ASSEMBLY SEQUENCE OPTIMIZATION OF WELDING FIXTURE BASED ON HYBRID HONGYI ZHANG, MINGMAO HU*, XIN CHEN, YU SUN, QUGUANG GUAN

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ABSTRACT: According to the characteristics of automobile welding fixture assembly, a variety of methods about the current algorithm of assembly sequence planning are summarized, and a targeted evaluation index which includes the angle of the assembly, stability, assembly direction, etc is selected. Then a set of evaluation is applied to ensure the simplicity and rapidity of the assembly process and the improved ant colony algorithm and genetic algorithm are adopted to improve the speed of the algorithm convergence. Finally, with welding fixture assembly optimization solution in a set of car side surround, the rationality of the evaluation methods and effectiveness of the algorithm are verified.

KEY WORDS: Welding jig, assembly sequence, evaluation function, ant colony algorithm.

1 INTRODUCTION

As an important part of the machining process, the fixture is a device for fixing the object of processing and limiting it to the correct position for processing or testing, which has high complexity, multi-dimensionality, and requires frequent disassembly and assembly. The processing of parts often consumes a lot of time, so it is very important to quickly plan a process sequence for assembly and disassembly to reduce the total assembly time.

Figure 1. Sample diagram of welding fixture

In a set of welding fixtures, a working platform has multiple sets of components used for fixing and clamping as shown in Fig.1. These components are located on a flat surface, and the orientation of the components is different, so the complexity of the plane is high, and it is affected by the stability of the assembly. At the same time, different components have interference in multiple directions during the assembly operation, and a large amount of time is wasted after interference. Combined with the influence of ergonomics, a new evaluation function needs to be considered to solve assembly sequence planning problems. An artificial ant colony algorithm combined with genetic algorithm is used to plan an assembly sequence which can improve the assembly efficiency and optimize the operation time.

In the early 1980s, Wesley (Wesley, 1980) began to study assembly sequence planning as a class of problems. In particular, the model of “Liaison graph” was used to express the assembly structure of products. In the assembly order evaluation model, Homem de Mello et al. (Homem and Sanderson, 1991) used assembly flexibility, parallelism, assembly time and assembly cost to evaluate assembly order. Laperriere (Laperriere and EIMaraghy, 1996) summarized the characteristics of the assembly process, and proposed evaluation indexes such as assembly stability, number of redirection, parallelism and assembly operation degree to evaluate the pros and cons of the assembly sequence. According to the characteristics of the welding fixture assembly, the weights of the available evaluation indexes are different, and the factors that mainly affect the assembly efficiency are analyzed. Finally, four evaluation indicators are considered, namely, the available assembly angle, assembly direction (considering ergonomics), assembly stability and redirection times.

With the further development of artificial intelligence, intelligent algorithms have been used in the field of assembly sequence programming for nearly 20 years. After Bonneville (Ghandi and
first used genetic algorithms to solve such problems, many intelligent algorithms were developed, such as simulated annealing, artificial immune algorithms, ant colony algorithms, particle swarm algorithms, etc. In a large number of studies, genetic algorithm and ant colony algorithm are widely used. The ant colony algorithm affects the probability of subsequent ants' path selection through the accumulation of ant release pheromone. It is characterized by distributed computing power, self-organization and positive feedback. In a large number of studies, genetic algorithm and ant colony algorithm are more common. The ant colony algorithm affects the probability of subsequent ants' path selection through the accumulation of ant release pheromone. It is characterized by distributed computing power, self-organization and positive feedback. However, the genetic algorithm shows a superior global search ability in solving the ASP problem. Therefore, ant colony algorithm and partial genetic algorithm are used in this paper, which can quickly perform global search and effectively avoid local optimum.

2 EVALUATION INDEX ANALYSIS

Assembly sequence planning problem (ASP) has certain characteristics for the welding fixture industry. Soldering fixtures are usually distributed on a flat surface, and the components are densely distributed. Firstly, the bottom plate is used as the positioning reference, and calibration is required after installing one component. However, due to the different sizes of each part, the assembly stability is affected. Therefore, the assembly angle needs to be considered. On the contrary, the fit of the parts can be neglected. Secondly, interference problems may occur in three directions. Because of the number and the high density of the parts, it is difficult to avoid the problem. The number of interference reductions will be used as an indicator, which means the number of redirection times will be reduced. Finally, the operational convenience factors are considered in ergonomics to make the evaluation function be more reasonable.

2.1 Assembly angle factor

The assembly angle (A) refers to the assembly angle of the parts without interference. The larger the assembly angle, the larger the available space for the assembly operation and the more convenient the assembly is, and the assembly angle (shown in Fig. 2) is considered to make the assembly operation of each step more convenient:

$$a_{ij} = \frac{a_{p_{ij}}}{U} \quad (1)$$

Where $a$ denotes the angle of restriction of the part $i$ on the plane of the part $j$, $\beta$ denotes the assembly angle available for the part $j$, and the total assembly angle is $360^\circ$. $\alpha$ and $\beta$ are group angles (and are circumferential angles).

$$A_{ij} = \begin{bmatrix} a_{11} & a_{12} & \Lambda & a_{1n} \\ a_{21} & a_{22} & \Lambda & a_{2n} \\ \Lambda & \Lambda & \Lambda & \Lambda \\ a_{n1} & a_{n2} & \Lambda & a_{nn} \end{bmatrix} \quad (2)$$

Where $a_{p_{ij}}$ represents the constraint angle of the loaded part $i$ to the next newly loaded part $j$, $0 \leq a_{p_{ij}} \leq 360^\circ$; $n$ represents the total number of assemblies; $U$ represents the total assembly angle allowed (no constraint is $360^\circ$), $a_{p_{ij}} \leq U$ , and $a_{ij}$ represents the ratio of constraint angle to total assembly angle, $0 \leq a_{ij} \leq 1$ ,and the assembly angle matrix $A_{ij}$ is a matrix of $n \times n$.

2.2 Assembly direction factors

The assembly direction (W) refers to whether the operation direction of the components in the process of loading the bottom plate meets the requirements of ergonomics. It is documented (Su and Lai, 2010) that according to human habits, when the assembly angle is the same, the process is easier. For example, the direction from top to bottom (Z-axis negative direction) and from far to near (Y-axis negative direction) are simpler and easier. On the contrary, it will become somewhat more difficult for people. Therefore, the evaluation function for defining the assembly direction weight is:

$$w_j = (1 - k_1)(1 + e^{-k_2(\theta_i - 90)\pi/180}) + k_1 \quad (3)$$

$$W_j = [w_1 \quad w_2 \quad \Lambda \quad w_n] \quad (4)$$

where $k_1$ and $k_2$ are the adjustment factors, $\theta_i$ is the angle between the actual assembly direction
and the negative direction of the z-axis, \( \theta_2 \) is the angle between the assembly direction and the negative direction of the y-axis, \( 0 \leq \theta_1 \leq 180^\circ \), \( 0 \leq \theta_2 \leq 180^\circ \), \( w_i \) is an evaluation function of the assembly direction when assembling, \( 0 \leq w_i \leq 1 \), and the \( W_i \) matrix is a \( 1 \times n \) matrix.

### 2.3 Assembly direction factors

Assembly stability (\( S \)) refers to whether the stability of the plane will be affected when the part is assembled. [3] Since the better the stability, the lower the assembly operation requirements, the assembly efficiency can be improved. There are many factors affecting the stability of the assembly, and the influence of gravity on the stability is considered in this paper.

A fixture assembly consists of \( n \) fixture parts, when part \( i \) is assembled, part \( j \) is not assembled without tilting or offsetting due to its own gravity, and thus the assembly operation is stable. Otherwise, the assembly operation is not stable. Its stability evaluation function matrix is as follows:

\[
S_{ij} = \begin{bmatrix}
  s_{i1} & s_{i2} & \ldots & s_{in} \\
  s_{i2} & s_{i2} & \ldots & s_{in} \\
  \vdots & \vdots & \ddots & \vdots \\
  s_{in} & s_{in} & \ldots & s_{in}
\end{bmatrix}
\]

(5)

Where \( S_{ij} \) indicates whether the assembly of the part \( j \) after the part \( i \) is assembled will affect the stability of the assembly, \( 0 \leq S_{ij} \leq 1 \).

### 2.4 Assembly direction factors

The number of redirections (\( D \)) refers to the number of times the assembly direction changes after the interference occurs due to the change in the assembly direction of the parts during the assembly operation. The assembly interference matrix is used to analyze the assembly direction of each part and each sub-assembly to obtain a feasible assembly direction.

The assembly direction of components can be adjusted to improve the assembly efficiency. Some parts are assembled along the direction parallel to the coordinate axis, and each component can be assembled in the direction of \(+X\), \(-X\), \(+Y\), \(-Y\), \(+Z\), to and \(-Z\) are assembled, so interference judgment is made from these six directions to obtain interference matrices of the six directions.

![Figure 3. Assembly interference diagram](image)

#### Table 1. Interference matrix of +X direction

<table>
<thead>
<tr>
<th>+Xdirection</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
<td>1</td>
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<td>4</td>
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<td>0</td>
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</tbody>
</table>

Taking the assembly distributed in Fig.3 as an example, the parts are distributed on the x-y plane. In the +X direction interference matrix, 0 and 1 indicate whether or not the component interferes during the assembly process. The definition is as follows: if the part assembly moves in the direction of interference with other parts in this direction, it means that the assembly operation is not feasible, which is defined as 1; if the part assembly operation does not interfere with other parts in this direction during the assembly operation, indicating that the part is assembled in this direction, and there is no need to change direction, which is then defined as 0. Because the part does not interfere with itself, the diagonal elements in the matrix are all defined as 0.

Assuming that there are \( n \) parts in the whole assembly process, the integrated assembly interference matrix is a matrix of \( n \) rows and \( 3n \) columns, which fully expresses the interference of the parts during assembly. It is defined as

\[
I_r = \begin{bmatrix}
  I_{x1x} & I_{y1y} & I_{z1z} & I_{x1x} & I_{y1y} & I_{z1z} \\
  I_{x2x} & I_{y2y} & I_{z2z} & I_{x2x} & I_{y2y} & I_{z2z} \\
  I_{x3x} & I_{y3y} & I_{z3z} & I_{x3x} & I_{y3y} & I_{z3z} \\
  I_{x4x} & I_{y4y} & I_{z4z} & I_{x4x} & I_{y4y} & I_{z4z} \\
  I_{x5x} & I_{y5y} & I_{z5z} & I_{x5x} & I_{y5y} & I_{z5z} \\
  \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  I_{xnx} & I_{yny} & I_{znz} & I_{xnx} & I_{yny} & I_{znz}
\end{bmatrix}
\]

(6)

Where \( I_{ijX} \) indicates the interference between part \( P_i \) and \( P_j \) part when part \( P_i \) is assembled in the +X direction. If there is interference between the two parts, \( I_{ijX} = 1 \), otherwise, \( I_{ijX} = 0 \). Similarly, the values of other elements in the interference matrix can be integrated.
3 EVALUATION FUNCTION

A set of assembly sequences is used to express the assembly sequence optimization problem of the fixture. The assembly O of the part is composed of five elements: the number P of the fixture component, the assembly angle A of the component, the assembly direction W of the component, the assembly stability of the component S, the number of the relocation of parts D, the expression code is defined asO = (P, A, W, S, D), the solution space of the part assembly sequence is composed of assembly operation indicators. Optimizing the assembly order of the parts is to find a part assembly order with the highest assembly efficiency, which is the best evaluation index. Based on the practical consideration of the problem, assembly sequence planning should meet six requirements:

(1) The assembly angle between the front and rear parts should be as large as possible;
(2) As far as possible, the convenience is satisfied during assembly;
(3) Assembly into a straight line operation;
(4) The stability of the assembly should be as high as possible;
(5) The number of interferences between parts during assembly should be minimized;
(6) The changes of assembly direction should be minimized during the whole process of assembly;

Based on these six aspects, a comprehensive processing of the evaluation function matrix of the assembly is required.

The assembly angle matrix A_{ij} is a diagonal element and each element is between 0 and 1. The matrix A_{ij} indicates the available assembly angle of the part j in the case where the part i has been assembled, and an assembly sequence is determined corresponding to a matrix of 1 × n, that is, a \( \hat{A}_{j} \) matrix.

The assembly stability matrix S_{ij} is an n × n matrix with a 0 diagonal element and each element varies from 0 to 1. The matrix S_{ij} indicates whether the part j is affected if the part i has been assembled. Determine an assembly sequence and locate the impact of each part on the stability of part j to form D_{ij} a 1 × n matrix, i.e. \( \hat{S}_{j} \) matrix.

Define the redirection order matrix, which is an n × n matrix. Element d_{ij} indicates whether an assembly direction changes from the assembly part i to the assembly part j. If it does not occur, then \( d_{ij} = 0 \); if it occurs, \( d_{ij} = 1 \). An n × n matrix is then constituted. After determining an initial sequence, a matrix of 1 × n is constructed, and the elements in the three directions of D_{ij} matrix are summed. Single terms are summed to obtain a \( \hat{D}_{j} \) matrix. This makes it possible to build the objective function

\[
f = w_{1} \* \hat{A} + w_{2} \* W + w_{3} \* \hat{S} + w_{4} \* \hat{D} + 1 \tag{7}
\]

where w1, w2, w3, and w4 are weighting coefficients of assembly angle, assembly direction, assembly stability, and redirection times respectively. \( w_{1} + w_{2} + w_{3} + w_{4} = 1 \), and A, W, S, and D are function values corresponding to them.

4 ALGORITHM OPTIMIZATION

4.1 Algorithm steps

Algorithm steps for optimization of hybrid algorithm based on ant colony:

(1) Initialization of parameter variables, randomizing an initial feasible solution,
(2) the selection range of each ant for the next part and the value of each parameter in the state transition probability formula are determined, and then the ant selects the assembly operation to perform next according to the state transition probability,
(3) determine whether the number of all assembled parts is equal to the total number of assembled parts,
(4) the best retention method is used to save the current preferred sequence,
(5) the genetic algorithm is used to hybridize and mutate the optimal sequence,
(6) the global pheromone concentration is updated by the quality of the optimal solution,
(7) Determine whether the number of loops of the algorithm reaches the set number of loops.
Parts variable initialization

By the state transition probability to choose the next operation

Local pheromone updating

Generate the most optimal assembly sequences

Whether the number of iterations to achieve specified values

The optimal sequence of output

**Figure 4. Algorithm flow chart**

4.2 State transition probability formula

The assembly state transition probability refers to the selection of the current assembly operation affecting the next assembly operation. In the algorithm, the ant from the assembly operation i to the assembly operation j is performed according to the probability of the roulette reading method. The magnitude of the assembly state transition probability is determined by the pheromone concentration from the component i to the component j as well as the heuristic function \( \eta_{ij}(t) \).

The state transition probability

\[
P_{ij}^{k}(t) = \begin{cases} 
\frac{\tau_{ij}(t)^{\alpha} \eta_{ij}(t)^{\beta}}{\sum_{S} [\tau_{iS}(t)]^{\alpha} [\eta_{iS}(t)]^{\beta}}, & j \in S \\
0, & \text{other} 
\end{cases} 
\]  

(8)

\[
\eta_{ij}(t) = \frac{1}{f_{ij}} 
\]  

(9)

\( \tau_{ij}(t) \) represents the residual amount of the pheromone on the path when the ant is transferred from the assembly operation i to the assembly operation j at time t, and \( \eta_{ij}(t) \) represents the heuristic information indicator on the path when the ant is transferred from the assembly operation i to the assembly operation j at time t (The sum function of the four evaluation indicators).

The pheromone updates rule formula on the path after all the ants have traversed all the components.

\[
\tau_{ij}(t+1) = (1 - \rho)\tau_{ij}(t) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k}(t) 
\]  

(10)

Where \( \rho \) represents the volatilization index of the pheromone on the path from time t to time t+1, and \( \Delta\tau_{ij}^{k}(t) \) represents the increase of the pheromone of the kth ant on the path (i, j) at timet in this cycle, and the value of \( \Delta\tau_{ij}^{k}(t) \) is defined as\( \Delta\tau_{ij}^{k}(t) = \begin{cases} 
Q, & \text{if kth ant passes the path } (ij) \text{ in this tour}, \\
0, & \text{else} 
\end{cases} 
\) where Q is the pheromone intensity. If the kth ant passes the path (ij) in this tour, \( S_{k} = f \). \( S_{k} \) represents the quality of the path and is also the objective function of the assembly sequence. The size of the value indicates the quality of the path.

4.2 Genetic variation

After the local pheromone update is completed and a superior assembly sequence is generated, the sequence is used as an initial solution to perform the genetic variation operation. In the ant colony algorithm, the e(i) to e(j) pheromone concentration increment is low, and e(i) and e(j) in the parent are misaligned, as shown in FIG. The result can make the algorithm converge quickly. In the ant colony algorithm, the e(i) to e(j) pheromone concentration increment is low, and the e(i) and e(j) in the parent are misaligned, as shown in Fig.5. The result can make the algorithm converge quickly.

**Figure 5. Cross schematic**

The update rule of the global pheromone is as follows, the pheromone quantity increment on the path is determined according to the quality of the solution. If the assembly angle of the assembly in the path is larger, the angle between the -z axis and the -y axis is smaller, therefore, r the assembly stability is higher, the assembly direction changes
are fewer, and the smaller the value of the objective function. The higher the quality of the solution, the more the pheromone is added to the path, and the path can be forced to appeal to subsequent ants.

5 ALGORITHM EXAMPLES

A car assembly company’s side-mounted welding fixture is given as an example, the 12 fixture parts are distributed on a bottom plate, as shown in Fig.6.

![Figure 6.Jig exploded view](image)

According to the actual measured value, the parameters are calculated as follows:

- assembly angle matrix A,
\[
A = \begin{bmatrix}
0.87 & 0.91 & 0.84 & 0.86 & 0.91 & 0.84 & 0.82 & 0.87 & 0.93 & 0.91 & 0.83 \\
0.87 & 0.82 & 0.81 & 0.82 & 0.87 & 0.84 & 0.82 & 0.83 & 0.84 & 0.82 & 0.94 \\
0.86 & 0.83 & 0 & 0.83 & 0.85 & 0.81 & 0.82 & 0.83 & 0.85 & 0.84 & 0.87 \\
0.92 & 0.93 & 0.84 & 0 & 0.84 & 0.85 & 0.87 & 0.86 & 0.87 & 0.92 & 0.86 & 0.88 \\
0.91 & 0.96 & 0.92 & 0.85 & 0 & 0.82 & 0.84 & 0.85 & 0.91 & 0.78 & 0.87 & 0.81 \\
0.85 & 0.84 & 0.83 & 0.91 & 0 & 0.88 & 0.83 & 0.95 & 0.81 & 0.83 & 0.85 \\
0.84 & 0.85 & 0.84 & 0.87 & 0.88 & 0.85 & 0 & 0.93 & 0.87 & 0.83 & 0.91 & 0.96 \\
0.8 & 0.91 & 0.85 & 0.88 & 0.87 & 0.92 & 0.88 & 0 & 0.89 & 0.87 & 0.89 & 0.91 \\
0.92 & 0.87 & 0.86 & 0.86 & 0.85 & 0.91 & 0.83 & 0.86 & 0 & 0.83 & 0.85 & 0.84 \\
0.81 & 0.92 & 0.91 & 0.82 & 0.81 & 0.88 & 0.86 & 0.9 & 0.88 & 0 & 0.83 & 0.83 \\
0.84 & 0.86 & 0.89 & 0.86 & 0.92 & 0.79 & 0.91 & 0.87 & 0.92 & 0.86 & 0 & 0.84 \\
0.88 & 0.91 & 0.93 & 0.87 & 0.83 & 0.82 & 0.83 & 0.86 & 0.85 & 0.91 & 0 & 0
\end{bmatrix}
\]

- assembly direction matrix W, where the adjustment factor \(k_1 = 0.4, k_2 = 0.01\),
\[
W = \begin{bmatrix}
0.71 & 0.51 & 0.35 & 0.54 & 0.67 & 0.45 & 0.23 & 0.56 & 0.82 & 0.24 & 0.47 & 0.53
\end{bmatrix}
\]

- assembly stability matrix S,
\[
S = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

Redirection order matrix D,
\[
D = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 2 & 2 & 1 & 3 & 0 & 1 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 1 & 2 & 0 & 2 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 3 & 2 & 1 & 0 & 0 \\
0 & 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\
2 & 0 & 0 & 0 & 0 & 3 & 0 & 0 & 1 & 3 & 0 & 0 \\
1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 2 & 0 & 1 & 2 & 0 & 0 & 0 & 0 & 0 & 2 \\
0 & 3 & 0 & 2 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 3 & 0 & 0 & 1 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 2 & 0 & 1 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

The number of ants m=50, pheromone importance factor alpha=1, heuristic function importance factor beta=5, pheromone volatilization factor rho=0.1, constant coefficient Q=1, maximum iteration number iter_max=200, genetic crossover probability pi= 0.75, probability of variation pm=0.1. With calculation, the minimum value of the evaluation is 16.251, and the optimal assembly sequence is:

P6-P7-P2-P8-P9-P11-P3-P12-P10-P1-P4-P5.

![Figure 7.Function convergence diagram](image)

It can be seen from the function convergence as shown in Fig.7 that the algorithm has reliability after 90 iterations approaching 16.251.

6 ALGORITHM EXAMPLES

The results of example verification show that for the assembly sequence planning of welding fixtures, the four indexes of assembly angle, stability, ergonomic directionality and direction interference matrix function assessment have good representativeness, which can effectively evaluate the efficiency and make the assembly process easier. The solution algorithm uses the ant colony algorithm combined with the genetic algorithm to obtain a fast convergence and a high global solution ability. The whole set of methods for solving the assembly sequence planning of welding fixtures has a high reference value for the welding fixture industry.
7 REFERENCES


