IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received 17 September 2023, accepted 11 October 2023, date of publication 16 October 2023, date of current version 2 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3324853

APPLIED RESEARCH

Optimization of Branch Pipe Routing Considering Tee Constraint Ant Lion

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ABSTRACT Considering the complex nature of branch pipes, which typically exhibit one-to-many characteristics, a transformation is implemented to facilitate one-to-one pipe routing. This approach primarily addresses the challenges related to routing sequence planning, branch point determination, and pipe direction. In terms of engineering practice, the optimal branch points are selected from a set of discrete points. Subsequently, the branch pipe routing sequence is determined based on the optimal distances between adjacent endpoints. Meanwhile, taking into account the constraints imposed by three-way pipe, the branch pipe issue is resolved employing the ant lion algorithm. During the layout solving process, the ant lion algorithm exhibits certain limitations, such as local optima and slow convergence speed. To overcome these deficiencies, enhancements are made and rigorous testing is conducted. The improved ant lion algorithm is then employed to achieve automated layout optimization of branch pipes, thereby enhancing layout efficiency. As for the branch pipe direction problem, inspiration is drawn from Electronic Design Automation (EDA) wiring. By integrating orthogonal and non-orthogonal pipes, a method is devised to achieve engineering aesthetics in general. Finally, the proposed method's effectiveness is verified through a joint simulation utilizing Siemens NX/GRIP and Matlab software. This verification ensures the soundness and applicability of the proposed approach to practical scenarios.

INDEX TERMS Branch pipe, "T" tee, engineering rules, ant lion algorithm.

I. INTRODUCTION

In the context of the "Made in China 2025" initiative and the adoption of Industry 4.0 technologies, China is actively incorporating advanced technologies such as machine learning, reinforcement learning, deep learning, and virtual reality into pipe design processes. The optimization problem of pipe routing is essentially about researching the pipe path nodes within the corresponding installation space, from the starting point to the end point, while satisfying specific engineering constraints and installation objectives. The pipe system is an integral part of complex equipment for its operation, control, and operation, carrying media such as fuel, lubricants, and air. With the exception of certain pipes directly connected to the casing surface, most pipes require complex systems comprising pipe joints and structural attachments. In the early stages, there was insufficient attention given globally to the external pipe systems of aerospace engines, leading to frequent occurrences of pipe rupture, oil leakage, and accidents. Rational pipe design plays an immeasurable role in ensuring the safety of complex equipment and holds significance in the research of complex equipment's pipe systems. The installation of branch pipes in aerospace engines belongs to typical Non-deterministic Polynomial-hard (NP-hard) problems. As the era progresses, the increasing number and diverse types of pipes pose profound influences on product reliability and design cycles, thereby introducing new challenges to pipe routing design. Previously, pipe installation relied mainly on the experience of technicians in manually routing pipes, resulting in reduced efficiency in automated pipe installation. Extensive research has been conducted by scholars domestically and internationally to address this issue. However, at present, a complete human-machine system for automated routing of branch pipes remains unavailable.

In the domain of automated pipe routing, Jwa-Geun Min et al. [1] introduced a jump point search algorithm

The associate editor coordinating the review of this manuscript and approving it for publication was Turgay Celik.

to enhance path finding speed and subsequently improved this algorithm for pipe routing in three-dimensional space. Zhou et al. [2] proposed a method that combines Lee's algorithm with genetic algorithms to achieve automatic pipe routing on the surface of an aero-engine. Shin et al. [3] leveraged the benefits of reinforcement learning in dynamic routing for automating pipe design, applying this approach in the realm of ship pipe design. Jiapeng et al. [4] enhanced the academic rigor of aero-engine pipe routing through the incorporation of an adaptive variable step into the Tenniu Whisker algorithm. They employed the raster method and the method of intersecting line segments to determine the interactions between pipes and obstacles, thus leading to improved pipe routing efficiency. In a similar vein, Liu et al. [5] proposed a heuristic strategy that leveraged direction information, an adaptive pseudo-random transfer strategy, an enhanced local pheromone update mechanism, and an improved global pheromone update mechanism. These enhancements were applied to the ant colony algorithm, resulting in significant improvements in the efficiency of pipe routing. These methods serve as valuable references for addressing more intricate branch pipe routing problems.

Regarding branch pipe, Park et al. [6] employed a cell generation technology-based piping design approach, which simplified the optimization problem associated with branch pipe routing. However, due to the limited generation mode of this method, it is not suitable for handling complex pipe routing designs. On the other hand, Xiaolan et al. [7] utilized the maze algorithm to simulate wave propagation characteristics and determine the location of tee points in two-dimensional planes with and without obstacles. Furthermore, Liu et al. [8] presented an intelligent routing method for branch pipe based on the Steiner tree principle, focusing on obstacle avoidance and utilizing particle swarm optimization. This approach effectively transformed the Steiner tree problem related to branch pipe routing into a graph-based Steiner tree problem. Similarly, Jiang et al. [9] also proposed an intelligent routing method for branch pipes based on the Steiner tree principle, applying optimization through particle swarm techniques to avoid obstacles. Additionally, Jiang et al., in their research, employed the co-evolution ant colony algorithm to address branch pipe routing, treating the branch pipe as a "one-to-many" problem. Liu et al. [10] applied the Steiner tree algorithm to address the issue of branch points in branch pipe routing, specifically focusing on obstacle avoidance. They formulated a multi-objective model with objective constraints including the number of branch points, optimal length, and smoothness. This approach aimed to find an optimal solution considering these objectives. Ma et al. [11] introduced a local quadratic learning probabilistic path diagram for the optimal design of non-rectangular branch pipe routing. They also considered the attachment of tee structures while optimizing the branch points. This addition of tee structure attachment constraints improved the efficiency and effectiveness of the optimal design for branch pipe routing. Wang et al. [12] utilized an improved co-evolutionary algorithm and proposed a strategy of decomposition before reconstruction to optimize the routing design of ship branch pipe. Their method aimed to enhance the efficiency and quality of pipe routing. However, it is noted that the constraints considered in the branch pipe routing were relatively limited and did not fully address the actual engineering requirements.

In summary, research on the optimal design of pipe routing has generated significant findings and is becoming increasingly mature. The focus has shifted from single pipe routing to multi-pipe routing and from single-target engineering constraints to considering multiple target engineering constraints simultaneously. On the other hand, research on branch pipe routing has been relatively limited, with previous studies primarily focusing on automatic pipe routing and using Steiner points to determine branch points. However, there has been a lack of consideration for "T" tee structure attachment constraints in automatic branch pipe routing design. Consequently, the optimal design of branch pipe system routing remains a complex problem that necessitates further in-depth research and investigation.

In this paper, we address the problem of branch pipe routing in aero-engine systems, specifically focusing on the "T" tee structure attachment. Taking into account the practical aspects of engineering, we propose a branch pipe routing design based on an improved ant lion algorithm. Our approach incorporates a series of engineering rules to ensure the routing meets the necessary criteria. To overcome the limitations of the original ant lion algorithm, which include local optima and slow convergence, we integrate multiple strategies to enhance its performance and increase the efficiency of the branch pipe routing process. Additionally, for the branch line orientation, we combine orthogonal and non-orthogonal lines to achieve an overall aesthetic effect. To validate the feasibility and efficiency of our proposed method, we developed a branch pipe routing system using the Siemens NX/Grip secondary development interface. We verify the effectiveness of our approach through test cases and simulated routing scenarios.

II. PROBLEM DESCRIPTION AND GENERAL DESIGN

A. PROBLEM DESCRIPTION

Complex equipment, such as an aero-engine, typically consists of numerous pipes and cables, and meeting the diverse pipe routing requirements can be challenging. Consequently, the design needs to be tailored to the specific circumstances. There are different pipe directions to consider, including orthogonal, non-orthogonal, and mixed-direction pipes. Additionally, pipes can be categorized into two types: endpoint pipe routing or branch pipe routing involving multiple pipes. When routing these pipes, various factors must be taken into account, such as electrical areas, high-temperature areas, and maintenance zones. Furthermore, several engineering rules, including routing space limitations, assembly considerations, and factors related to vibration and maintenance, need to be considered. Given the high 3D constraints associated with aero-engine branch pipe routing, finding a feasible solution can be difficult. To address this challenge, the aero-engine model is layered using the projection method, as depicted in Figure 1.

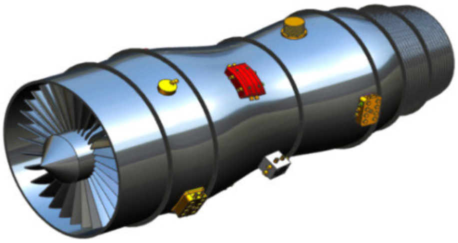


FIGURE 1. Simplified CAD model of an aero-engine.

In practical engineering, tee structure accessories are commonly used for fluid connection, diversion, and summation at branch pipe branch points due to their wide applicability. There are various types and shapes of tee structure parts, with "T" tee structure parts being more widely employed in engineering practice. Therefore, this paper primarily focuses on the application of "T" tee connections in branch pipe routing [13].

To facilitate the discussion on tee structure accessories, a simplified CAD model of the tee structure attachment is established, as illustrated in Figure 2. The coordinate system of the tee structure attachment is established in the figure $\{M', e_1', e_2', e_3'\}$, M' represents the position of the center point of the tee, and e_1', e_2', e_3' is the unit vector satisfying the right-hand relationship. According to the knowledge of spatial geometry, the affine coordinate transformation is introduced, and (x, y, z) and (x', y', z') are the coordinates of a point in $\{M', e_1', e_2', e_3'\}$ and $\{M, e_1, e_2, e_3\}$ respectively, and the coordinate transformation formula is as follows:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} \tag{1}$$

where the matrix $A = (a_{ij})$ is the transition matrix from σ_1 to σ_2 satisfying

$$(e_1', e_2', e_3') = (e_1, e_2, e_3) \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \tag{2}$$

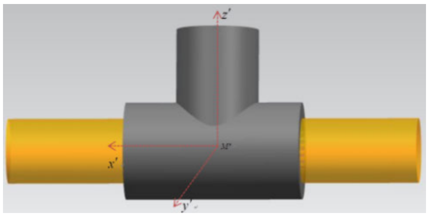


FIGURE 2. Simplified CAD model of tee structure attachment.

In a branch pipe routing system, the tee structure attachment has certain geometry and size constraints, resulting in the need for welded short pipes at the three ends of the tee attachment. During the branch pipe routing process, a certain distance must be stretched out in advance to ensure proper connection between the tee attachment and the pipe. Furthermore, the position parameters of the tee structure attachment directly influence the routing path of the pipe as it changes at the tee's center point. To simplify the calculation of the tee structure attachment's posture, the affine coordinate transformation derived from spatial analytic geometry is introduced, providing a more intuitive understanding.

B. ABBREVIATIONS AND ACRONYMS

Theoretically, the branching point of the branch pipe can be determined using the Steiner tree algorithm, which finds application in cable routing, ship design, and aero-engine pipe design. If the tee situation is taken into further consideration, the branching point can be optimized. However, in practice, engineers often utilize conventional two-end pipes, selecting a tee node in the generated pipe and connecting it as the starting point with other end points to form a "T" tee at the connection location. By traversing all branch end points, the branch pipe is obtained. In this paper, the aesthetics of engineering are considered. Although the shortest non-right-angle pipe may appear irregular and its length may not be optimal in terms of overall pipe aesthetics, it is necessary to balance aesthetics with functionality. Simultaneously, this approach allows the pipe to navigate around obstacles in space while combining both orthogonal and non-orthogonal directions. As depicted in Figure 3, the general pipe direction fulfills the requirements of the shortest path while maintaining a clean and aesthetically pleasing appearance.

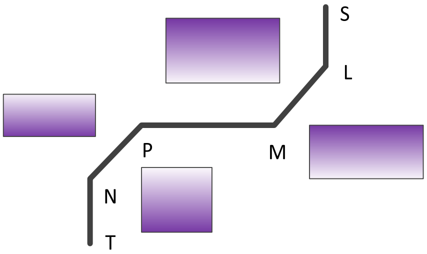


FIGURE 3. Mixing of orthogonal and nonorthogonal orientations.

In this paper, the optimized design of aero-engine branch pipe routing combined with "T" tee is mainly considered but not limited to the following engineering rules and constraints:

1. Total length of pipe

The total length of the pipe must be reduced as much as possible to save routing space and reduce material costs;

2. Obstacle avoidance

The pipe system must be laid avoiding obstacle areas, O stands for obstacle

$$O_G = \bigcup_{i=1}^{n} O_i = O_1 \cup O_2 \cup O_3 \ldots \cup O_n \tag{3}$$

where O_1 represents the high temperature area, O_2 represents the equipment maintenance area, O_3 represents the electrical area, O_n represents other areas, and the pipe routing cannot interfere with other pipes.

3. Pipe direction

Combined with engineering aesthetics, the branch pipe direction as far as possible to show the ''meter'', and the bending angle shall not be less than 90°.

4. Pipe reliability

The pipe should be laid as close as possible to the surface of the aero-engine magazine in order to install and obtain a better vibration.

The optimized design of aero-engine branch pipe routing is realized jointly by Siemens NX and MATLAB, in which the geometric information extraction of CAD lay-up model and visualization of pipe generation are realized by Siemens/NX Grip secondary development, and the pipe algorithm is realized automatically by MATLAB. The overall flow chart is shown in Figure 4.

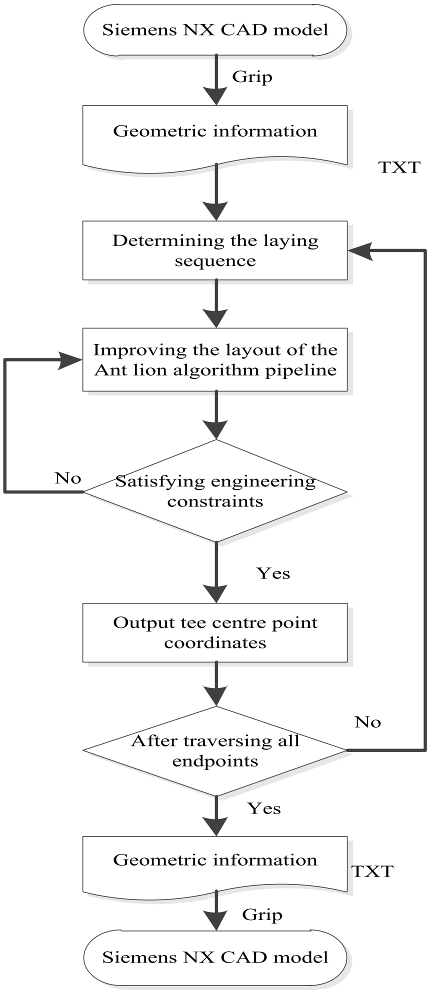


FIGURE 4. Aero-engine branch pipe overall design flow char.

III. IMPROVED ANT LION ALGORITHM

A. INTRODUCTION TO THE BASIC ANT LION ALGORITHM

The ant lion algorithm, proposed by Mirjalili S in 2015, is a novel heuristic that mimics the hunting behavior of ant lions in nature. These creatures move along a circular trajectory, using their powerful jaws to dig conical pits in the sand. Once the trap is prepared, the ant lion hides at the bottom of the cone, patiently waiting for an unsuspecting ant to fall into it. As soon as the ant lion detects the presence of its prey, it swiftly captures it. The algorithm emulates this process by implementing steps such as random ant wandering, trap setting, ant luring, ant capturing, and trap rebuilding. For a detailed explanation of the basic ant lion algorithm, please refer to [14].

B. ANT LION ALGORITHM IMPROVEMENT

The ant lion algorithm has been identified to have significant drawbacks in specific practical applications, specifically in terms of local optima, slow convergence speed, and other defects. To address these existing issues, this paper proposes a variety of strategies to fuse and enhance the ant lion algorithm. The proposed improvements focus on four key aspects: population initialization, ant random wandering, ant position update, and elite ant lion handling. To facilitate the enhancement process, this paper introduces the incorporation of Tent mapping, adaptive bounds, Gaussian variation, and the golden sine algorithm. These techniques are utilized to optimize each of the four aspects mentioned above. By implementing these strategies, it is expected that the ant lion algorithm will overcome its current limitations and exhibit improved performance in practical applications

1) TENT CHAOTIC INITIAL POPULATIONS

Tent mapping [15], [16] is a segmented linear mapping function whose mapping morphology graph resembles a tent, hence the name Tent mapping. The Tent algorithm involves fewer parameters, is simple to operate, and the mapping presents a relatively uniform distribution density of results with good ergodicity, whose mathematical expression is as follows:

$$x_{n+1} = \begin{cases} 2\mathrm{x}_n & 0 \le x_n \le 0.5 \\ 2(1\text{-}\mathrm{x}_n) & 0.5 < x_n \le 1 \end{cases} \tag{4}$$

The Tent mapping function requires a Bernoulli shift transformation, and after the Bernoulli transformation is

$$x_{n+1} = (2x_n) \bmod 1 \tag{5}$$

The original ant lion algorithm generates the initial positions of the ant lions and ants randomly, leading to unsatisfactory results. To address this limitation, this paper proposes a method to enhance the diversity of the population generation process. Specifically, characteristics of the Tent chaotic mapping with uniform distribution, uncertainty, and ergodicity are leveraged. By incorporating the Tent chaotic mapping, the algorithm preserves the diversity of the population. This, in turn, improves the convergence speed and enhances the global search capability of the algorithm. The Tent chaotic mapping's attributes, such as uniform distribution, uncertainty, and ergodicity, contribute to a more effective exploration of the search space, ultimately leading to better results. Overall, these improvements aim to overcome the drawbacks of the original ant lion algorithm and enhance its performance by introducing a more deliberate and diverse initialization scheme using the Tent chaotic mapping technique.

2) ADAPTIVE BOUNDARY IMPROVEMENT RANDOM WANDERING

In the basic ant lion algorithm, an adaptive boundary strategy [17] is proposed for ants randomly wandering, with the aim of enhancing the diversity of ants wandering around the ant lion. In the ant lion algorithm, the ants wander around the ant lion, and in the same iteration, all the ants wander along the same boundary, which is not conducive to finding the global optimal solution of the algorithm. Therefore, the ant random wandering species is introduced into the adaptive boundary strategy whose formula is as follows:

$$\rho = 0.5 + 1/\left(1 + \exp\left(\left(2 * m - pop\right)/pop\right)\right) \tag{6}$$

$$I = 10^{\omega}\frac{t}{T}\rho \tag{7}$$

$$t > \begin{cases} 0.1T & \omega = 2 \\ 0.5T & \omega = 3 \\ 0.75T & \omega = 4 \\ 0.9T & \omega = 5 \\ 0.95T & \omega = 6 \end{cases} \tag{8}$$

where, m represents the order of adaptation of ant lions and pop represents the number of ant lions. In general, the value of I increases with the number of evolutionary generations, and the traps for ants to wander randomly decrease, which is beneficial for the algorithm to find the global optimal solution.

3) GAUSSIAN VARIATION TO UPDATE ANT LOCATIONS

Gaussian variation [18], [19] can enhance the local search ability of the metaheuristic algorithm. In order to avoid the ant lion algorithm from falling into local optimum, Gaussian variation is used to update the position of ants. The Gaussian variance and the specific function expression of ant position update are as follows:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}e^{\frac{(x-\mu)^2}{2\sigma^2}} \quad -\infty < x < +\infty \tag{9}$$

$$x_{n+1} = x_n + G(0, 1) * x_n \tag{10}$$

where x_{n+1} represents the updated position of the ant, and x_n represents the current position of the ant. The use of Gaussian variation for the ant position update effectively improves the iterative process of the algorithm which still has poor individuals, enabling the ant to perform chaotic search and improving the overall search efficiency and robustness.

4) GOLDEN SINE IMPROVES ELITE ANT LION

The Golden Sine algorithm [20], [21], [22] is an innovative meta-heuristic algorithm designed to solve optimization problems. It draws inspiration from the sine function in mathematics and incorporates the golden mean to conduct a stepwise iterative search. Initially, a set of S individual positions is randomly generated. The variable $x_i^T = (x_{i1}, x_{i2} \ldots x_{in})^T$ represents the position of the i-th individual in the d-dimensional individual space at the T-th iteration. In the $T+1$ iteration, the i-th individual's position is updated using the following formula:

$$\begin{aligned} x_i^{T+1} \\ &= x_i^T * \left|\sin\left(R_1\right)\right| + R_2 * \sin\left(R_1\right) * \left|x_1 * P_i^{(t)} - x_2 * x_i^{(t)}\right| \end{aligned} \tag{11}$$

$$x_1 = a(1-r) + b \cdot r \tag{12}$$

$$x_2 = a \cdot r + b(1-r) \tag{13}$$

$$r = \left(\sqrt{5} - 1\right)\Big/2 \tag{14}$$

In the above equation, R_1 and R_2 represent the random numbers, $R_1 \in [0, 2\pi], R_2 \in [0, \pi]$; x_1 and x_2 represent the coefficients on the golden mean to narrow the search space;P_i^t represents the current optimal position; a and b represent the search interval; and r represents the environmental partition ratio. Combining the sine function with the golden mean ratio, the maximum or minimum value of a single peak function can be found faster. Therefore the algorithm has good convergence speed, good robustness, easy implementation etc. Therefore the algorithm is mixed with other methods in the study.

The golden sine algorithm is introduced at the position update of the elite ant lion, which can traverse all values of the sine function when determining its position, making the search more comprehensive. At the same time, the distance and direction of the position update are randomly controlled by R_1 and R_2, and the search space is continuously reduced to quickly guide the individual ant lion to converge to the optimal value, thus improving the convergence speed and accuracy of the algorithm.

C. IMPROVING THE PSEUDOCODE OF THE ANT LION OPTIMIZATION ALGORITHM

In summary, the pseudocode of the improved ant lion algorithm is as follows:

D. TEST CASES

In order to assess the effectiveness of the proposed improved algorithm described in this paper, a comparative analysis is conducted with other optimization algorithms, namely Particle Swarm Optimization (PSO), Whale Optimization Algorithm (WOA), and Ant Lion Optimization (ALO). These algorithms are applied to a set of classical test functions with diverse characteristics to evaluate the performance of the improved ant lion algorithm across different dimensions.The experiments are carried out with a fixed dimension of 30, an iteration number of 100, and an optimum value of 0 for all test functions. The specific details of the test functions

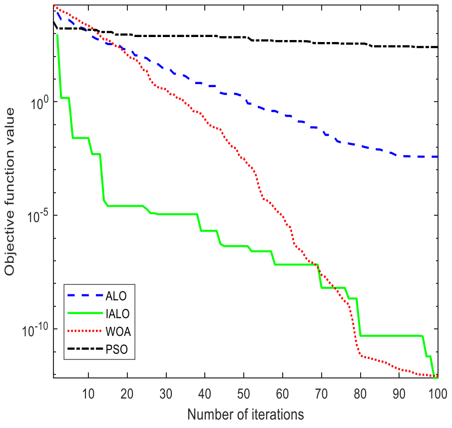
Algorithm 1 The Improved ALO

```
Initial the primary population of ALO
Initialize the locations of ants and ant lions using Tent mapping strategy Eq. (4)
Calculate each fitness value and record the optimal value
Pick the best ant lion as the elite ant lion and record its location
While iteration < max iteration
    For every ant
        Select an ant lion using the roulette method
        Create random wandering and refer to Eq. (6) for adaptive improvement
        Update the position of the ants according to the Gaussian variation of Eq. (10)
    End for
    Calculate the value of the fitness function for each ant
    For each ant lion
    If the ant lion is more adapted, the ant lion will eat the ants and replace them accordingly
    End if
    End for
    If the ant lion is better than the elite ant lion, then the elite ant lion is updated using Eq. (11)
End while
Return archive
```

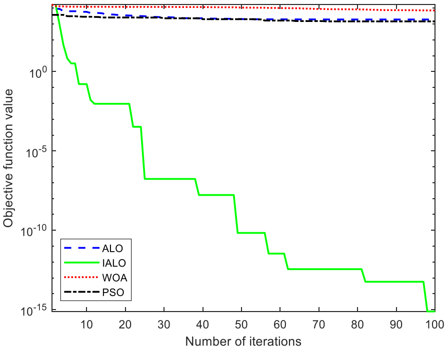
are presented in Table 1. The iterative convergence curves obtained during the experiments for each test function are depicted in Figure 5.

TABLE 1. Test function specific information.

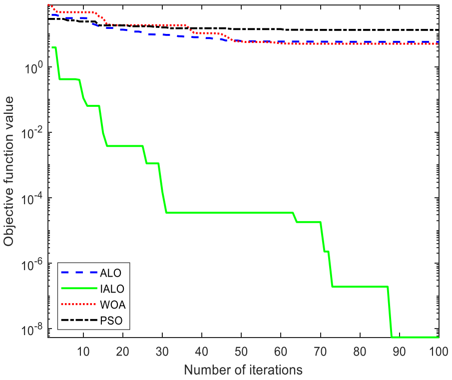
Function	Scope
$F_1(x)=\sum_{i=1}^{n}x_i^2$	$[-100,100]$
$F_2(x)=\sum_{i=1}^{n}\left(\sum_{j=1}^{i}x_j\right)^2$	$[-100,100]$
$F_3(x)=max_i\left\{\lvert x_i\rvert,1\le x\le n\right\}$	$[-100,100]$
$F_4(x)=\sum_{i=1}^{n-1}\left[100\left(x_{i+1}-x_i^2\right)^2+\left(x_i-1\right)^2\right]$	$[-5,5]$
$F_5(x)=\sum_{i=1}^{n}\left(\left[x_i+0.5\right]\right)^2$	$[-100,100]$
$F_6(x)=\sum_{i=1}^{n}ix_i^4+random[0,1)$	$[-1,1]$
$F_7(x)=\sum_{i=1}^{n}\left[x_i^2-10\cos(2\pi x_i)+10\right]$	$[-5,5]$
$F_8(x)=\frac{1}{4000}\sum_{i=1}^{n}x_i^2-\prod_{i=1}^{n}\cos\left(\frac{x_i}{\sqrt{i}}\right)+1$	$[-0.5,0.5]$



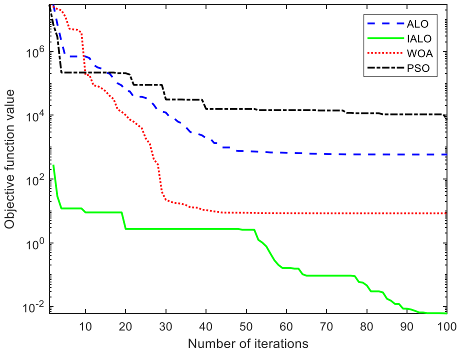
F_1 test function image



F_2 test function image



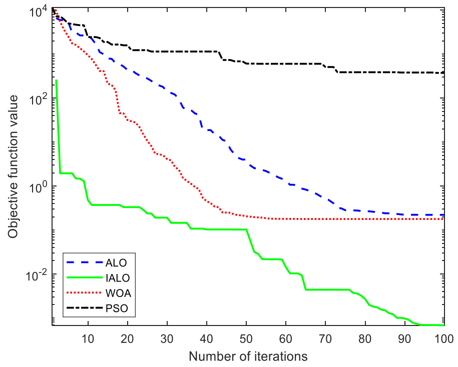
F_3 test function image



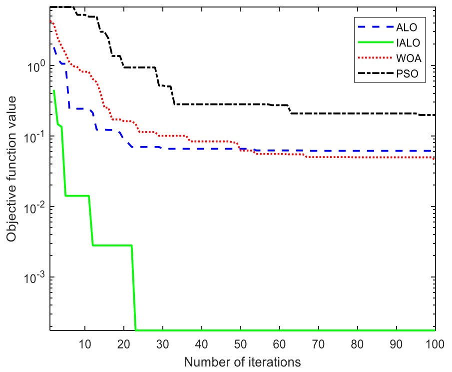
F_4 test function image

FIGURE 5. Iterative convergence curves of different test functions.

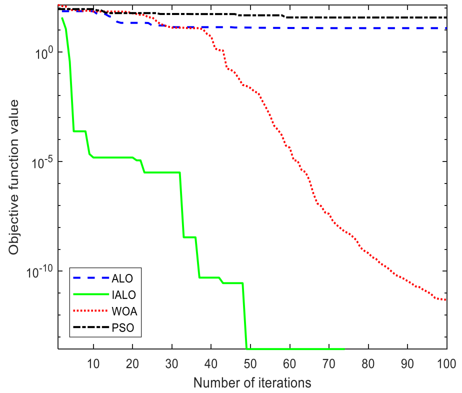
To further validate the performance of the improved ant lion algorithm, the same set of test functions ($F_1(x)$ to $F_8(x)$) are used again, this time with a dimension of 10 to ensure consistency. The four algorithms are executed 15 times under identical conditions. The optimal values, mean, and variance of the test functions are calculated based on the 15 runs



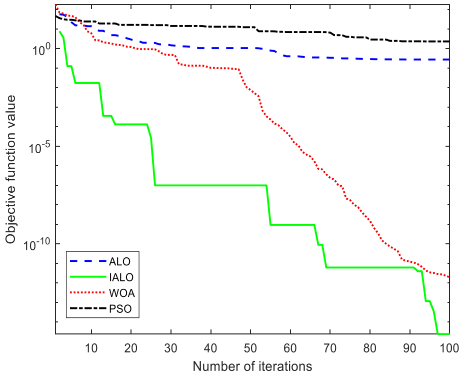
***F*₅ test function image**



***F*₆ test function image**



***F*₇ test function image**



***F*₈ test function image**

FIGURE 5. ***(Continued.)*** **Iterative convergence curves of different test functions.**

and the specific results are provided in Table 2. By conducting these experiments and analyzing the data, the aim is to compare the performance of the Improved Ant Lion Optimization (IALO) with the other algorithms (PSO, WOA, and ALO) in terms of optimizing the given test functions.This information will help assess the effectiveness and efficiency of the proposed algorithm in solving optimization problems when compared to existing techniques.

TABLE 2. **Experimental results of test functions(10 dimensions).**

Function	Algorithm	Optimum	Average	Variance
$F_1(x)$	PSO	2.23E+02	2.94E+02	2.24E+02
	WOA	7.32E-14	5.75E-13	1.44E-12
	ALO	6.15E+00	6.94 E+00	1.16 E+01
	IALO	2.96 E-20	3.76E-16	1.65E-13
$F_2(x)$	PSO	1.88E+02	1.57E+03	1.19E+03
	WOA	3.54E+03	1.34E+03	3.15E+03
	ALO	1.34E+03	1.48E+03	5.65E+02
	IALO	7.27 E-25	1.68 E-13	2.63 E-12
$F_3(x)$	PSO	5.45E+00	9.48 E+00	2.23 E+00
	WOA	5.45E+00	2.67E+01	1.44E+01
	ALO	9.88E+00	1.09 E+01	3.22 E+00
	IALO	1.12E-13	1.68E-07	8.23E-07
$F_4(x)$	PSO	9.56E+04	3.03E+04	2.81E+04
	WOA	8.58E+00	8.82E+00	2.19E-01
	ALO	1.26E+03	2.15E+03	1.81E+03
	IALO	4.15E-04	1.92E-03	4.54E-03
$F_5(x)$	PSO	2.99E+02	2.36E+02	1.40E+02
	WOA	3.26E-01	3.22E-01	1.63E-01
	ALO	9.19E-03	3.14E-04	2.02E+00
	IALO	2.36E-05	2.05E-04	3.14E-04
$F_6(x)$	PSO	1.08E-01	1.51E-01	5.67E-02
	WOA	2.84E-03	7.05E-03	1.07E-02
	ALO	1.04E-01	7.51E-02	1.02E-01
	IALO	6.31E-05	9.69E-04	9.50E-04
$F_7(x)$	PSO	1.39E+01	6.22E+01	9.02E+00
	WOA	9.66E-13	1.04E+01	1.39E+01
	ALO	2.19E+01	1.86E+01	8.45E+00
	IALO	1.42 E-14	0.00 E+00	6.91 E-14
$F_8(x)$	PSO	2.58E+00	3.78E+00	1.76E+00
	WOA	9.43E-01	9.43E-01	2.65E-01
	ALO	1.69E-01	1.40E-01	2.10E-01
	IALO	0.00 E+00	1.37 E-14	3.08 E-13

Based on the above eight classical test functions as examples, the improved ant lion algorithm is compared with three other representative algorithms. It can be seen that the convergence effect and speed of the improved algorithm have been significantly improved, and it can quickly jump out of the local optimum and search for the global optimum solution, thus verifying the effectiveness of the improved method. However, the above improved ant lion algorithm through multi-strategy fusion has the limitation of slow running time. The enhanced algorithm, when tested using standard test functions, takes approximately 4 seconds to complete a single run.

IV. BRANCH PIPE SEQUENCE PLANNING

In engineering practice, pipe routing involves not only determining the path of an individual pipe but also considering the feasibility and optimality of overall pipe routing. The branch pipe system comprises main pipes, branch pipes, nested pipes, and more. A branch pipe consists of multiple pipes where a starting point corresponds to multiple end points [23], [24]. When optimizing the routing design for branch pipe, it is challenging to achieve complex routing objectives by solely considering pipe constraints and routing space. It is important to also consider the impact of existing pipe routing on subsequent pipe. Additionally, the branch pipe is characterized by the known locations of multiple end points. Typically, the routing order of the branch pipe is determined in advance. This involves selecting two end points first and finding the branch point, which serves as the center of the "T" tee structure attachment between the two points. Then, the center point of the branch pipe's tee is determined as the starting point. Subsequently, the routing process involves traversing all end points of the branch pipes in sequence.

The problem of determining the one-to-many routing order of branch pipes is highly complex. Some engineering rules and expert experience can be ambiguous and difficult to express quantitatively. Integrating all engineering rules into an algorithm becomes challenging. Instead, a combination of engineering rules can be used to provide an initial optimized routing scheme, which can then be adjusted as needed. Before determining the one-to-many routing order, an initial endpoint is randomly selected from all endpoints. The shortest distance between two adjacent endpoints is considered the primary routing target for the pipe, prioritizing efficiency and distance optimization. Secondly, when dealing with the branch pipe routing order, it is crucial to ensure a sequential connection of the pipes. Additionally, it is important to consider the interference between the already laid pipes and those yet to be laid. In such cases, the distance between two endpoints can be considered a viable adjustment scheme if the initial sequence does not yield a satisfactory solution. However, relying solely on a single algorithm to solve the branch pipe routing sequence is limited. It is necessary to employ human-computer interaction to determine a reasonable solution. Therefore, the main steps of the branch pipe routing sequence decision algorithm are as follows (after considering the above considerations):

Step 1:Map the end points of the branch lines on the surface of the aero-engine magazine to the two-dimensional plane, and get the plane coordinates $M = \{x_1, y_1, x_2, y_2, \ldots, x_n, y_n\}$ to form the set P;

Step 2:Prioritize the two endpoints with the best distance as a sequence of priority planning branch line endpoints;

Step 3:Select the coordinates of the initial point to its neighboring points as the start and end points of the pipe S and T, and lay the pipe;

Step 4: Determine the coordinates of the center point of the tee structure attachment (i.e. the branch point of the branch pipe) by calculating the optimal distance from the set of other remaining unlayed end points P' to the layable area of the tee structure attachment using the exhaustive method $O = \{a_i, b_i\}$;

Step 5:Take the center point of the tee structure attachment as the starting point and prioritize the two end points with the best distance as the sequence planning for branch pipe, select the tee point to its neighboring points and carry out pipe in sequence;

Step 6: Repeat Step4∼ Step5 above, iterate the end point coordinates of all branch pipes on the surface of the aero-engine magazine, that is, generate $(n-1)$ edges and lay the pipes;

Step 7: If the branch routing constraint cannot be satisfied, otherwise return to Step 2 to readjust or make the distance between the two endpoints suboptimal as the routing target, until a more ideal solution is reached.

V. BRANCH PIPE ROUTING MODEL

A. CODING DESIGN

Using the above improved ant lion algorithm for solution, a "T" tee node is used as an example for coding design, so the coding method is fixed-length coding, and the node coordinates of the pipe are calculated through the coding form of the pipe path node, the coding of the stretching length of the left and right ends of the tee structure attachment and the stretching length of the pipe interface. At the same time, the location of the tee must be selected in accordance with certain engineering rules constraints, and the mathematical description of the specific coding method of the branch pipe is:

$$L_a = (L_S, L_1, L_2, L_T, \theta) \tag{15}$$

where L_S represents the length of the starting point, L_T represents the length of the end point, L_1 represents the length of the left end point of the tee node, L_2 represents the length of the right end point of the tee node, θ represents the rotation angle of the tee node, the pipe method meets the requirements of three-stage piping, and the pipe routing path pattern is shown in Figure 6.

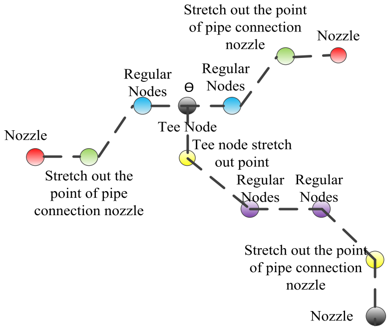


FIGURE 6. Pipe routing path pattern diagram.

In order to comply with the "meter" type constraint of the branch pipe and guarantee a well-planned routing for the welded short pipe of the tee structure attachment, it is necessary to allocate a gap as an obstacle in the unarrangeable area of the pipe and the bend. After performing the necessary adjustments, the routing area of the tee structure attachment is depicted in Figure 7. The square markings in the figure indicate the specific locations that should be designated as obstacles within the branch pipe. Conversely, the remaining portions of the pipe, which are not marked, represent the routing area available for the tee structure attachment.

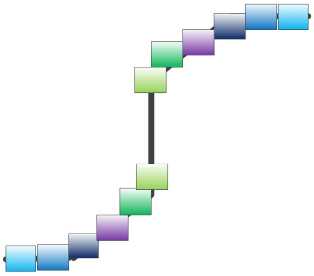


FIGURE 7. Tee structure accessories can be cloth area diagram.

In Figure 7, the routing area of the tee structure attachment is known, and the problem can be transformed into a shortest path from a point to a line segment that satisfies the branch pipe routing constraints. In dealing with this problem, some discrete and uniformly distributed points are selected in the routing area of the tee structure attachment $N = \{m_1, m_2, \ldots, m_n\}$. In this paper, $n = 10$ uses the exhaustive method to determine a relatively better path one by one to determine the center point of the tee structure attachment (i.e. branching point) for pipe routing. Figure 8 shows the schematic diagram of the selection of the center point of the tee structure component.

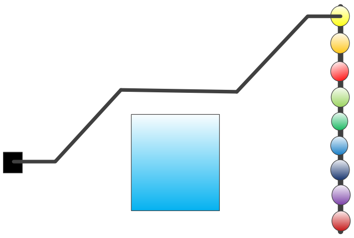


FIGURE 8. Example diagram of center point selection of tee structure components.

B. CONSTRAINT PROCESSING AND OBJECTIVE FUNCTION EVALUATION

Regarding the constraints proposed for branch pipe routing, the treatment of obstacles involves considering not only the existing obstacles in the routing environment but also preventing any obstacle relationship between the pipe being laid and the already laid pipe. Consequently, the laid pipe is also considered as an obstacle. To avoid obstacles intersecting, a penalty function is employed to act as a restraining mechanism. For irregular obstacles, a technique known as ''convex package'' processing is adopted, which creates a convex envelope around the obstacles while also leaving a specific clearance for pipe routing in areas such as high-temperature zones and maintenance areas. The coordinates of special points are extracted from the 3D CAD model and saved in a TXT file [25], [26].

Regarding the pipe direction, adjustments are made to the branch pipe routing path pattern and the value of θ, representing the center point of the tee structure attachment, to achieve an overall ''meter'' shape for the pipe direction. Furthermore, although the bend corner is constrained, it may not be sufficiently smooth. To optimize the bend corner, the radius of curvature in differential geometry can be utilized by performing circle inversion. The three-dimensional coordinate information of the branch pipe is extracted, and the corner points along the laid pipe's path are rounded, resulting in a process called smoothness processing. This process aims to enhance the overall smoothness and aesthetic appeal of the branch pipe. As the tee node is aligned in a straight line, its position is not currently considered. Figure 9 illustrates a schematic diagram depicting the pipe after the pipe path nodes have undergone inverse rounding.

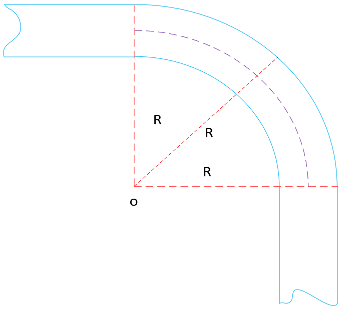


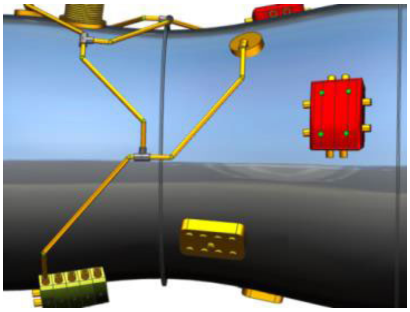
FIGURE 9. Example Pipe bend radius rounding treatment.

According to the engineering rules and experts' experience, the length of pipe not only affects the stability and economic cost of pipe, but also has a certain impact on the overall beauty of pipe, so the length is used as the optimization target by the improved ant lion algorithm. The total length of pipe path L is the minimum, m represents the number of pipe path nodes, (x_i, y_i) is the coordinates of each path node and $i = 1, 2 \ldots n$ is the number of nodes of the path.

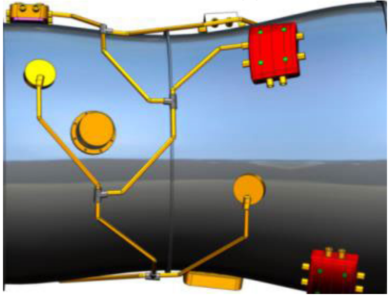
$$L = \sum_{i=1}^{m-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \tag{16}$$

VI. SIMULATION VERIFICATION

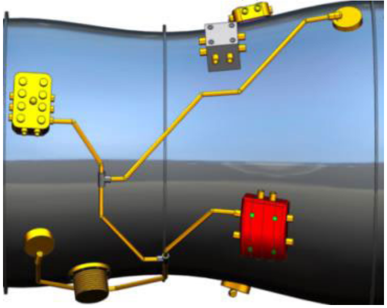
According to the methodology and algorithms investigated in this paper, a simulation experiment was designed to optimize the routing of branch pipe in aero-engines. The computer hardware used for the experiment consisted of an Intel®Core™i5-7200U CPU @ 2.50GHz, 2.70 GB of RAM. MATLAB R2018b was utilized as the algorithm programming environment, while Siemens NX 11.0 served as the simulation environment. The Grip secondary development language in Siemens NX was employed to visualize the data stored in TXT files. In the simplified CAD model of the aero-engine, there were a total of 6 branch pipe endpoints and 9 obstacles. To achieve the pipe routing, the proposed method for automatic branch pipe routing optimization was employed. Considering the random nature of the ant lion algorithm, representative results were selected based on 8 tests. The routing simulation diagrams illustrating the optimized pipe routing are presented in Figure 10 and Figure 11.



Perspective (a)



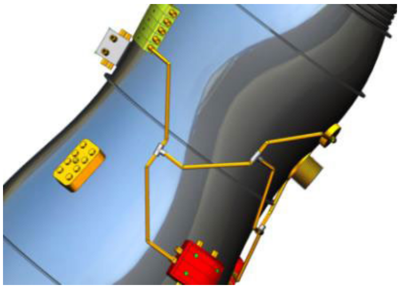
Perspective (b)



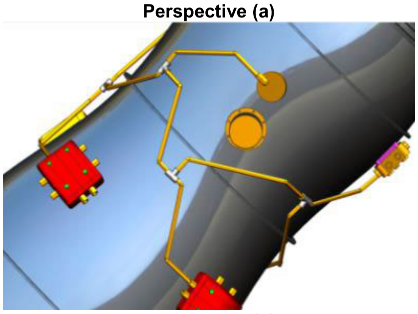
Perspective (c)

FIGURE 10. **Branch pipe routing calculation example one.**

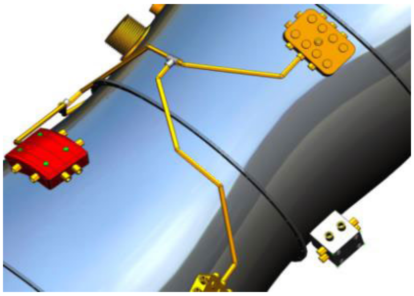
As shown in the visualization diagram of branch pipe routing calculation, the pipe routing plan uses 4 "T" tee structure components, which successfully avoids obstacles and basically meets the above-mentioned engineering rules constraints. The overall direction of the pipe shows the constraint requirements such as "meter" shape, and the routing scheme is more neat and beautiful and meets the engineering aesthetic requirements, which verifies the reasonableness and feasibility of the proposed method.



Perspective (a)



Perspective (b)



Perspective (c)

FIGURE 11. **Branch pipe routing calculation example two.**

VII. SUMMARY AND OUTLOOK

The routing of branch pipe systems in aviation engines is a highly complex issue, which, in theoretical terms, belongs to the class of NP-hard problems and holds a crucial position in the overall design of aviation engine pipes. Apart from considering the optimization design of the pipes, the positioning of "T" tee needs to be taken into account in order to improve the overall mechanical performance of the aviation engine. The exhaustive method is employed to determine the positions of "T" tee (i.e., branch points of the branch pipes) one by one. This study uses a combination of mixed orthogonal and non-orthogonal pipe layouts to achieve the objective of engineering aesthetics while considering the overall visual appeal of the system. Compared to traditional branch pipe routing, utilizing obstacle-avoiding Steiner trees to locate branch points is theoretically feasible. However, in practical pipe routing, the one-to-many approach is predominantly used, which is more aligned with engineering realities. To overcome the limitations of ant lion optimization algorithms when applied to engineering problem solving, a combination of multiple strategies is integrated to achieve satisfactory results while also enhancing the overall efficiency of pipe installation.

This paper focuses on the branch pipe system of aviation engines as the research object, with length considered as the single objective and others as constraint conditions, thus addressing a relatively specific problem. However, the efficiency is significantly reduced due to the discrete point selection method used for determining branch points. In the next research step, a multi-objective algorithm will be employed to optimize the pipe design by considering more engineering constraint objectives, thereby better meeting the practical requirements of pipe routing. When determining the positions of branch points, smart optimization algorithms should be considered for secondary optimization to improve the routing efficiency of the branch pipes from a global perspective, aiming to achieve the best possible positions.

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