

Research on Agricultural Machinery Operation Path Planning for Irregular Fields in Hilly Areas

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Abstract

Aiming at the problems of complex shape of irregular fields, frequent turning of agricultural machinery operation and low operation efficiency in hilly and mountainous areas, a path planning method of agricultural machinery operation based on minimum turning times was proposed. Firstly, the field boundary model is constructed by using Gauss-Kruger projection and grid method, and the irregular fields are divided into convex polygons, concave polygons and complex polygons according to the theory of computer graphics. Secondly, the field classification is realized by concave and convex judgment and polygon subdivision, and the safe operation area is constructed on this basis. Then, the simulated annealing algorithm is used to search the best operation direction, the operation angle is determined with the minimum number of turns as the optimization goal, and the reciprocating straight path is generated based on the active side table method. Finally, combined with the constraints such as the minimum turning radius of agricultural machinery, the turning decision model is constructed to realize the complete operation path planning. The simulation results of typical hilly fields show that the proposed method can achieve more than 90 % operation coverage in different types of irregular fields and effectively reduce the number of turns, which has good applicability and practical value.

Keywords

Hilly area, Irregular plots, Agricultural machinery operation, Path planning, Turning number optimization.

1. INTRODUCTION

Hilly and mountainous areas account for about 70% of China 's land area, cultivated land area accounts for 34.62% of the country, and sown area accounts for 34.20% of the country [1]. This area is an important crop production base for grain and oil, fruits and vegetables, tea, potatoes and other crops in China, and it is also an area with low level of agricultural mechanization in China.

Precision agriculture is an important trend of agricultural development in this century. In the process of modern agricultural production, automatic navigation technology of agricultural machinery has become increasingly popular and has become the basis for the implementation of precision agriculture. Pose information acquisition, path planning and navigation control constitute three key technologies of automatic navigation of agricultural machinery[2][3]. The application of large-scale agricultural machinery navigation and path planning in regular fields in China has matured[4][5].Due to the complex geographical environment, fragmented distribution of fields and different shapes in hilly and mountainous areas, there are few studies on automatic navigation and path planning of agricultural machinery in this area.

Path planning is a key step in the automatic navigation and operation of agricultural machinery. The main goal is to efficiently realize the full coverage of farmland through the rational planning of the operation path in the field area^[6]. Reasonable operation route can improve the efficiency of agricultural machinery, help to avoid the waste of resources and the frequent increase of operation caused by repeated operation or omission of operation area^[7]. Nilsson et al.^[8] expressed the coverage trajectory of farmland as the trajectory of the main working area, the ground channel and the turning trajectory to construct a virtual road network map. Finally, the coverage path planning was carried out based on the map. Experiments show that the method is universal for all types of single fields.

Aiming at the uncertain scene of agricultural machinery operation, Liang et al.^[9] proposed an improved iterative greedy algorithm for multi-machine dynamic path planning. Zhai et al.^[10] designed a path planning method for block nesting operation mode based on AB line. Chen et al.^[11] proposed a path planning method considering multi-constrained scenarios based on the hybrid rules of simulated annealing algorithm, row number disassembly and traversal synthesis. Li Wenfeng et al.^[12] proposed a multi-field path planning method based on improved ant colony algorithm and A * algorithm. Shen et al. ^[13] designed a full coverage path planning scheme for hilly and mountainous areas based on three-dimensional terrain, and solved the optimal path based on the optimal energy consumption. Based on Floyd and improved genetic algorithm, Zhou et al. ^[14] proposed a traversal path planning of agricultural robot in hilly and mountainous farmland environment, and used reciprocating coverage operation mode to plan the path of a single field.

In the study of path planning in irregular fields, Evans et al^[15] transformed the farmland harvesting operation path into a traveling salesman problem, and optimized the operation route by genetic algorithm. The mathematical model of the optimal harvesting path of a single harvester in irregular fields was constructed, which effectively reduced the increase of operation time and energy cost of agricultural machinery due to invalid operations. Han et al^[16] proposed a road planning method for polygonal irregular fields, and developed a field path planning algorithm based on X-shaped turning mode. The feasibility of the algorithm was verified in convex and concave paddy fields.

In summary, most of the existing research on agricultural machinery operation path planning is aimed at regular polygonal large fields in plain areas, while the actual operation of farmland in hilly and mountainous areas is complex, and the irregular fields with different shapes are mostly irregular. The applicability of the previous research on regular fields is not high. In a few studies on the path planning of agricultural machinery operation in hilly and mountainous areas, a simple way is usually used to plan the path. For example, path planning is carried out in the direction parallel to each side of the field boundary. Finally, the path with the least total distance is selected as the agricultural machinery operation path, or the longest side parallel to the field boundary is selected as the operation direction. These methods do not consider the impact of the number of turns on the cost of agricultural production, and the field boundary may have obstacles such as high field stems and trees. Frequent turns will increase the invalid operation time of agricultural machinery and the risk of operation safety.

In view of the above problems, this study aims to explore an unmanned agricultural machinery operation path planning method suitable for irregular fields in hilly and mountainous areas. In this paper, the Gauss-Kruger projection method and the grid method are used to establish the boundary model of irregular field blocks, and then the irregular field blocks are classified and processed, including the judgment of the concave and convex of the field blocks and the subdivision of the concave polygon field blocks. The working area of the processed field blocks is constructed, and the active side table method is proposed to construct the straight line path. By analyzing the path planning mathematical model of three turning

modes, the turning decision model is constructed. Finally, the global path planning program design and simulation analysis are carried out based on Python, and the global path planning in different types of fields is finally realized.

2. ASSUMPTIONS

This study makes the following assumptions about the environmental conditions of agricultural machinery operation path planning in irregular fields :

- (1) The slope of the working field is not more than 6 °, and the influence of elevation change is ignored.
- (2) There are no obstacles in the working area of the field.
- (3) When establishing the boundary model based on the latitude and longitude data of the vertex of the field, the small shape difference and the position difference are ignored.
- (4) The location of agricultural machinery in and out of the field needs to be determined in advance, which is not part of the path planning scheme.

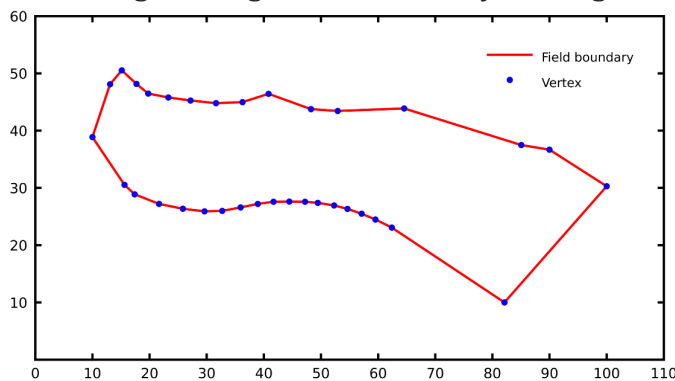
3. IRREGULAR FIELD DATA ACQUISITION AND PROCESSING

3.1. Irregular farmland boundary modeling

By extracting the boundary points of the target field from Google Earth or other GIS systems, latitude and longitude coordinates can be obtained. Through the Guass-Kruger projection, the latitude and longitude coordinates of these boundary points are transformed into x and y coordinates in the Cartesian plane coordinate system, and these coordinate points are connected to establish the boundary model of irregular fields. When selecting the vertex of the field, it is necessary to ensure that any straight line boundary is only connected by two vertices. Figure 1 is the field boundary modeling.



(a) Extracting the target field boundary in Google Earth.



(b) Transform to two-dimensional coordinate system

Figure 1. Field boundary modeling

3.2. Irregular field treatment

3.2.1 Irregular field classification

Hu[17] and chen[18] et al. divided the field into three regular polygonal fields : rectangular, right-angle trapezoid and ordinary trapezoid in the path planning of farmland in plain areas. This high-standard farmland provides convenience for agricultural machinery to achieve precise navigation and linear operation. When Michel et al. studied the path planning scheme, the field shape was extended to irregular convex polygons, concave polygons with only one concave vertex, and complex polygons with a medium curve boundary, which effectively solved the problem of agricultural machinery operation path planning under complex fields. In the actual working environment of hilly and mountainous areas in China, the situation of cultivated land is complex. The field is usually composed of more than four boundaries, and some fields also contain concave points and curve boundaries. The complex diversity of field shapes makes the mature path planning scheme in the plain area and the field classification method in the existing research unable to be directly used.

Based on the theory of computer graphics and the actual characteristics of cultivated land in hilly and mountainous areas, this study classifies irregular field shapes into three categories : convex polygons, concave polygons and complex polygons. Among them, the boundaries of convex polygons and concave polygons are composed of straight lines. Concave polygons include all cases containing one or more concave points. Complex polygons are more diverse in boundary forms, and their curve boundary length and curvature changes are more complex. Based on the above three types of fields, the classification is carried out to improve the applicability and operation efficiency of agricultural machinery operation path planning in hilly and mountainous areas of China.

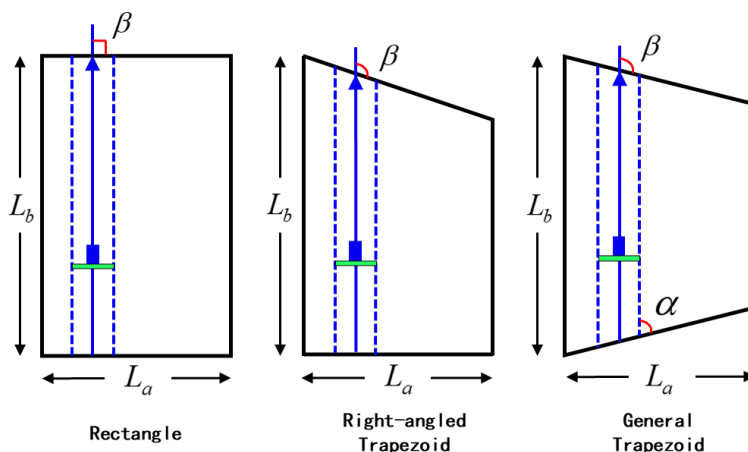


Figure 2. Regular polygon field

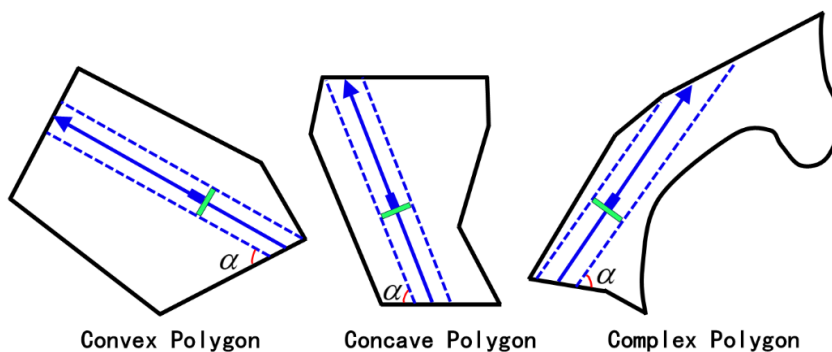


Figure 3. Irregular polygonal field

3.2.2 The definition and judgment method of field convexity

For irregular fields, concave and convex judgment is an important reference factor for agricultural machinery path planning and field safety operation area division, which will directly affect whether agricultural machinery can perform operation tasks efficiently and safely. As shown in Figure 4, the vertices of the polygon are arranged counterclockwise, and two adjacent vertices form a boundary vector, which traverses the polygon boundary in the direction of vertex arrangement. The rotation direction between the two adjacent boundary vectors $\overrightarrow{P_{t-1}P_t}$ and $\overrightarrow{P_tP_{t+1}}$ is consistent with the traversal direction, then the intersection point P_t of the two edges is the convex vertex of the polygon, otherwise it is the concave vertex. For a polygon composed of straight line boundaries, there are concave points, which are concave polygons, and all convex points, which are convex polygons.

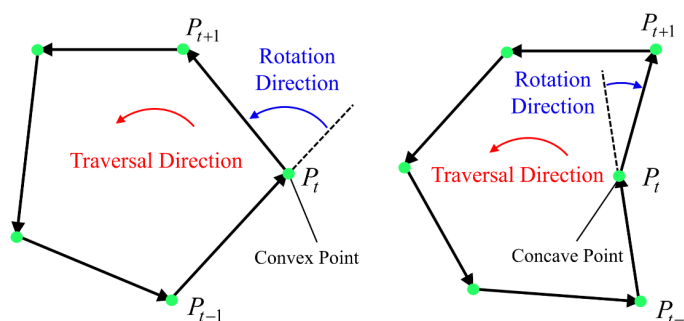


Figure 4. Vertex concavity and convexity judgment of polygon

It is stipulated that the vertices ($P_1, P_2, P_3, \dots, P_n$) of the field are arranged in a positive direction counterclockwise. Among all the vertices of the target field, the feature points with the largest x coordinate and the smaller y coordinate are selected, which are usually located in the lower right corner of the field. The vertex is a convex vertex of the field. By comparing the cross product of the adjacent edge vectors of each vertex of the irregular field with the direction of the normal vector at the convex vertex, the judgment of the convexity of the vertex of the field is:

1. Calculate the cross product of the two adjacent side vectors where the feature points are located. Let P_t be a convex vertex of a polygon. The formula for calculating the cross product of two adjacent side vectors at point P_t is as follows:

$$\vec{n}_t = \overrightarrow{P_{t-1}P_t} \otimes \overrightarrow{P_tP_{t+1}} \tag{1}$$

2. According to the counterclockwise direction, the cross product of the two adjacent side vectors of the remaining vertex P_m is solved in turn :

$$\vec{s} = \overrightarrow{P_{m-1}P_m} \otimes \overrightarrow{P_mP_{m+1}} \tag{2}$$

3. Judging the concavity and convexity at vertex P_t .

$$\lambda = \vec{n}_t \otimes \vec{s} \tag{3}$$

If $\lambda > 0$, then the vertex P_t is a convex vertex ; if $\lambda < 0$, then the vertex P_t is a concave vertex. Since the straight line boundary of the field in Section 3.1 is only connected by two vertices, the case of $\lambda = 0$ is not considered. Figure 5 shows a concave polygon field.

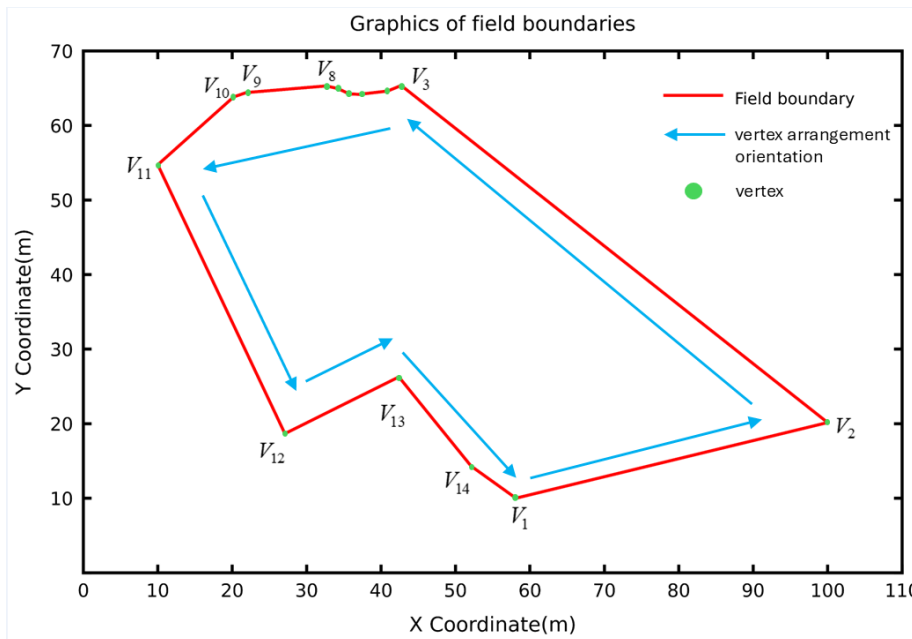


Figure 5. Concave polygon field

4. IRREGULAR FIELD PATH PLANNING

4.1. Field operation area division

The boundary area of farmland generally has geographical features such as ridges, roads or irrigation canals. The terrain conditions in this area are complex, and there may be significant height differences between adjacent fields. When agricultural machinery turns around, it is limited by the minimum turning radius(r), and the working width(W) of the implements attached during the operation will further increase the difficulty of turning. Therefore, when planning the operation path, the safety of the operation must be considered, and sufficient areas are reserved for agricultural machinery to turn and pass in and out of the field boundary area. In this paper, the target field is divided into two sub-regions : the ground area and the safe operation area. The ground area is operated separately after the completion of the operation task in the safe operation area. The ratio of safe operation area to field area is defined as coverage.

When generating the safe operation area, according to the shape of the polygonal field, each straight line boundary is contracted inward along the angular bisector, and the arc boundary is translated inward. The width of the contraction or translation is, and the width of the reserved ground area is calculated according to Formula (4) :

$$W_h = r(1 + \cos\psi) + 0.5w \tag{4}$$

4.2. Path planning model based on the least number of turns

4.2.1 Best operating angle

For the convex polygon field, when the path planning is carried out in the direction parallel to the longest boundary of the field, the number of turns is the least[19]. For concave polygon fields and complex polygon fields that need to be segmented into safe operation areas, the operation path parallel to the longest boundary of the field may be cut off by the segmented region boundary, and it is not suitable to continue to use the direction parallel to the longest edge as the operation direction.

In the safe working area, the agricultural machinery is transferred from a straight path to the next adjacent straight path, and the two straight paths are connected by a turning path. Therefore, after the operation direction used to plan the straight path is determined, the number of turns can be calculated by the number of intersections between the straight path and the safe operation area. The angle between the direction with the least number of turns and the X positive half axis is the best operation angle. This paper uses a simulated annealing algorithm to solve for the optimal operating angle, which is between 0° and 180° . The search process for the optimal operating angle is shown in Figure 6.

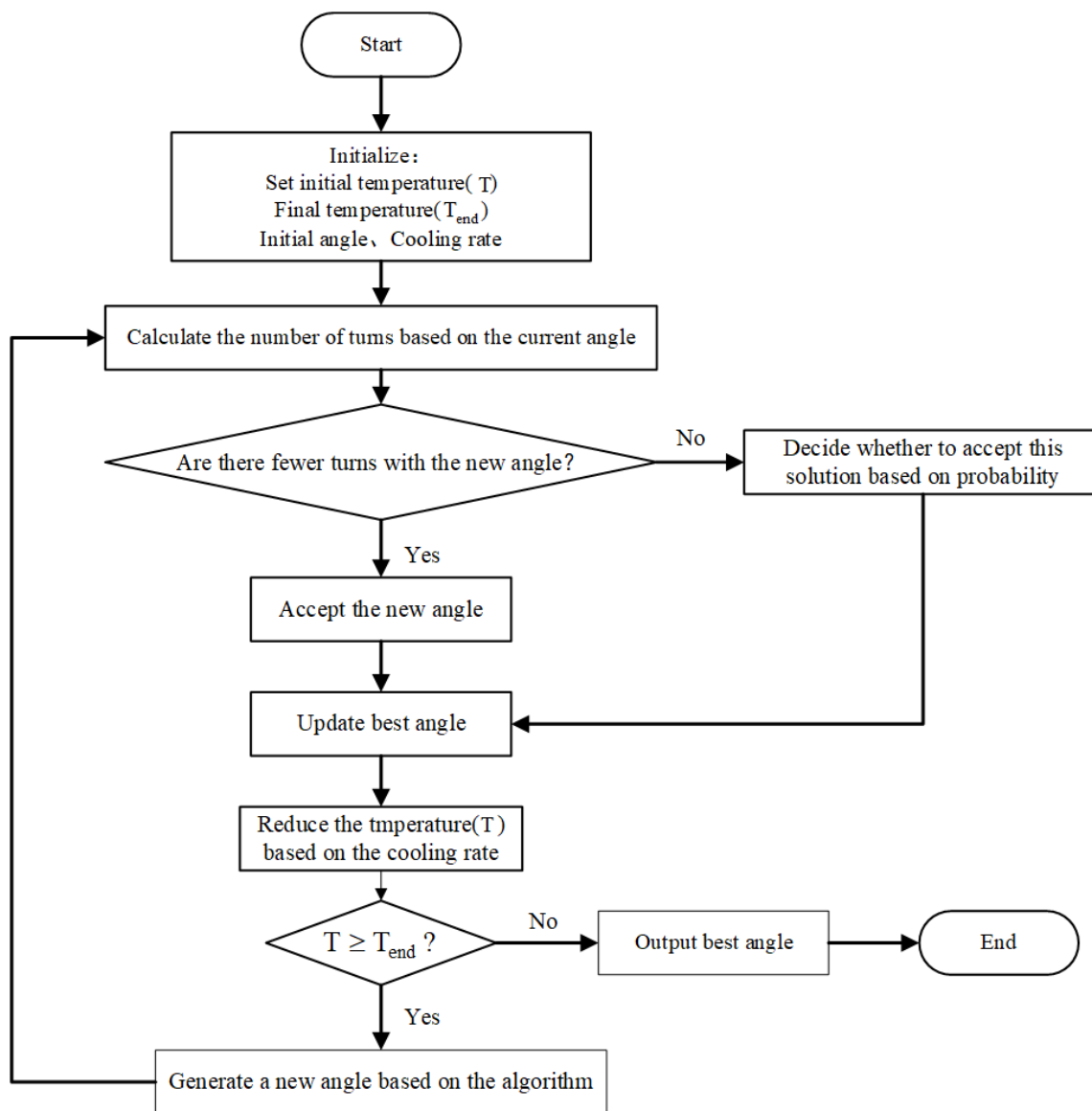


Figure 6. Overview of simulated annealing algorithm

4.2.2 Linear path planning

When the agricultural machinery works continuously in the field, the straight path is the main driving mode. At present, the planning methods of straight path in agricultural machinery operation are mainly divided into three types : random type, spiral type and reciprocating type. The spiral path planning has high coverage and does not need to reserve the head area, but it has many turning times and high turning energy consumption cost, which is suitable for fields with rectangular boundaries. Reciprocating path planning needs to reserve the turning area of

the head, and there is no repeated path, but the turning mode is complex. Therefore, this study adopts reciprocating traversal path planning.

In this paper, the method of linear path planning is based on the optimization algorithm of active edge table. A series of horizontal scanning lines are used to scan the polygon boundary of the working area line by line, and the intersection of each scanning line and the polygon boundary is calculated. The specific treatment method is :

(1) Firstly, the field is rotated according to the optimal working direction angle, and the rotation matrix is as follows :

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \quad (5)$$

In the formula, α is the best working angle, (x, y) is the vertex of the field before rotation, and (x', y') is the vertex of the field after rotation.

(2) For each given scan line $Y = y$, if there are job boundaries in the edge table corresponding to the current scan line, these job boundaries are transferred to the active edge table and arranged in ascending order according to their X coordinate values.

(3) In the active edge table, the line segments defined by the job boundary are paired in sequence. If they are completely located inside the polygon, they are regarded as effective filled line segments and used to construct the job path.

(4) After processing the current scan line, update the X coordinate of the scan line, and perform the operation of $X = X + w$, that is, add a job width value.

(5) According to the value of Y_{max} , the operation boundary that no longer intersects with the next scan line is removed from the active edge table.

(6) For each remaining edge in the active edge table, according to the formula $X = X + dX * w$, update their X coordinate values.

(7) Repeat the above steps until all the job boundaries in the active edge table are processed and deleted, and the straight line job path in the polygon job area is filled.

(8) The field and the straight line path are inversely rotated to the original direction of the field. At this time, the straight line operation path pair is used for the best operation direction in the original direction. The inverse rotation matrix is as follows :

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} x' \\ y' \end{pmatrix} \quad (6)$$

4.2.3 Turning path planning

The minimum turning radius(r), working width(w) and turning area width(W_h) of agricultural machinery jointly determine the turning mode of agricultural machinery. Existing research incorrectly classifies agricultural machinery turning systems into four typical models : ' flat turning ', ' U-shaped turning ', ' bulb turning ' and ' fishtail turning '. ' R-shaped turning ' can be regarded as an innovative variant of ' bulb turning '. The above four turning methods are different in the difficulty of turning, the length of turning path, the cost of turning path, the size of reserved turning space and the risk of soil compaction. In general, the fishtail turn and horizontal turn have relatively small demand for turning space, but their path geometry is more complex ; U-turn and flat turn are relatively simple to achieve, while bulb turn usually requires more turning space and longer path length. Combined with the research in this paper, the turning decision model shown in Figure 7 is constructed.

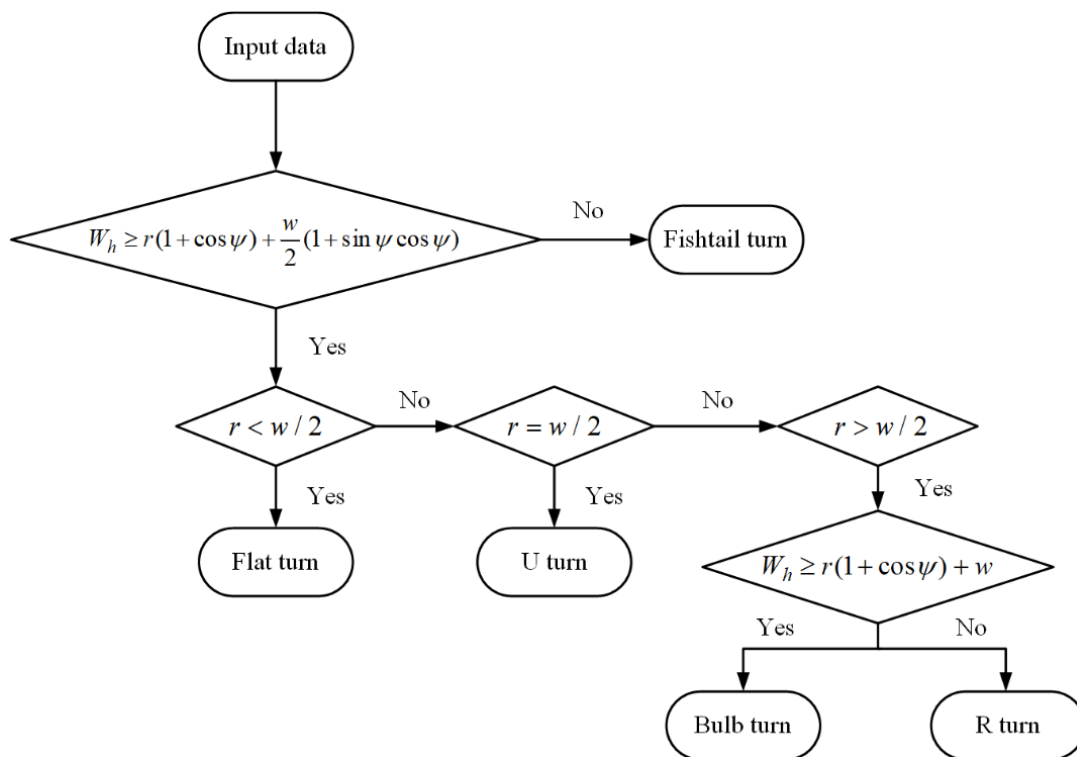


Figure 7. Turning decision model

5. SIMULATION AND RESULT ANALYSIS OF IRREGULAR FIELD PATH PLANNING

5.1. Simulation conditions and data sources

The field data used in the simulation experiment is derived from Google Earth, and three typical irregular fields located in Pidu District of Chengdu City are selected as the research objects. By extracting the longitude and latitude coordinates of the boundary vertices of the field, and using the Gauss-Kruger projection, it is converted into a polygonal boundary model in the plane rectangular coordinate system. In order to ensure the comparability of simulation analysis, the operation parameters of agricultural machinery are set uniformly : the width of agricultural machinery operation is 0.8 m, the minimum turning radius is 1 m, and the reserved width of the ground is calculated according to Formula (4). At the same time, it is assumed that the field slope is small and there are no obstacles to highlight the performance of the path planning method itself.

Under the above conditions, the path planning program is developed based on Python, and the field classification processing, the best operation angle search, the straight line path generation and the turning path planning are completed in turn, and the complete operation path is finally obtained.

5.2. Path planning results analysis

According to the selected three fields, the path planning is carried out respectively, and the operation path planning is shown in Figure 8, Figure 11, and Figure 13. From the overall results, the planned path can achieve effective coverage of the safe operation area of the field, the path distribution is uniform, and there is no obvious phenomenon of missing tillage or repeated operation.



Figure 8. Field 1

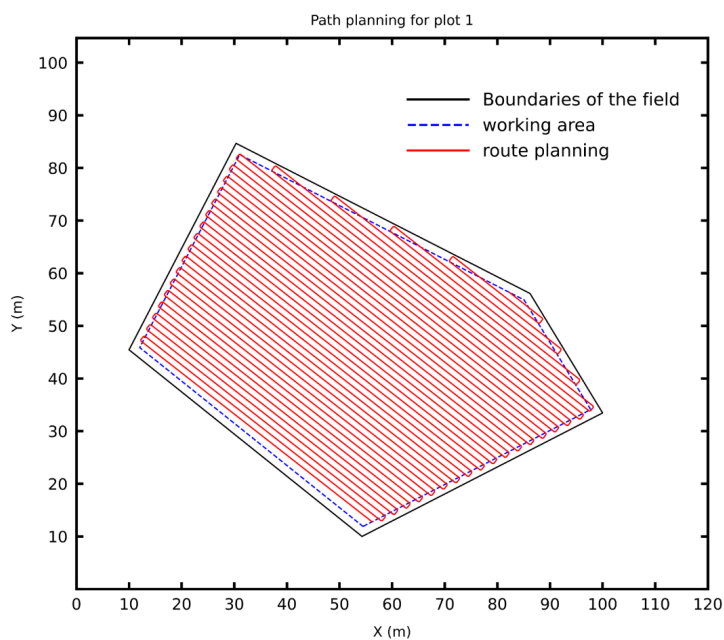


Figure 9. Path planning of field 1



Figure 10. Field 2

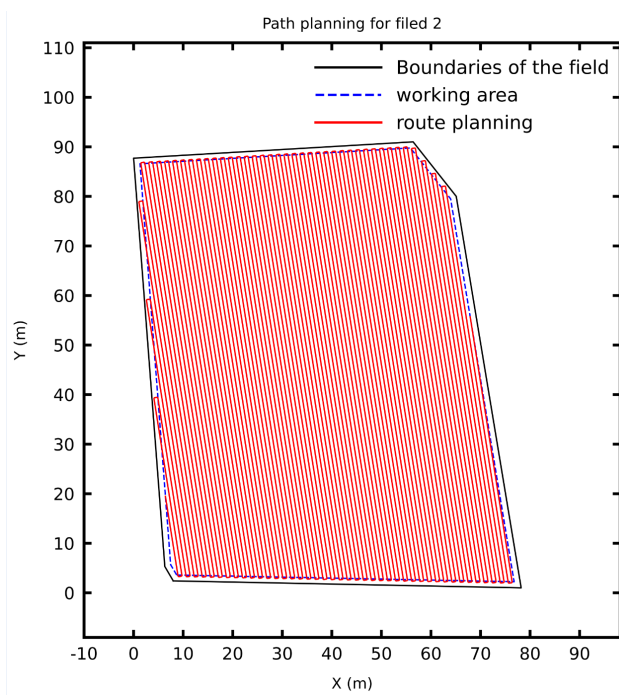


Figure 11. Path planning of field 2



Figure 12. Field 2

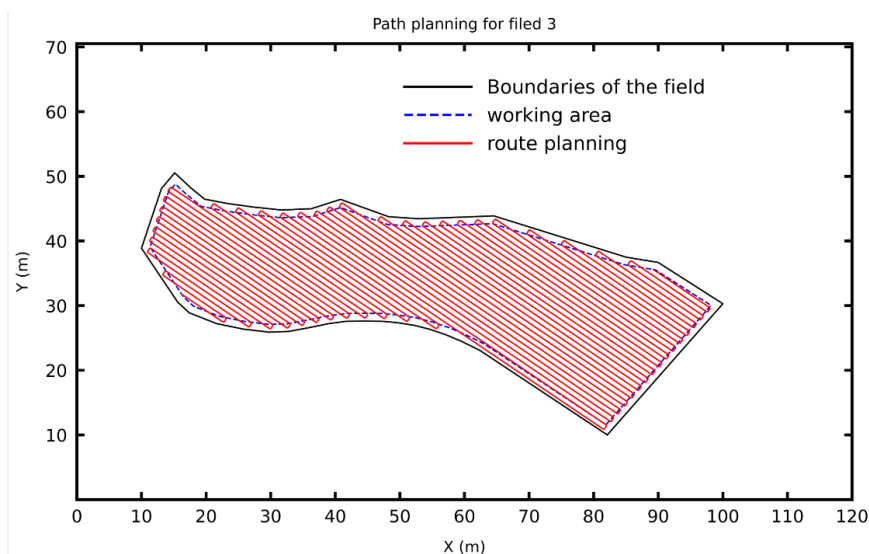


Figure 13. Path planning of field 3

Table 1 shows that the operational coverage rate of all three fields exceeded 90%, with field 3 achieving the highest coverage rate at 96.81%, indicating that the proposed method still

possesses high coverage capability even under complex field conditions. This is mainly attributed to the classification and processing of irregular fields and the rational construction of safe operating areas. Regarding the number of turns, different fields exhibited variations due to differences in shape complexity and area. Field 1 required 65 turns, while the largest field, 3, required 162 turns. Overall, the number of turns increased with increasing field area and shape complexity; however, under the same conditions, the proposed method effectively reduced unnecessary turns and improved path planning efficiency. From the perspective of optimal operating angles, the optimal operating directions differed significantly among different fields. For example, the optimal operating angle for field 2 was 99° , while for field 3 it was 30.99° , indicating that the traditional method of simply "parallel to the longest side" is insufficient for complex fields, while the angle search method based on turn count optimization presented in this paper has better adaptability.

Table 1. Field path planning results

Filed Number	Field area	Working area	Number of turns	Coverage	Optimal working angle
1	3653.95	3439.63	65	94.13%	141.99°
2	5894.9	5413.7	71	91.84%	99°
3	35125	34004.81	162	96.81%	30.99°

6. CONCLUSION

(1) Aiming at the complex shape of irregular fields in hilly and mountainous areas, a classification method based on convex polygons, concave polygons and complex polygons is proposed. Combined with concave-convexity judgment and polygon subdivision, unified modeling and processing of different types of fields are realized.

(2) Taking the minimum number of turns as the optimization goal, the path planning model of agricultural machinery operation is constructed. The simulated annealing algorithm is used to determine the optimal operation direction, and the reciprocating straight path is generated by combining the active edge table method. At the same time, the turning decision model is established to realize the complete path planning process.

(3) The simulation results show that the proposed method can effectively reduce the number of turns and improve the operation efficiency in the irregular fields of typical hilly and mountainous areas, and the operation coverage rate is more than 90 %, which verifies the feasibility and applicability of the method.

In summary, the method in this paper can provide theoretical basis and technical reference for automatic navigation and path planning of agricultural machinery in hilly and mountainous areas.

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