Research on a method of digital map generation for tracked equipment maneuvering on soft ground

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Abstract. The mobility of equipment refers to the ability of fast driving under various road, ground and terrain conditions that may be encountered in the tactical background. In recent years, with the rapid development of national defense and aerospace, tracked equipment is required to reach more and more areas. However, due to its low bearing capacity and low adhesion capacity, soft roads such as sandy land, swamp, farmland, tidal flat and lunar soil are easy to cause subsidence, resulting in low driving efficiency or even inability to drive, which seriously restricts the feasibility of driving equipment. In this paper, considering the characteristics of tracked equipment, through the superposition of multi-layer spatial information such as slope, aspect, soil and elevation data, based on equipment dynamics, fuzzy theory and ant colony algorithm, the generation of mobile digital map and mobile path planning of tracked equipment under soft road and complex terrain are studied, which has important practical significance.

1. Introduction
The mobility of equipment refers to the ability of fast driving under various road, ground and terrain conditions that may be encountered in the tactical background. Mobility can be divided into highway mobility and off highway mobility, especially for tracked equipment, soft ground and other off highway mobility[1]. Road mobility digital map has been common at home and abroad. Tencent map, Baidu map, Google map and other major domestic and international maps all provide visual expression of road mobility. In the world, the digital map of equipment mobility under the condition of static off highway terrain has been launched in the early 20th century. The North Atlantic Treaty Organization (NATO) reference NATO Reference Mobility Model (NRMM) combines several mobility related technologies into a comprehensive model to predict mobility[2]. These NRMM based researches are all aimed at specific areas, which are not suitable for the landform characteristics of China. Therefore, it is not suitable for the mobility analysis of tracked equipment and the development of mobility data map of tracked equipment in China. Although the research on equipment mobility has been carried out in China, there is no published and practical digital map product for equipment mobility (in off highway terrain). Therefore, this paper studies a digital map generation method for tracked equipment maneuvering on soft ground.
2. Trafficability calculation of tracked equipment

The trafficability of crawler equipment is related to its own maneuverability, and also closely related to the ground soil conditions interacting with the crawler. Crawler equipment generally runs on soft ground with high water content, such as swamp, mud land, paddy field, shallow lake and beach ground[3].

When evaluating the mobility of equipment in soft soil (such as trafficability, obstacle surmounting, steering, etc.), the criteria for evaluating the driving performance of various equipment are different according to their functions and requirements. However, from the perspective of equipment ground mechanics, the evaluation of equipment mobility is mainly to evaluate the trafficability of equipment on soft ground[4].

The driving ability of tracked equipment on soft ground depends on the traction of the hook, that is, the difference between the maximum value of tangent traction $F_{H_{\text{max}}}$ (provided by ground thrust) and the driving resistance $R$:

$$DP = F_{H_{\text{max}}} - R$$

(1)

Where $DP$ is the tractive force of crawler equipment, which can be used to characterize not only the driving ability of ground soil, but also the trafficability of crawler equipment, such as the ability to generate acceleration, climbing or instrument load. Therefore, the trafficability index of crawler equipment is as follows:

$$\Pi = \frac{DP}{W} - \phi - f$$

(2)

The higher the value of the equipment $\Pi$, the greater the effective traction force, the stronger the climbing ability and obstacle crossing ability of the equipment, and the better the acceleration performance of the equipment.

When the slip ratio $i = 100\%$, $F_{H_{\text{max}}}$ is approximately:

$$F_{H_{\text{max}}} = AC + W \tan \varphi$$

(3)

So:

$$\phi = \frac{F_{H_{\text{max}}}}{W} = \frac{c}{p} + \tan \varphi$$

(4)

and

$$f = \frac{R}{W} = \frac{1}{(n+1)L} \left( \frac{p}{K} \right)^{\frac{1}{n}}$$

(5)

The results are as follows:

$$\Pi = \phi - f - \frac{c}{p} \tan \varphi - \frac{1}{(n+1)\sqrt{L}} \left( \frac{p}{K} \right)^{\frac{1}{n}}$$

(6)

In order to characterize the trafficability of tracked equipment more comprehensively and evaluate the influence of parameters of tracked equipment and soil mechanical properties on trafficability of tracked equipment, the slip phenomenon and track prick effect of tracked equipment should also be considered.

When the track slip ratio and the track prick effect are considered, the traction force $F_{\text{Max}}$ is $F_{H_{\text{max}}}$:

$$F_{H_{\text{max}}} = bL \left( 1 + \frac{2h}{b} \right) + W \tan \varphi \left( 1 + 0.64 \left( \frac{h}{b} \right) \arctan \left( \frac{h}{b} \right) \right) \times \left[ 1 - \frac{k}{iL} (1 - e^{-\gamma/\gamma}) \right]$$

(7)

There:

$$R = \gamma \frac{z \cot \alpha + zC[1 + \cot \alpha \cdot \cot \alpha + \varphi]}{2 \cos \varphi_\alpha \cdot \cot (\alpha + \varphi) - \sin \varphi_\alpha}$$

(8)

Under the assumption of uniform load, the trafficability evaluation index of tracked equipment can be obtained:
The workability of the ground can be measured by the approximate effective traction provided by the soil per unit load area under uniform pressure:

$$\Pi = \frac{1}{W(n+1)(k_c + k_f)^{1/n}} \times \left( \frac{W_y}{L} \right)^{1/n} \left[ 1 + \frac{h}{b} \left( 1 + 0.64 \left( \frac{h}{b} \arctan \left( \frac{h}{b} \right) \right) \right) \times \left[ 1 - \frac{k}{L} \left( 1 - e^{-L/k} \right) \right] \right]$$ 

(9)

For the evaluation of soil drivability, more attention is paid to the influence of soil mechanical parameters on its drivability, so the track slip and track sting effects are ignored:

$$\pi = \frac{DP}{A} = \frac{F_{\text{max}} - R}{A}$$ 

(10)

Here $\pi$ Also known as the "drivability function" for a given soil, it provides the basic relationship between the effective traction per unit load area and the soil pressure. If $\pi$ is less than or equal to 0, the crawler equipment can not run; if $\pi > 0$, it means that the crawler has reserved traction. The higher the value $\pi$ is, the stronger the carrying capacity of the crawler equipment is. The crawler equipment can perform climbing, acceleration, braking and other operations.

3.Trafficability evaluation of tracked equipment based on fuzzy theory

The traction coefficient, driving efficiency and maximum speed of tracked equipment are all accurately quantified. However, for a certain evaluation index, it is difficult to use a simple value to clearly distinguish the good from the bad. It is often combined with qualitative evaluation grades, such as "good", "general" and "poor" to evaluate the trafficability. Therefore, it is necessary to establish the corresponding relationship between the evaluation grade and the numerical index, which is often set according to the actual experience and is a more subjective and fuzzy concept.

Fuzzy mathematics is a subject dealing with and studying fuzzy phenomena. Fuzzy theory is based on fuzzy sets. Its basic spirit is to accept the fact that fuzzy phenomena exist, take dealing with things with fuzzy and uncertain concepts as its research goal, and actively quantify them into information that can be processed by computers. It has a good applicability to the complex nonlinear system which is not easy to model. Based on the characteristics of fuzzy theory, combined with the thinking mode of fuzziness for ground trafficability evaluation of tracked equipment, this paper proposes a multi evaluation index fusion method based on fuzzy theory, which integrates three independent evaluation indexes of traction coefficient, driving efficiency and maximum speed, and finally realizes the comprehensive evaluation of ground trafficability of tracked equipment, At the same time, the evaluation grade and the evaluation result of accurate value are given.

The corresponding steps are as follows:

(a) Establishing fuzzy inference system

Based on the theoretical model of ground trafficability of tracked equipment above, it is assumed that these main physical quantities have been accurately predicted by equipment configuration parameters and soil parameters, and the function curves of three indexes with respect to slip rate are obtained. Therefore, in the case of a specific slip rate, the three indexes can give accurate values. In order to build a fuzzy inference system, the first step is to transform the precise input quantity into the fuzzy input quantity expressed by linguistic value. The fuzzification of input variables is mainly divided into two steps: determining the fuzzy set corresponding to input variables and determining the specific form of membership function.
When more fuzzy states are used to describe each variable, the rules are more flexible and the final result is more accurate; at the same time, the fuzzy rules are more complex and difficult to formulate. Therefore, simplicity and accuracy should be considered when determining the fuzzy state. Three states are defined for the three independent evaluation indexes, namely "low (L)", "medium (M)", "high (H)": in order to make the final result more accurate, five states are defined for the generalized ground trafficability, namely "poor (L)", "poor (LM)", "general (M)", "good (MH)", "good (H)".

Generally speaking, the steeper the shape of membership function is, the higher the system resolution is; The slower the change, the better the stability of the system. According to the current experimental experience, the accurate index value is mapped to the corresponding fuzzy state in the following way:

Z-type membership function is used in L1 state of [0.1, 0.3] for Traction coefficient Π, triangle membership function is used in M1 state of [0.15, 0.55], and S-type function is used in H1 state of [0.4, 0.7].

The L2 state of driving efficiency TE adopts Z-type membership function, the corresponding parameter setting range is [0.1,0.35], the M2 state adopts triangle membership function, the range is [0.15,0.7], and the H2 state adopts S-type function, the range is [0.55,0.7].

Z-type membership function is used for L3 state of maximum speed VM, and the corresponding parameter setting ranges are [0.1,0.4], triangle membership function is used for M3 state, and the range is [0.2,0.7], S-type function is used for H3 state, and the range is [0.5,0.8]. For generalized ground trafficability, Z-type membership function is used for L state, and the corresponding parameter setting range is [0,0.225]. Triangle membership function is used for LM, m and MH States, and the range is [0.175,0.425], [0.375,0.625], [0.575,0.825], respectively. S-type function is used for H state, and the range is [0.775,1].

(b) Fuzzy rule making and fuzzy reasoning
Fuzzy rules are usually formulated based on the knowledge or experience of experts in this field. At present, considering that the expert experience that this system can refer to is less, in addition, the real vehicle test experience of ground trafficability of tracked equipment is still lacking. Therefore, a set of demonstrative fuzzy reasoning rules is used to explain the process of fuzzy reasoning system and preliminary test verification. In the process of establishing fuzzy rules, the influence of the three indexes on the generalized ground trafficability is regarded as the same level, that is, the influence weight is the same. In practical application, the fuzzy rules can be adjusted according to the different requirements of each index, which reflects the flexibility of fuzzy rule making. If the system emphasizes the traction coefficient of wheeled equipment, when the traction coefficient is in L1 state, the generalized ground trafficability level in the corresponding rules can be appropriately lowered, and the max-min algorithm is used for fuzzy reasoning.

(c) Deblurring
After fuzzy reasoning, the result is expressed by fuzzy set language. For practical applications, the first mock exam is also needed. This way can facilitate the comparison of the wheeled equipment's passing quality under the same fuzzy state. The two most commonly used methods of defuzzification are maximum membership method and centroid method. Compared with the maximum membership method, the centroid method considers the influence of the smaller membership value on the result, so the output surface is smoother and the result is more reasonable. For the ground trafficability evaluation of tracked equipment, it is often implemented in offline environment, so there is no strict real-time requirement, and the centroid method is more suitable.

4. Generation of mobility map of tracked equipment
In order to better present the maneuverability of tracked equipment, the maximum driving speed of vehicles in different geographical environments is calculated here, and different colors are distinguished in the map. The calculation and rendering process of maneuverability map is as follows:

(1) Based on the existing geographic information platform, a new data set representing slope information is generated from DEM. Get the slope direction of the grid surface, create contour lines
according to the grid surface, calculate the curvature of the grid surface, calculate the volume change between the two surfaces, and judge the slope of each pixel on the grid surface.

(2) According to the calculated terrain data and soil bearing capacity data, combined with the corresponding vehicle mobility model, the maximum speed of vehicles in each grid is calculated.

(3) Map the speed to different color values, and use the color to dye the grid. The image effect is shown in Figure 1 below.

(4) The dyed layer with traffic speed indication is superimposed on the original 3D map.

Then the mobility map of the tracked equipment can be generated. Figure 1 shows one of the fragments.

Figure 1 Example of mobility map of tracked equipment

5. Global path planning of digital mobile map based on improved ant colony algorithm

According to the analysis of mobility map and soil environment type, different road finding results can be achieved by setting priority of different demands. The following are several strategies of path planning in this paper.

(1) Shortest time: This is the default route finding method, searching for the shortest path passing through between the set start and end point.

(2) Road priority: in the process of path planning, by increasing the weight value of the road area, the road area is preferred in the process of road searching.

(3) No road priority: in the process of path planning, the road free area is preferred as the passing option to avoid passing through the road area.

(4) Jungle priority: in the process of path planning, according to the soil environment type, the jungle area is preferred as the passing road.

(5) Concealment priority: in the process of path planning, according to the soil environment type, the area with strong concealment is preferred as the passing area, such as tunnel, forest and other difficult to detect areas.

In order to realize these strategies, Ant Colony Algorithm (ACA) can be used to get an optimal path by autocatalytic method.

The movement and communication process of ant colony is defined as follows:

(a) Search range: sets the range value of each ant to search once to limit the ants during movement

The ability of the group to observe and move the surrounding environment.

(b) Local environment: ants need to perceive the surrounding environment information, and randomly select one of the eight nodes around according to the pheromone size. When passing through the sub grid, the pheromone of the current grid will be reduced accordingly.

(c) Rules of movement and foraging: each ant moves towards the direction of pheromone. If the past place is avoided as far as possible, it will traverse the nodes as much as possible to prevent the colony from losing the optimal path due to "precocious".
(d) Obstacle avoidance rule: in ant colony algorithm, the grid that the ant meets obstacles will randomly select another direction to continue to search for the end point. If all the grids around the ant have been traversed, the optimization will be ended and the ant fails to find the route.

(e) Communication rules: ants have the ability to choose paths independently on individuals and spread pheromones in the path they pass through; In the population, although the behavior of each ant is random, the existence of pheromones will make the ant colony choose the optimal path to pass through.

Set the number of ants as m and the number of iterations as K. Firstly, the path selection mechanism is defined. The individual ant can choose 8 nodes around to move, and Roulette is used. Assuming that the grid coordinates of the equipment from step t to the grid are (Xt, Yt), and the grid coordinates of the next step are allow (Xt, Yt), then the probability of the trafficable grid in step t + 1 is:

$$P(X_{t+1}, Y_{t+1}) = \frac{\tau^\alpha(X_{t+1}, Y_{t+1})H^\beta(X_{t+1}, Y_{t+1})}{\sum\tau^\alpha(X_t, Y_t)H^\beta(X_t, Y_t)}$$  \hspace{1cm} (13)

After the probability is determined, the ant's next step of the grid can be determined randomly by roulette. Where t + 1 step lattice

The H value of heuristic information of network is set to the inverse of Euclidean distance. The calculation formula is as follows: (dest.x, dest.y) is the coordinate value of target point, η Is the distance factor.

$$H(X_{t+1}, Y_{t+1}) = \frac{\eta}{\sqrt{(X_{t+1}-\text{dest}.X)^2 + (Y_{t+1}-\text{dest}.Y)^2}}$$  \hspace{1cm} (14)

Then, the pheromone concentration is updated. Considering the randomness of probability selection, the ant may fall into the "dead road" caused by obstacles. When combined with the equipment mobile digital map, the basic ant colony algorithm can not meet the global path planning of equipment, such as the terrain slope is uncertain, the ground attribute information is complex, etc., and there is no corresponding response strategy in the algorithm, So we need to modify the state transfer formula to realize the global path planning on off-road road which is in line with the actual terrain environment.

In the process of specific improvement, tabu table, i.e. taboo table, is established to record the grid that cannot be passed in the map. If the grid is lake or the gradient difference is too large, tabu (i, j)=1, it is not allowed to pass, otherwise it can pass.

Secondly, the heuristic function H is changed to apply to soft pavement, and the specific formula is as follows:

$$H(X_{t+1}, Y_{t+1}) = \begin{cases} \frac{1}{\Delta D + h(X_{t+1}, Y_{t+1})} & \text{tabu}(X_{t+1}, Y_{t+1}) = 0 \\ 0 & \text{tabu}(X_{t+1}, Y_{t+1}) = 1 \end{cases}$$  \hspace{1cm} (15)

There ΔD is the actual distance from grid (Xt, Yt) to (Xt+1, Yt+1), h is the Euclidean distance from (Xt+1, Yt+1) to the end point, and j is the ground attribute coefficient, which is used to adjust the influence of ground attributes. Based on the heuristic function, the state transition probability p is calculated:

$$P(X_{t+1}, Y_{t+1}) = \begin{cases} \frac{\tau^\alpha(X_{t+1}, Y_{t+1})H^\beta(X_{t+1}, Y_{t+1})}{\sum\tau^\alpha(X_t, Y_t)H^\beta(X_t, Y_t)} & H(X, Y) \neq 0 \\ 0 & H(X, Y) = 0 \end{cases}$$  \hspace{1cm} (16)

Finally, roulette is used to decide the next route of the ant. After the ant colony completes a move, the pheromone is updated locally, and the grid pheromone on the passing path is reduced, so as to increase the probability of the next ant searching for other non passing grids and prevent the ant from converging to a suboptimal route prematurely. The formula is as follows, where γ is the volatility coefficient of local pheromone:

$$\tau(X_t, Y_t) = (1 - \gamma) \times \tau(X_t, Y_t)$$  \hspace{1cm} (17)
When all ants complete the path search, they will update the global pheromone. Here, greedy pheromone update strategy is used. According to the calculated path, add the planned path in the map interface. The path display effect is shown in Figure 2.

![Figure 2 path planning based on improved ant colony algorithm](image)

6. Conclusion
In view of the shortcomings of the maneuverability of track equipment on the loose ground and other non highway roads, this paper analyzes and calculates the passing evaluation index of track type equipment on the soft ground from the point of equipment ground mechanics, and establishes three index evaluation system based on fuzzy theory. In order to better present the maneuverability of crawler equipment, the maximum speed of vehicles in different geographical environment is calculated, and the map of maneuverability is calculated and rendered, and different colors are used to distinguish them in the map. Finally, based on the improved ant colony algorithm, according to the analysis of mobility map and soil environment type, the different road finding results of crawler equipment are realized by setting different priority of different demands, which provides a good reference for the generation and application of digital mobile map of tracked equipment.

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