Research on Algorithm of Sewing Path Generation for Satellite Multi-layer Thermal Insulation

Zhe Wang*, Hao Fu, Ziqi Fan
Beijing Institute of Spacecraft Environment Engineering, Beijing, China

*Corresponding author e-mail: jljj3478@163.com

Abstract: The production mode of hand-sewn for complex shape multi-layer thermal insulation (MLI) of satellite has seriously affected its production efficiency and quality. Automatic sewing technology is an important means to improve MLI production efficiency. First, the problem of automatic creation of sewing patterns and paths needs to be solved, but there is no targeted research on MLI with special sewing requirements. In this paper, the principles of the sewing path are determined by combing the boundary conditions. Based on the chain code histogram and its spatial distribution entropy, the internal opening of MLI can be quickly identified to determine the nodes through which the sewing path passes. Then, the simulated annealing algorithm which can quickly converge to the global optimal solution is used to solve the NP-hard problem and realize the generation of the sewing path. For the special sewing requirements, the Laguerre diagram-based A-Star algorithm is used to realize the avoidance sewing path to the internal opening, and the MLI contour reinforcement sewing path planning is abstracted into the inward quantitative offset line generation problem of the contour. So the problem of automatic generation for sewing path of complex shape MLI can be solved.

1. Introduction
The multi-layer insulation for satellite (hereinafter referred to as MLI) consists of reflective screens and spacer layers [1] and the material of the reflective screens and the spacer layers are light and thin. In order to prevent the material from being changed after the cutting and forming and the expansion of the MLI in the rail which will affect the heat insulation performance, it is necessary to perform the sewing before the MLI cutting and forming. There are two methods for MLI sewing, that is, sewing a straight line along the length of the material by hand or using a multi-needle quilting machine. With the rapid development of China's space industry and the increasing demand of complicated MLI, the two methods of sewing cannot meet the requirements in terms of efficiency and quality. Hand sewing is inefficient, and multi-needle sewing does not meet the fixed requirements of small and complex MLI. With the development of single-needle quilting technology, custom flower-shaped sewing of spacecraft MLI of any size and shape is achieved, but the problem that ensues is the determination of the sewing path.

In the CNC sewing process, optimizing the sewing path of complex flower shapes has always been the focus of industry research, and it is of great significance to improve sewing efficiency. For this problem, the literature [2] and the literature [3] use the three-dimensional raster scanning technology and the binocular vision automatic seam recognition method to plan the three-dimensional surface stitching path, but it is obviously not suitable for the two-dimensional plane complex path planning. In
literature [4], based on the greedy strategy optimization algorithm, the machining contours are reordered while determining the needle points in each contour to obtain an optimized machining path, but the purpose of the method is to shorten the idle stroke of the needles between the patterns, without considering the problem of opening avoidance. Literature [5] solves the problem of automatic generation of embroidery trajectory through geometric calculation and graph theory, but this method is only suitable for solving the traversal sewing problem. Literature [6] and [7] have studied the fidelity of the pattern, but the method is based on the optimization of the known sewing path.

In this paper, the principles of the sewing path are determined by combing the boundary conditions. Based on the chain code histogram and its spatial distribution entropy, the internal openings of MLI are quickly identified to determine the nodes through which the sewing path passes. Then, the simulated annealing algorithm with the characteristic of quickly converge to the global optimal solution is used to solve the NP-hard problem and realize the sewing. For the special sewing requirements of MLI, the Laguerre diagram-based A-Star algorithm is used to realize the avoidance of the internal openings, and the final sewing path is generated. The effectiveness of the algorithm is verified by simulation, and the problem of automatic generation of complex sewing path of MLI on the surface of satellite is solved.

2. Analysis of sewing boundary condition

2.1. Analysis of sewing requirements

The purpose of sewing the MLI is to fix the multilayer material, but the sewing also causes a change in the layer density, which affects the thermal insulation performance of the MLI.

First, when there is no contact between the reflective screens, heat is conducted through radiation. According to formula (1), the greater the layer density, the less the amount of radiative heat transfer, and the better the thermal insulation performance [8].

\[
q = \frac{\sigma A \left( T_1^4 - T_2^4 \right)}{(n+1) \left( \frac{2}{\varepsilon} - 1 \right)}
\]

\( \sigma \) is the Sterling-Boltzmann constant. \( A \) is the area of the reflective screen. \( T_1 \) and \( T_2 \) are the internal and external surface temperatures. \( n+1 \) is the number of reflective screen layers and \( \frac{2}{\varepsilon} - 1 \) is the system emissivity.

However, as the layer density increases, the contact between the reflective screen and the spacer layer creates contact thermal conduction, which reduces thermal insulation performance. And there is a certain contact thermal resistance on the contact surface of the MLI reflective screen and the spacer layer, which will cause a local high temperature region inside the MLI. According to the thermal resistance calculation formula per unit area (2), the single point contact radius \( a \) is determined by the contact stress of the spacer layer and the reflective screen, and the nominal thermal flow path \( b \) is determined by the number of contact points per unit area, that is, the sewing tightness [9]. \( f \) is the contact thermal resistance factor and \( k \) is the thermal conductivity coefficient.

\[
\frac{1}{R} = \frac{4ka}{\pi b^2 f}
\]

Therefore, the sewing process requires simultaneous control of layer density, contact stress and number of contact points. That is, while ensuring that the shape of MLI does not change due to the displacement of the multilayer material, the layer density is kept within a certain range. Therefore, the stitching stitch should first be in the area where the shape change is easy, that is, around the cutting line, including the contour of MLI and the inner openings, and the remaining area can be stitched by the line between the openings. Due to the deformation wrinkles and positioning errors of the MLI during the automatic cutting process, it is necessary to leave a margin for the cutting error for the automatic cutting, which is determined to be 5 mm by the test. During the sewing process, each stitching and seaming is reinforced and stitched, which will increase the local contact thermal resistance. This provides boundary conditions for sewing path generation:
1. The sewing path passes through all the cutting line areas, namely the inside of the contour line and the outside of the internal opening;
2. The distance from the path to the cutting line should be greater than 5mm to prevent the stitching from being cut during the cutting process;
3. The sewing path should be a continuous path with no free travel to prevent multiple local thermal resistances;
4. When the above conditions are met, the sewing path is minimized, thereby improving the sewing efficiency.

2.2. Analysis of the shape of MLI
The outer contour of the MLI is arbitrary and is a combination of arc and straight line. The internal opening shape is a finite set, which can be obtained by exhaustively, and then separately analyzed by the samples [10].

The internal openings are mainly the following:

- Circular opening
- U-groove opening
- H-shaped opening
- I-shaped opening
- Cross opening
- I-shaped opening
- Square opening
- Waist opening

According to the positional relationship with the outer contour, the inner figure can be further divided into two types, which intersect with the outer contour and not with the outer contour.

3. Fast recognition of MLI graphics
Since the MLI contains a plurality of discontinuous openings, each opening needs to be sewn at its periphery to form a closed figure. In order to abstract the path generation into an NP-hard problem [11], we abstract the surrounding sewing line of each opening into a special point. Using the abstraction and encapsulation methods in the object-oriented object, all internal points are masked out, and only one point is provided as an interface, which can be transformed into a path optimization problem between these special points. Here, the abstraction is the center point of the open shape as shown in Figure 1. In order to improve the coordinate calculation efficiency of the center point, the direction chain code can be used to distinguish the pattern more effectively. On the basis of the chain code histogram, the chain code string is rotated and normalized by introducing the spatial distribution entropy of the chain code [12]. The chain code feature of the obtained graphic is:

$$ F = \langle (h_1, E_1), (h_2, E_2), \ldots, (h_n, E_n) \rangle $$

(3)

Then define the similarity according to the chain code characteristics:

$$ S_{(x, y)} = \sum_{i=0}^{n} \min(h_{Xi}, h_{Yi}) \times \min(E_{Xi}, E_{Yi}) $$

(4)

This method ensures the similarity of the spatial distribution of chain code features while ensuring the similarity of chain code histograms.

The coordinates of the center point can be quickly determined while the internal opening shape is judged. For example, for a U-slot opening, the coordinates of the point O \((x_0, y_0)\) is:
4. Internal sewing path generation

When the coordinates of the center points are determined, a sewing path can be randomly generated. But the unoptimized sewing path may be lengthy, reducing the sewing efficiency, and the path crossing also increases the number of contact points. In the path optimization method, the preferred method for calculating all paths using permutation and combination is inefficient when the number of internal openings is large, and the simulated annealing algorithm\[^{[13]}\] can quickly converge to the characteristics of the global optimal solution, which can improve the efficiency of path optimization.

Suppose there are \( n \) openings, denoted by 1, 2, 3, ..., \( n \), \( n+1 \) are both the initial opening and the final opening of the path. Let \( d_{ij} \) be the distance from opening \( i \) to opening \( j \), and the simulated annealing algorithm for this problem is described as: \( M \) is all paths passing through each opening once, denoted as \( \{M_1, M_2, ..., M_{n+1}, M_{n+2}\} \), and the initial solution is \( \{1, 2, 3, ...,n,n+1,n+2\} \). The objective function is the total length of the path:

\[
F(M_1, M_2, ..., M_{n+1}, M_{n+2}) = \sum_{i=1}^{n+1} d(m_i, m_{i+1}) \tag{6}
\]

To generate a new path for the minimum value of the function, randomly generate integers \( i \) and \( j \) between 1 and \( n \).

\[
\eta = (i + \frac{\beta T_n n}{\gamma} + \frac{i}{n})^\%n \tag{7}
\]

\( \beta \) is the correction factor, and when \( i>\eta \), or \( 1<\eta \), exchange \( M_i \) and \( M_\eta \), a new path is produced.

The specific path optimization steps are as follows:
1. \( T \) is the length of the initial path \( S \), and new solution and variable Markov chain length \( L_k \)\[^{[14]}\] can be found according to the experimental;
2. When the number of disturbances is less than \( L_k \), a new path \( S' \) is generated according to the new path generation principle;
3. Calculate the increment \( \Delta t' = f(S') - f(S) \), and \( f(S) \) is the path length function;
4. If \( \Delta t' < 0 \), \( S' \) is a new path, otherwise \( S' \) is accepted as a new path with probability \( \exp(\Delta t'/T) \), and the optimal path is updated;
5. If the termination condition is met, the current optimal path is selected, and the iteration is ended;
6. If \( T \) decreases and \( T>0 \), skip to step 2.

For the MLI internal opening as shown in Figure 2, the optimal path shown in Figure 3 can be generated.

5. Open avoidance algorithm

Although the internal sewing path generation algorithm can quickly obtain the shortest sewing path, but since it uses the opening center point as the path node, the path will be cut through the openings. And the current sewing path algorithm is the path of the idle path without considering the opening avoidance problem. This section will apply the A-Star algorithm\[^{[16]}\] based on the Laguerre diagram\[^{[15]}\] to achieve the avoidance of the MLI sewing path to the internal openings.

![Figure 2. MLI graphics](image1)

![Figure 3. Internal sewing optimal path for MLI](image2)
5.1. A-Star algorithm avoidance path planning

A-Star algorithm is a heuristic graph search algorithm. It can evade path planning for arbitrarily shaped obstacles under multiple constraints. By selecting appropriate heuristic functions, the generation value of each extended node is calculated and evaluated. The node with the best value is expanded until the target node is found.

The A-Star algorithm contains two types of nodes. One is a node that has been extrapolated but has not been extended, and the other is a node that has been extended. For the extended node, a cost evaluation is required, and the cost function is generally of the form:

\[ f(n) = g(n) + h(n) \]  

(8)

\( g(n) \) is the cost that has been consumed from the start node motion to the node \( n \), expressed as the path length. \( h(n) \) is the cost that is estimated to be consumed from the motion of the node \( n \) to the target node, expressed in terms of Euclidean distance. \( f(n) \) is the cost of the best path from the starting node to the target node.

Judging whether the extended node is in the opening avoidance area can be determined by the method of making rays from the node. If the intersection point is even (such as \( P_{n+2} \) in Fig. 4), the node is not in the avoidance area, otherwise it is judged to be in the avoidance area (\( P'_n \) in Fig. 4). The efficiency of the algorithm can be improved by judging whether the search range can be narrowed within the avoidance area. As shown in Fig. 4, \( P'_{n+2} \) needs to be excluded, and \( P_{n+2} \) is a suitable expansion node.

![Figure 4. Node expansion area judgment](image)

5.2. Optimization of avoidance path based on Laguerre diagram

Due to the close proximity of some of the openings, the avoidance path should be between two consecutive openings in order to reduce the length of the sewing path and avoid the path cannot be sewn along the originally planned global path because of the unavoidable selection of the starting point and the target point. Therefore, before using the A-Star algorithm, path planning can be performed based on the Laguerre diagram, and the path optimization is selected in advance.

The path planning of Laguerre diagram is a new method based on graph theory. Suppose there is a set of circles, the center of any circle \( C_i(O_i, r_i) \) is \( O_i \), the radius is \( r_i \). Defines the square of the distance from any point \( A \) in the plane to the tangent point is the Laguerre distance from the point to circle:

\[ d(a, C_i) = \sqrt{d(a, O_i)^2 + r_i^2} \]  

(9)

The Laguerre edge defined by the circle \( C_i(O_i, r_i) \) and the circle \( C_j(O_j, r_j) \) is a line formed by points equal to the Laguerre distance of the two circles. By dividing the entire task into overlapping optimization intervals that are constantly moving forward, the local optimization of online scrolling replaces the unchanging global optimization. Path re-planning will only be triggered when an event is encountered, that is an opening is encountered. Before re-planning the path, it is necessary to design the size of the re-planning area. Using the circumscribed circle method, the circle and the opening avoidance area are cut out as much as possible, and the opening avoidance area is simplified into a circle. Since the edge of the avoidance area needs to be sewn, the vertex closest to the planned path of the avoidance area needs to be used as a node in the A-Star algorithm after generating the planned path.
5.3. avoidance path algorithm simulation

Taking the MLI graph shown in Fig. 2 as an example, the avoidance path is planned on the basis of the internal sewing path of Fig. 3. Firstly, the avoidance region is generated according to the boundary condition that the distance from the cutting line should be greater than 5 mm, as shown in Fig. 5.

![Figure 5. Avoidance zone generation](image)

The circumscribed circle of each avoidance area is then generated using the circumscribed circle method, as shown in Fig. 6.

The path planning diagram obtained by using the Laguerre algorithm for path planning in the simplified avoidance area is shown in Fig. 7.

![Figure 6. Avoidance zone simplification](image)

![Figure 7. Laguerre algorithm path planning](image)

Finally, the simplification is simplified, and the A-Star algorithm is used for path planning. After generating the planning path, the vertices closest to the planning path are taken as a node in the A-Star algorithm, and the obtained path planning diagram is shown in Fig. 8.

![Figure 8. A-Star algorithm path planning](image)

The algorithm can combine the sewing path and the contour of the avoidance area, without repeated sewing process, and complete the reinforcement sewing around the opening and the inner opening avoidance of the MLI at one time, without the need to disconnect.

6. trajectory equation establishment of contour

The above algorithm solves the problem of internal sewing path planning and opening avoidance. For the sewing problem of the contour line, this paper abstracts the problem as the inward quantitative offset line of the contour. But if each line constituting the contour is offset separately, the phenomenon of offset line crossing occurs [17]. The equations of the positional relationship between the contour component line and its contoured sewing path are established, and all the bias lines are obtained [18]. Then, intercept the line segment according to the intersection to obtain a closed contour path [19].

As shown in Fig. 9, for any point A₀(x₀, y₀) on the contour line, the normal of the point is made inward along the contour, and the offset distance L is taken along the normal line. Then, the offset point A,L of the point is obtained. Let the angle between the normal at A₀ and +X be θ, then the coordinates of A,L(xₖ, yₖ):  

\[
\begin{align*}
xₖ &= x₀ + L \cos θ \\
yₖ &= y₀ + L \sin θ
\end{align*}
\]  

(10)
When an MLI profile consists of $n$ line segments, it is thus possible to obtain $n$ sets of equations, and $n$ sets of $A_L$.

$$A_{Li} = \{(x_{Li}, y_{Li}) | x_{Li} = x_{0i} + L \cos \theta, y_{Li} = y_{0i} + L \cos \theta, 1 \leq i \leq n \} \quad (11)$$

Counterclockwise numbering of the line segment, find the intersection of any one of the offset line segments and its adjacent offset line segment. When obtain the end point of the offset track, that is, the range of $x_{Li}$ and $y_{Li}$, the offset line segment equation of the $i$-th line is:

$$\begin{align*}
  x_{Li} &= x_{0i} + L \cos \theta \\
  y_{Li} &= y_{0i} + L \sin \theta
\end{align*}\quad (12)$$

and

$$\begin{align*}
  x_{Li} &\in \left[ x_{L_{\min}}, x_{L_{\max}} \right] \\
  y_{Li} &\in \left[ y_{L_{\min}}, y_{L_{\max}} \right] \\
  (x'_{Li}, y'_{Li}) &\in \left( A_{Li} \cap A_{L(i+1)} \right) \cup \left( A_{Li} \cap A_{L(i-1)} \right)
\end{align*}\quad (13)$$

When $A_{Li} \cap A_{L(i+1)} = \emptyset$ or $A_{Li} \cap A_{L(i-1)} = \emptyset$, calculate whether $A_{Li}$ has an intersection with other contour offset lines. If there is an intersection, the point is the endpoint of $A$. If there is still no intersection with other contour offset lines, then determine if $A_{L(i+1)}$ and $A_{L(i-1)}$ intersect. If $A_{L(i-1)} \cap A_{L(i+1)} = \emptyset$, no offset is made, and $A_{L(i-1)}$ and $A_{L(i+1)}$ are adjacent trajectories \[20\]. If $A_{L(i-1)} \cap A_{L(i+1)} = \emptyset$, extend $A_{Li}$ and bias line of its disjoint neighbor respectively. And the intersection of the lines is the end point of $A_{Li}$.

Therefore, on the basis of Fig. 8, the final sewing path is as shown by the solid line in Fig. 10.

7. Conclusion

For the MLI special sewing requirements, the Laguerre diagram-based A-Star algorithm and the MLI contour inward quantitative offset line generation can effectively solve the problem of automatic generation of the complex sewing path, and realize the automatic sewing and automatic cutting of complex shape MLI.

References

[1] Sun Hui, Xu Shuyan, Sun Shouhong, Qu Hongfeng. Processing of Multilayer Insulation Blankets[J]. Aerospace Materials & Technology, 2011(3): 81-83

[2] WU Yongsheng, WANG Tianqi, LI Liangyu, LI Jinzhong, DU BoyuFengmu. Automatic path planning technology of stitching robot for composite fabric with curved surface [J]. MATERIAL SCIENCE & TECHNOLOGY, 2017, 25(2):16-21
[3] LI Jinzhong, WANG Tianqi, HE Junjie, LI Liangyu, HOU Yangqiang. Fabric curved surface seam extraction using binocular vision and stitching path planning [J]. Journal of Textile Research, 2017, 38(8):156-160

[4] HE Aijun, TANG Luxin, LIU Hui, ZHANG Zhijun. Study on model and algorithm of path optimization for pattern quilting [J]. Chinese Journal of Scientific Instrument, 2007, 28(8):546-549

[5] HE Yuanjun, SUN Chengshan, CAO Jinyong. An Algorithm of Finding Path of Embroider Suture Needle [J]. Chinese Journal of Computers, 2003, 26(9):1211-1216

[6] LI Yefan, ZHANG Kailong, YAO Longhui, ZHOU Xingshe. Optimized generation algorithm of various styles patterns for intelligent sewing equipment [J]. Computer Engineering and Applications, 2012, 48(8):168-171

[7] ZHANG Kailong, LIANG Ke, CHAI Hua, ZHOU Xingshe, WANG Bowei. Design of high-fidelity sewing pattern file format [J]. Computer Engineering and Applications, 2007, 43(20):101-103

[8] Zhang Xiaoning. RESEARCH OF HEAT TRANSFER IN MULTILAYER INSULATION FOR SPACE VEHICLES [D]. Harbin Institute of Technology, 2007

[9] Wan Xiaopeng, Hou Chi, Zhao Meiying. Numerical Analysis of Multi-Layer Insulation Foils' Thermal Resistance's Influence on Thermal Conductivity [J]. Journal of Northwestern Polytechnical University, 2009 (3): 310-315

[10] YAO Leibo, GUO Chao, ZHANG Weimin. Fast Geometry Figure Recognition Algorithm Based on Edge Pixel Point Eigenvalues [J]. Application Research of Computers, 2011, 28(11): 4386-4388

[11] VLADIMIR D, ZORAN S, An efficient transformation of the generalized traveling salesman problem into the traveling salesman problem on digraphs [J]. Informatics and Computer Science, 1997, 102: 105-110.

[12] HU Xiaohong. Quick Recognition Algorithm for Geometry Figure Based on Chain Code Feature [J]. Journal of Jilin University (Science Edition), 2015, 53 (3): 489-493

[13] Kirkpatrick S, Gelatt C D Jr, Vecchi M P. Optimization by simulated annealing [J]. Science, 1983, 220: 671-680.

[14] WU Lili, WANG Zhiren, ZHU Chengjuan. Evolutionary strategy based on simulated annealing algorithm to solve the system of nonlinear equations [J]. Journal of Hefei University of Technology, 2008, 20 (2): 301-304

[15] Berg M D, Kreveld M V, Overmars M, et al. Computation geometry algorithms and applications [M]. 3rd ed. Berlin: Springer-Verlag, 2008.

[16] Yao J F, Lin C, Xie X B, et al. Path planning for virtual human motion using improved A star algorithm [C]. Proc. of the 7th International Conference on Information Technology: New Generations, 2010: 1154-1158.

[17] ENGLERT P, PARASCHOS A, DEISENROT M P, et al. Probabilistic model-based imitation learning [J]. Adaptive Behavior, 2013, 21(5): 388-403.

[18] Wu Chuanyu, He Leiying, Li Qinhuian, Hu Xudong. CAD-Based Method for Generating Spraying Trajectory of Adhesive on Shoe Soles [J]. Journal of Computer-Aided Design & Graphics, 2008, 20 (5): 678-682

[19] Kineri Y, Endo S, Maekawa T. Surface design based on direct curvature editing [J]. Computer-Aided Design, 2014, 55: 1-12

[20] Xu G, Hui K C, Ge W B, et al. Direct manipulation of free-form deformation using curve-pairs [J]. Computer-Aided Design, 2013, 45(3): 605-614