A simple and effective assembly sequence design method

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Abstract. Assembly sequence design is a very complex problem in military enterprises due to the particularity of the military industry and the batch production. This paper proposed a method based on the existing expert knowledge and experience used to plan the assembly sequence. The method of assembly sequence design method is quantitative calculated based on five indexes, including assembly element benchmark index, assembly adjacency index, assembly process complexity index, assembly accuracy index, symmetry index of assembly primitives. And then construct geometric interference matrix to analyze the geometric feasibility of the assembly sequence. Finally, the procedure of assembly process sequence planning of flat-plate fuze is taken as an example to verify the effectiveness of this method. This method is suitable for the assemblies with less number of parts. It has been proved that this method based on the existing expert knowledge and experience, can quickly plan the assembly process sequence of parts.

1. Introduction

Intelligent assembly is an important part of intelligent manufacturing, even more serious, some assembly processes of products can take more than 50% of the total production circle [1]. Assembly is an important basic link of the whole product cycle, the assembly process of the product accounts for 20%-70% of the total production process. The assembly sequence planning is an important research topic of intelligent assembly.

At present, assembly sequence planning is a very complex problem in military enterprises due to the particularity of the military industry and the batch production. Now, there are many existing assembly sequence design methods, such as disassembly method, assembly limited constraint method, assembly relationship matrix method, genetic algorithm and ant colony algorithm and so on. Klier, F. et al. adopt visual 3D data to improve the agility of disassembly and recycling, which can guide the assembly sequence planning [2]. Some researchers used collision detection and two-dimensional views to generate assembly sequence [3]. Geometrical feasibility interference data are used by researchers to generate the assembly sequence [4]. The cut-set method developed by Baldwin et al is quite impressive to obtain optimal assembly sequence for a given product [5]. Bonneville et al. have applied simple single point cross-over and mutation operator to solve assembly sequence planning [6]. Lu and Zhuo used a simple ant colony Optimization algorithm to design assembly sequence [7]. Cao and Xiao proposed a novel immune approach called immune optimization approach, to generate the optimal assembly sequence [8]. Tseng et al. used the binary tree algorithm to generate the initial population as feasible sequence [9]. Recently, the AI techniques attracted the engineers to solve
assembly sequence planning efficiently due to their flexibility in implementation [10]. The AI algorithms for assembly sequence planning have several limitations such as high computational time and local search space.

These methods do not consider the guiding role of human knowledge or expert opinions on assembly sequence planning. These methods that required high level of designers are difficult to be implemented. However, the human knowledge or expert opinions often play a multiplier role with half the effort. So, in this paper, a method based on the existing expert knowledge and experience is used to plan the assembly sequence.

2. Assembly sequence evaluation and design method

In order to plan the assembly process, firstly, the hierarchical structure of the components in the assembly object is analyzed. Based on the existing assembly system, the functional requirements of assembly objects are analyzed. The assembly object composed of several components is divided according to a certain level, which can be divided into the smallest primitives. And each primitive can be a part or an assembly unit.

In general, in the actual assembly process, the more difficult the assembly process is, the more priority should be given to assembly. But this method can not quantitatively characterize the assembly priority of parts. This paper uses the “assembly priority” to evaluate. The “assembly priority” of assembly primitives is used to quantitatively characterize the assembly priority of the assembly parts. Therefore, this paper mainly evaluates the “assembly priority” from the following five aspects:

1) Assembly element benchmark index: \( f_1(x) \). In the Equation (1), \( x_1 \) indicates the number of times that the part is used as the assembly benchmark for other parts. If the number of assembly benchmark is large, the corresponding assembly component should be assembled first. It is stipulated that if the assembly datum number of other parts is greater than 4, the benchmark index of the assembly primitive can be expressed as 1; if it is less than 4, the benchmark index is linear with the datum number, as shown in Equation (1).

\[
f_1(x) = \begin{cases} 
1 & x_1 > 4 \\
0.25 \cdot x_1 & x_1 \leq 4 
\end{cases}
\] (1)

2) Assembly adjacency index: \( f_2(x) \). It is mainly used to represent the number of adjacent parts in contact with the part. Theoretically, the more the number of contact parts is, the larger the index is, and the stronger the demand for priority assembly of the part is. It is stipulated that if the number of contact or assembly relations with other parts is greater than 4, the assembly adjacency index can be expressed as 1, and if it is less than 4, the assembly adjacency index is linear with the datum number, as shown in Equation (2).

\[
f_2(x) = \begin{cases} 
1 & x_2 > 4 \\
0.25 \cdot x_2 & x_2 \leq 4 
\end{cases}
\] (2)

3) Assembly process complexity index: \( f_3(x) \). In this paper, assembly time is used to represent the complexity index of assembly process, and the time required for each assembly process is estimated based on assembly experience and knowledge, and the results are normalized. If the complexity index of the most complex assembly process can be expressed as 1, then other assembly process complexity indicators can be obtained according to the assembly time proportion relationship, as shown in Equation (3).

\[
f_3(x) = x_3
\] (3)

4) Assembly accuracy index of parts and components: \( f_4(x) \). In theory, the higher the assembly accuracy requirements, the higher the assembly priority. It is stipulated that if the assembly accuracy of the parts to be assembled is required, the assembly accuracy index of the parts shall be 1, and the others shall meet the following mathematical Equation (4). If the assembly accuracy requirement is better than 5 \( \mu m \), it can be regarded as high precision and should be given priority; if the assembly accuracy requires 5-20 \( \mu m \), it can be regarded as general accuracy; if the assembly accuracy is less
than 20 μm, it can be regarded as low precision. Based on these two cut-off points of 5 and 20 microns, the coefficient in Formula (4) can be constructed as Equation (4).

\[
f_s(x_s) = \begin{cases} 
1 & x_s \leq 5 \\
\frac{4}{3} - \frac{x_s}{15} & 5 < x_s \leq 20 \\
0 & x_s > 20 
\end{cases} 
\] (4)

5) Symmetry index of assembly primitives: \( f_s(x_s) \). In Equation (5), \( x_s \) represents the number of symmetry of the assembly object about \( xoy, yoz, xoz \) symmetry planes. For example, when the assembly object is a steel ball, there are three symmetrical faces. If the part with low symmetry, it has poor assemblability. In theory, the part with low symmetry index should be given to assembly first. There is a mathematical relationship between the symmetry index and the symmetry number of assembly primitives, as shown in Equation (5).

\[
f_s(x_s) = 1 - \frac{x_s}{3} 
\] (5)

Based on the above analysis and modeling priority index, the weighted method is used to model the five priority indexes, and the calculation Equation (6) of the comprehensive assembly priority index of the assembly object is obtained.

\[
F = \sum_{i=1}^{5} \alpha_i f_i(x_i) 
\] (6)

Where the definition of \( x_i, (i = 1,2,3,4,5) \) is the same as that in Equations (1)-(5).

According to the Equation (6), the higher the comprehensive assembly priority index is, the more priority the assembly object should be. The weight coefficient of each sub index in evaluating assembly priority can be calculated by using Analytic Hierarchy Process (AHP), according to different assembly objects and requirements.

3. Geometric feasibility analysis of assembly sequence

In Section 2, the assembly priority of the assembly object is evaluated and calculated, and the assembly sequence can be preliminarily obtained. Then, the geometric feasibility of the assembly sequence must be calculated and verified. Since the assembly object of the part can be assembled along three translational axes, that is, six directions, the geometric interference judgment and verification of the preliminary assembly sequence from six directions are carried out in this paper. Based on the assembly process of the assembly platform, the movement direction of the parts is parallel to the axis X, Y and Z, so the allowable assembly direction set is \( D \in \{+X, +Y, +Z, -X, -Y, -Z\} \), with a total of six direction. The interference matrix in the coordinate system can be constructed. There are two cases in which part a is assembled to part B and part B is assembled to part A. The interference matrix \( I_A \) of part A to B along the positive direction of the coordinate axis is the same as that of the assembly interference matrix of Part B along the negative direction of the coordinate axis.

According to the definition of interference matrix \( I_k \), the interference matrix formula is constructed.

\[
I_k = \{I_{iq}\}, I_{iq} = \begin{cases} 
1 & P_i \text{ interferes with } P_j \text{ during assembly along direction } k \\
0 & P_i \text{ does't interfere with } P_j \text{ during assembly along direction } k \end{cases} \quad k \in \{+X, +Y, +Z\} 
\] (7)

Assuming that the assembly object contains \( n \) parts, then the geometric interference matrixes \( I_A, I_B, I_C \) can be established respectively when assembling along the three axes, as shown in Equations (8)-(10).
The geometric interference matrix based on the above equations can calculate the geometric feasibility of the existing assembly sequence. The geometric interference matrix can analyze and judge the geometric feasibility of assembly the $P_i$ part after completing assembly the $P_{i-1}$ part, that is, the geometric feasibility when assembling the $P_i \ (2 \leq i \leq n)$ parts.

\[
I_x = \begin{bmatrix}
I_{11} & I_{12} & \cdots & I_{1n} \\
I_{21} & I_{22} & \cdots & I_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
I_{n1} & I_{n2} & \cdots & I_{nn}
\end{bmatrix}
\] (8)

\[
I_y = \begin{bmatrix}
I_{11} & I_{12} & \cdots & I_{1n} \\
I_{21} & I_{22} & \cdots & I_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
I_{n1} & I_{n2} & \cdots & I_{nn}
\end{bmatrix}
\] (9)

\[
I_z = \begin{bmatrix}
I_{11} & I_{12} & \cdots & I_{1n} \\
I_{21} & I_{22} & \cdots & I_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
I_{n1} & I_{n2} & \cdots & I_{nn}
\end{bmatrix}
\] (10)

The geometric interference matrix based on the above equations can calculate the geometric feasibility of the existing assembly sequence. The geometric interference matrix can analyze and judge the geometric feasibility of assembly the $P_i$ part after completing assembly the $P_{i-1}$ part, that is, the geometric feasibility when assembling the $P_i \ (2 \leq i \leq n)$ parts.

**Figure 1.** The calculation and analysis flow chart of assembly direction feasibility.

Firstly, the cumulative interference value is calculated according to the Equation (11), and the multiplication value is calculated. If the value is 0, that is, the cumulative interference value in a certain direction is 0, the assembly without geometric interference can be carried out; if the value is greater than 0, there is interference in the assembly process, which the assembly process is not feasible.

\[
V_x(P_i) = \sum_{j=1}^{i-1} I_{P_jP_i}, \quad V_x(P_i) = \sum_{j=1}^{i-1} I_{P_jP_i}
\] (11)

\[
f_y(P_i) = V_x \cdot V_y \cdot V_z \cdot V_{x'} \cdot V_{y'} \cdot V_{z'}
\] (12)

The $V_x(P_i)$ in Equation (11) represents the cumulative value of interference in the direction assembly of parts, according to the geometric interference matrix, and the $V_x(P_i)$ is the represents the cumulative value of interference in the opposite direction. If the cumulative value of several references is 0, which means that the assembly can be carried out, otherwise the assembly can not be carried out. The calculation process is shown in Figure 1.

**4. Case verification of assembly sequence planning**

In order to make the verification of this method typical, this paper select flat-plate fuze as the research object, which has seven parts of flat-plate fuze, as shown in Figure 2. The assembly sequence planning process of flat-plate fuze is used to verify the effectiveness.
The assembly task involves assembling the baffle, rear seat, and spring into the base part. The product includes part 1 Backboard, Part 2 Substrate, Part 3 Baffle, Part 4 Rear seat, Part 5 Spring 1, Part 6 rear Spring 2 and Part 7 front board. Assembly sequence planning is carried out according to the method mentioned above.

![Assembly Diagram](image)

**Figure 2.** The diagram of fuze parts.

4.1. **Structure hierarchical division of parts to be assembled**

Because the flat-plate fuze has been divided into the smallest basic element parts in the hierarchical division, there is no component, so the structure hierarchical division can be ignored.

4.2. **Assembly priority assessment and analysis**

1) According to the definition and Equation (1) of assembly element benchmark index, the number of times and benchmark index of each part can be obtained, as shown in Table 1.

| Part   | 1 Backboard | 2 Substrate | 3 Baffle | 4 Seat | 5 Spring1 | 6 Spring2 | 7 Frontboard |
|--------|-------------|-------------|----------|--------|-----------|-----------|--------------|
| $x_i$  | 5           | 5           | 2        | 1      | 0         | 0         | 0            |
| $f_i(x_i)$ | 1           | 1           | 0.5      | 0.25   | 0         | 0         | 0            |

2) According to the definition of assembly adjacency relationship index and Equation (2), the number and index of assembly adjacency relationship can be obtained, as shown in Table 2.

| Part   | 1 Backboard | 2 Substrate | 3 Baffle | 4 Seat | 5 Spring1 | 6 Spring2 | 7 Frontboard |
|--------|-------------|-------------|----------|--------|-----------|-----------|--------------|
| $x_2$  | 5           | 5           | 3        | 3      | 2         | 2         | 1            |
| $f_j(x_j)$ | 1           | 1           | 0.75     | 0.75   | 0.5       | 0.5       | 0.25         |

According to the definition of assembly process complexity index and Equation (3), the ratio of assembly process consumption time to the most complex connection time of each part can be obtained, as shown in Table 3.

| Part   | 1 Backboard | 2 Substrate | 3 Baffle | 4 Seat | 5 Spring1 | 6 Spring2 | 7 Frontboard |
|--------|-------------|-------------|----------|--------|-----------|-----------|--------------|
| $x_3$  | 0.8         | 0.8         | 0.7      | 0.7    | 1         | 1         | 0.7          |
| $f_i(x_i)$ | 0.8         | 0.8         | 0.7      | 0.7    | 1         | 1         | 0.7          |

According to the definition of component precision assembly index and Equation (4), the assembly accuracy requirement and assembly accuracy index can be obtained, as shown in Table 4.
Table 4. Precision assembly index of each part of flat-plate fuze.

| Part | 1 Backboard | 2 Substrate | 3 Baffle | 4 Seat | 5 Spring1 | 6 Spring2 | 7 Frontboard |
|------|-------------|-------------|----------|--------|-----------|-----------|-------------|
| $x_i$ | 10          | 10          | 5        | 5      | 10        | 10        | 20          |
| $f_i(x_i)$ | 2/3        | 2/3         | 1        | 1      | 2/3       | 2/3       | 0           |

According to the definition of symmetry index of component assembly primitive and Equation (5), the symmetry and corresponding symmetry index of each part can be obtained, as shown in Table 5.

Table 5. The symmetry index of each part of flat-plate fuze.

| Part | 1 Backboard | 2 Substrate | 3 Baffle | 4 Seat | 5 Spring1 | 6 Spring2 | 7 Frontboard |
|------|-------------|-------------|----------|--------|-----------|-----------|-------------|
| $x_i$ | 1           | 1           | 1        | 1      | 1         | 1         | 1           |
| $f_i(x_i)$ | 2/3        | 2/3         | 2/3      | 2/3    | 2/3       | 2/3       | 2/3         |

Based on the comprehensive analysis of the above five assembly priority indexes, the weight vector of each index on its assembly priority calculated by AHP is $[0.3 \ 0.25 \ 0.25 \ 0.12 \ 0.08]$, then the total assembly priority index of the above seven parts is shown in Table 6.

Table 6. The total assembly priority index of each part of flat-plate fuze.

| Part | 1 Backboard | 2 Substrate | 3 Baffle | 4 Seat | 5 Spring1 | 6 Spring2 | 7 Frontboard |
|------|-------------|-------------|----------|--------|-----------|-----------|-------------|
| F    | 0.88        | 0.88        | 0.69     | 0.61   | 0.51      | 0.51      | 0.29        |

According to the priority values shown in Table 6, part 1 and 2 have the highest priority value, and the feasible assembly sequence is $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$, or $2 \rightarrow 1 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$, or $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 6 \rightarrow 5 \rightarrow 7$, or $2 \rightarrow 1 \rightarrow 3 \rightarrow 4 \rightarrow 6 \rightarrow 5 \rightarrow 7$.

4.3. The analysis of assembly geometry feasibility

According to the actual situation, interference matrices are constructed in the direction of $+X, +Y, +Z$, as shown in Equation (13).

$$
I_x = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 0 & 1 & 1 & 0 & 1 \\
0 & 1 & 1 & 0 & 0 & 1 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix},
I_y = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 1 & 0 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 0 & 1 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 \\
\end{bmatrix},
I_z = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 0 \\
\end{bmatrix}
$$

(13)

In order to simplify the calculation, the difference between the above four assembly sequence schemes lies in the problem of installed Part 1 or 2 first, and pre installed Part 5 and 6 first.

This paper take the first assembly part 1 and assembly part 5 as examples to verify. $V(P_1)=[V_{x_1}, V_{y_1}, V_{z_1}]=[1 \ 1 \ 0 \ 1 \ 1 \ 1]$, $V(P_5)=[1 \ 1 \ 0 \ 1 \ 1 \ 1]$, $V(P_2)=[2 \ 2 \ 0 \ 2 \ 2 \ 0]$, $V(P_6)=[2 \ 3 \ 0 \ 3 \ 3 \ 1], V(P_7)=[4 \ 4 \ 0 \ 5 \ 5 \ 0], V(P_8)=[0 \ 0 \ 0 \ 0 \ 0 \ 0]$.

According to the above Equation (12), the calculation is as follows: $f_i(P_i)=V_{x_i} \cdot V_{y_i} \cdot V_{z_i} \cdot V_{x_i} \cdot V_{y_i} \cdot V_{z_i} = f_i(P_2) = f_i(P_4) = f_i(P_5) = f_i(P_6) = 0$, the calculation result equals to 0, which shows that the assembly sequence meets the geometric feasibility and requirements.

Assuming the part 2 and 5 are assembled first, the calculation is as follows: $V(P_2)=[1 \ 1 \ 1 \ 1 \ 1 \ 1]$, $V(P_5)=[1 \ 1 \ 1 \ 1 \ 1 \ 0]$, $V(P_7)=[2 \ 2 \ 0 \ 2 \ 2 \ 0]$, $V(P_8)=[2 \ 3 \ 0 \ 3 \ 3 \ 1]$, $V(P_9)=[4 \ 4 \ 0 \ 5 \ 5 \ 0]$, $V(P_{10})=[4 \ 4 \ 0 \ 5 \ 5 \ 0]$. 

4.3. The analysis of assembly geometry feasibility

According to the actual situation, interference matrices are constructed in the direction of $+X, +Y, +Z$, as shown in Equation (13).

$$
I_x = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 0 & 1 & 1 & 0 & 1 \\
0 & 1 & 1 & 0 & 0 & 1 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix},
I_y = \begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 0 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 0 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix},
I_z = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
$$

(13)
\( V(P_t) = [0 \ 0 \ 0 \ 0 \ 7], f_x(P_t) = V_x \cdot V_y \cdot V_z \cdot V_{lx} \cdot V_{ly} \cdot V_{lz} \neq 0 \). The result calculated by Equation (12) is not zero, which shows that it is not feasible to install part 2 first, i.e. geometrically infeasible.

Suppose that part 5 is installed before Part 6, \( V(P_t) = [1 \ 1 \ 0 \ 1 \ 1 \ 0] \). It can be obtained by substituting it into Equation (12), \( f_x(P_t) = V_x \cdot V_y \cdot V_z \cdot V_{lx} \cdot V_{ly} \cdot V_{lz} = 0 \), and the result shows that the scheme meets the geometric feasibility.

In summary, the assembly sequence of the fuze is that 1→2→3→4→5→6→7 or 1→2→3→4→6→5→7. The result shows that it is feasible to install 5 or 6 first.

The assembly process planning process of flat-plate fuze verifies the effectiveness of the method. The method have no limitations such as high computational time. And this method is suitable for the assemblies with less number of parts.

5. Conclusions

In this paper, a simple and effective assembly sequence design method based on the existing expert knowledge and experience is proposed. This paper construct geometric interference matrix to analyze the geometric feasibility assembly sequence. The assembly process sequence planning process of flat-plate fuze can verify the effectiveness of this method. The result shows that this method can quickly plan the assembly process sequence of parts. And this method can provide theoretical guidance and technical support to plan the assembly sequence for other precision micro parts.

In the future, the assembly sequence design method can integrate the soft computing method. Furthermore, DFA concept is applied to get the better assembly sequence.

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