[Robust performance ER]</th>
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<tbody>
<tr>
<td>basic ant colony algorithm</td>
<td>0.0696</td>
<td>0.0696</td>
</tr>
<tr>
<td>improved ant colony algorithm</td>
<td>0</td>
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It is clear that the speed of the iteration is improved by improved ant colony algorithm significantly, time decreases, and the average path of each iteration decreases. So the improved ant colony algorithm is more optimal than basic ant colony algorithm.

(2) Path planning of wall climbing robot on the vertical wall environment based on the minimum gravity consumption algorithm

Fig. 10 The vertical wall environment

From the results of the path planning, wall climbing robot moves horizontally along the red line to the target point at the beginning of the path planning, and then climbs to the location of the target point along the direction in the path process. Wall climbing in the low position experiences a longer time in the process of the path planning, so the gravity consumption of wall climbing robot is smaller. Such an algorithm only considers the gravity consumption.

(3) Path planning of wall climbing robot on the vertical wall environment based on the fusion of ant colony algorithm and the minimum gravity consumption

Fig. 11 The vertical wall environment
From the simulation it can be seen that both the gravity consumption and the shortest path optimization of wall climbing robot are considered during path planning. In the beginning, wall climbing robot moves along the red line to the bottom of the target point in accordance with the minimum gravity consumption. In the process of climbing, the path length should be considered in accordance with ant colony algorithm. The simulation of wall climbing robot shows that the algorithm is correct.

**Summary**

In the path planning of wall climbing robot, the environment model is built using an improved grid method. The path environment of wall climbing robot is described with the links of the matrix and graph theory. In the plane environment path planning of wall climbing robot using basic ant colony algorithm and improved one is done. The improved ant colony algorithm includes the deadlock easing method, double pheromone updating strategy and two strategies of random. Performance of improved ant colony algorithm is well improved. In the vertical wall surface, the paper proposes the minimum gravity consumption algorithm and the fusion with ant colony algorithm for path optimization. Simulation results show that the proposed algorithm is effective. The paper provides a very good reference for path planning of wall climbing robot.

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**References**


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