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Ant Colony Optimization Algorithm-Based Disassembly Sequence Planning

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***Abstract* - Disassembly sequence planning (DSP) plays an important role in the product life cycle process. It is an important factor that determines quality and cost of the product assembly. Cost in assembly can be reduced by the implementation of generating automatic product assembly and disassembly sequences, and selecting the optimum sequence in product assembly process.The advantages and disadvantages of disassembly sequences not only determine the efficiency and cost, but also affect the efficiency in product assembly, maintenance and recovery phase. In this paper, the relevant domestic assembly/disassembly planning research results and progress are summarized. Ant Colony Algorithm is suggested to be used in the optimization of the Disassembly Sequence in the paper, on which the optimized model of disassembly sequence consisting of three factors including the component number, disassembly tools and disassembly direction is built. It also analyzes the optimized modeling methods of disassembly sequence, builds a disassembly matrix, introduces the algorithm framework and put forward the solution procedures for the disassembly sequence optimization with ant colony algorithm to get the effective disassembly sequence of the products. Finally, a case study is presented to validate the proposed method. In the case, ant colony algorithm is applied to DSP respectively, and the results verify the advantages of the ant colony algorithm in solving the ASP problem. At last, the work of this paper is summarized and the future researches are given.**

Index Terms - Ant Colony, Optimization, Disassembly Sequence Planning, Disassembly Matrix

Ⅰ. INTRODUCTION

In product design stage, assembly sequence, assembly paths, viability of assembly, ease of assembly, the cost of assembly and so on are mainly studied and evaluated. According to statistics, in some industrialized countries, for about one-third of the manpower are engaged in activities related to product assembly and more than 40% of the production costs is connected with product assembly. Required hours in assembling products accounted for 40-60%[1] of total working hours, so assembly is an important part of the product life cycle and important process of Product Realization.

Professor Boothroyd from MIT launch the concept of Design For Assembly (DFA) which advocates increasing the convenience in the period in product design to reduce assembly time, cost etc[2]. Assembly Sequence Planning [3]is one of the key research fields of DFA. In the given product design scheme, the exploring reasonably practicable assembly sequences, selecting the optimal sequence from the assembly sequences and guiding product assembly to achieve the desired assembly objectives are the research contents of the product sequence planning. In fact the product assembly process is a process of increasing space constraints. On the contrary, the disassembly process is a process of decreasing space constraints. Under the condition that disassembly process is the reverse process corresponding to assembly process. In assembly state, the quantity of geometric constraint is more than its corresponding disassembly process. Many assembly sequence planner tried to study assembly sequence planning through disassembling products, and then take the reversal of disassembly sequence as the product assembly sequence [4][5].The methods of sequence of DSP are varied. Homem de Mello[6] and Sanderson propose a method using the disassembly method to resolve the assembly sequence, This disassembly sequence optimization methods is based on the graphics decomposition and graphics search mechanism. Through obtaining the links of priority constraint, disassembly sequence is acquired between the parts in the disassembly process. Literature [7] proposes that using the interactive disassembly sequence and computer automated reasoning to gain sequence under virtual prototyping technology. In recent years, Neural networks, genetic algorithms, Petri network model can also be used for the DSP. Literature [8] studied the disassembly and recovery problem based on the principle of the best economic interests. In Wisconsin University of USA, the selective DSP of Wave Propagation is proposed [9] [10] [11] and the devastating disassembly is also studies in-depth [12] [13].

Assembly/disassembly plan has actually a problem of combination explosion and the number of assembly sequence assembly will exponential increase with the increasing of number of assembly parts, the result of combination explosion makes conventional polynomial function algorithm ineffective. Therefore, many kinds of heuristic algorithms to calculate a viable solution emerged in a limited period of time and made success to a certain extent. The evolutionary algorithms, from the principle of biology with its strong global search ability, have become an important tool to solve combinatorial optimization problems and ant algorithm is one of them. Italian scholars, such as Dorigo are inspired from the phenomenon that the groups of ants can always find the shortest path from the food source to the nest in the process of finding food. A model of ant algorithm ants—system (AS) [14] is developed and used to solve combinatorial optimization problems with very good results. Later, in view of the deficiencies of AS, improvements to the ants system have been proposed including outstanding program ant system [15], ant system based on static map[16], the largest and smallest ant system etc[17]. These models of ant algorithms established are inspired by ants foraging behavior following a basic framework, that is ant colony optimization (ACO) model[18] concluded by Dorigo. Many experiments show that the model of ant algorithm developed under the ACO to solve classic combinatorial optimization problems, such as traveling salesman problem (TSP) [19], quadratic assignment problem (QAP)[20], shop scheduling[21], vehicle routing problem[22], and got better results than the bionic algorithms ,such as artificial neural network (ANN) and the genetic algorithm (GA).Thus, in view of the merit that ant algorithm can solve combinatorial optimization problems , It is essential to use ant algorithm for the issues of assembly/disassembly sequence planning.

In this paper, Ant Colony Algorithm is suggested to be used in the optimization of the Disassembly Sequence. Disassembly matrix of the optimized modeling methods is made. The algorithm framework is constructed to put forward the solution procedures for the disassembly sequence optimization with ant colony algorithm. Finally, a case study is presented to validate the proposed method and the possible following future research directions are given.

Ⅱ. THE CONSTRUCTION OF OPTIMIZATION MODEL FOR DISASSEMBLY SEQUENCE

Since assembly and disassembly process are reversible, a better assembly sequence can be got after the obtaining of better disassembly sequence. The process of the disassembly through the following three assumed conditions correspond the process of ants feeding.

【Assumption 1】Any track linking ants between food with the nest may corresponds to a possible disassembly of the assembly sequence, and the opposite corresponds to the assembly sequence.

【Assumption 2】The starting post of ant's track corresponds the first disassembled part in disassembly sequence and terminal post corresponds to the latest assembled part.

【Assumption 3】the length of ant's track corresponds to the cost of disassembly in the process of DSP.

Meanwhile, as the adoption of ant algorithm used for assembly/disassembly sequence optimization, the assembly sequence and optimization of assembly sequence needs tobe evaluated at the same time. This can save a lot of time in assembly planning. The cost of components assembly/disassembly is closely related to the number of part, the direction of assembly/disassembly re-positioning and the frequency of replacing tools. Therefore, the theories of evaluating optimal sequence of disassembly are the least number of directions of re-positioning and the number of replacing tool. In view of the following characteristics of ant algorithm: the space of ant algorithm is described by the road map, the structure of their solutions are got according to the visit of each node with probability. A graph can be used to describe the assembly sequence optimization process. Three kinds of information of assembly, the number the components of assembly/disassembly, the direction of assembly/disassembly of parts and the tool are include by any node corresponding to an assembly/disassembly operation in the assembly/disassembly process. Figure 1 shows the structure node of the assembly/disassembly.

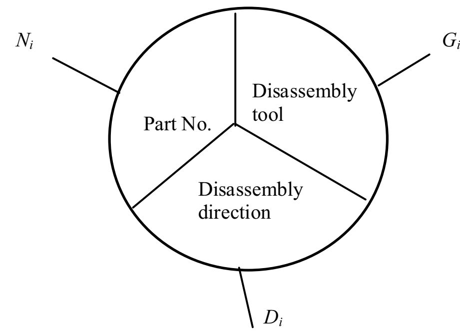

Fig. 1 The description of node map

Symbols in the map note as following:

$$\begin{aligned} N_i &\in \{n_1, n_2 \dots n_n\} \\ G_i &\in \{g_1, g_2 \dots g_n\} \\ D_i &\in \{d_1, d_2 \dots d_n\} \end{aligned} \tag{1}$$

In which, N_i is the number of product components which can be any component involved in operation of product assembly/disassembly; G_i is a tool for assembling the parts got from tool list of assembly/disassembly parts; D_i is the assembly direction of parts in the current 3D coordinates,such as +x, +y, +z that are got from Matrices of disassembly of assembly. In the basis of assembling node, the searching model of ants' initial solution of ants shown we can construct in figure 2.

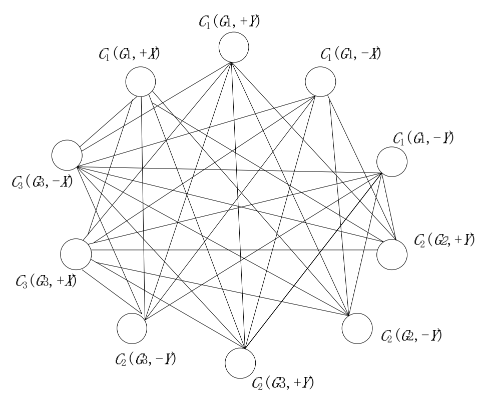

Fig. 2 The initial solution space model ants can search

In figure 2, one node $C_i(G_i, D_i)$ represents one operation of assembly/disassembly, using disassembly tools G_i disassembly parts C_i along direction D_i. Assembly/disassembly process optimization can be induced in the planning when the ants choose a series of different nodes. A series of ant-node component can be seen the final results of optimal sequence according to the probability.

III. THE FEATURES OF ASSEMBLY/DISASSEMBLY SEQUENCE OPTIMIZATION MODEL

In the initial solution space model, one node $C_i(g',d')$ represents one operation of assembly/disassembly, using tools g disassembly parts C along direction d; any track $C_i(g',d')C_j(g'',d'')$ corresponds to a sequence of process of assembly/disassembly; after using disassembly tools g demolish parts C_i along direction d, then using disassembly tools g assembly/disassembly parts C_j along direction d. According to ant algorithm and the specific characteristics of optimization in assembly/disassembly sequence, DSP optimization model has the following features:

【Feature 1】At the current node $C_i(g',d')$ and the t moment, the ant selects the next node $C_j(g'',d'')$ to be disassembly under probability which decided commonly by the concentration $\tau_i(g',d'),j(g'',d'')$ of the track $C_i(g',d')C_j(g'',d'')$ and guide factor of disassembly tools and direction $\eta_i(g',d'),j(g'',d'')$. Its value decided by the following formula:

$$p_{i(g',d'),j(g'',d'')}(t)=\frac{[\tau_{i,j}(t)]^{\alpha}[\eta_{i,j}(t)]^{\beta}[D_{i,j}(t)]^{\gamma}}{\sum_{r=1}^{l}\sum_{s=1}^{m}\sum_{k=1}^{n}[\tau_{i,\gamma(s,k)}(t)]^{\alpha}[\eta_{i,\gamma(s,k)}(t)]^{\beta}[D_{i,\gamma(s,k)}(t)]^{\gamma}} \quad (2)$$

In which $\tau_i(g',d'),j(g'',d'')$ is the concentration of informational hormones on the track $C_i(g',d')C_j(g'',d'')$ in the t moment. $\eta_i(g',d'),j(g'',d'')$ is guiding factor of disassembly tools used to choose trails without informational hormone in the track, it is be described as following:

$$\eta_{i(g',d'),j(g'',d'')}(t)=\begin{cases}1 & \text{if } g'=g'' \\ 0.1 & \text{if } g'\neq g''\end{cases} \quad (3)$$

When the tools of disassembly are the same between node of candidate and current node of disassembly, the value guiding factor of disassembly tools is 1, else 0.1. If there is no informational hormone in such track, the probability of choosing the same node with tools of disassembly by ants will be greater resulting in guiding ants to choose track sequence with lower cost of assembly/disassembly. $D_i(g',d'),j(g'',d'')$ is is used to guide ant choosing the direction of disassembly and re-position the road with less number, The expression as following:

$$D_{i(g',d'),j(g'',d'')}(t)=\begin{cases}1 & \text{if } d'=d'' \\ 0.1 & \text{if } d'\neq d''\end{cases} \quad (4)$$

The role and significance of formula 4 is the same with the above. It is used to guide ant choosing the direction of disassembly and re-position the road without informational hormone in the track to obtain track sequence with lower cost of assembly/disassembly.

In formula (2), α, β, γ are respectively weight of $\tau_i(g',d'),j(g'',d'')$, $\eta_i(g',d'),j(g'',d'')$, $D_i(g',d'),j(g'',d'')$, which are all non-negative. l is the number of node demolished in the next step. m is the number of tools of disassembly can be used in the node of disassembly r. n is the number of direction of disassembly, which can be used in the node of disassembly r.

【Feature 2】Ant left information hormone in the path which can affect the later ants leading ant groups to make optimal solution. In the track, informational hormones will be volatile over time, thus ant tracks need to be updated for a period. The method used to updating track in the ant algorithm: based on the quality of solution ants decides the number of increase of information hormones in the track after the completion of one track. At t moment, to the No. K ant, its incremental concentration in the edge of the track links to the quality of sequence of disassembly S_N after completing one track:

$$\Delta\tau_{i(g',d'),j(g'',d'')}(t)=q\frac{S_N}{N} \quad (5)$$

In formula (5), q is a constant, as quality of disassembly and assembly sequence S_N is closely related to the disassembly costs, so S_N can be expressed in the following formula (6):

$$S_k=S_{k-1}+\eta_{i,j}(t)+D_{i,j}(t) \quad k=1,2,\ldots\ldots,\mathrm{N} \quad (6)$$

So ant ended each track, the concentration of informational hormones is updated as following:

$$\begin{aligned}&\tau_{i(g',d'),j(g'',d'')}(t+\Delta t)= \\ &(1-\rho)\tau_{i(g',d'),j(g'',d'')}(t)+\Delta\tau_{i(g',d'),j(g'',d'')}(t)\end{aligned} \quad (7)$$

Where ρ is the factor of volatile concentration in track, the Range for ρ is $0<\rho<1$.

IV. THE SOLUTION OF DISASSEMBLY SEQUENCE OPTIMIZATION MODEL

A. Simplification of Disassembly Matrix

Using ant algorithm in the process of assembly sequence optimization, ants completed a disassembly operation in the current node and constructed next feasible solution in the search space. The disassembly tools can be selected from the aboved content in the list of tool of disassembly. Removable parts and possible disassembly direction can be derivational through the establishment of the assembly and disassembly matrix.

To determine detachable parts and the detachable direction of the components, this chapter established the disassembly matrix I, which is the assembly matrix of disassembly express relationships among the various parts. According to the location and orientation of bound parts to determine the possible disassembly direction in the assembly and disassembly process, the disassembly matrix of assembly showing as formula (8):

$$I=\begin{bmatrix} I_{11x}I_{11y}I_{11z} & I_{12x}I_{12y}I_{12z} & \cdots & I_{1nx}I_{1ny}I_{1nz} \\ I_{21x}I_{21y}I_{21z} & I_{22x}I_{22y}I_{22z} & \cdots & I_{2nx}I_{2ny}I_{2nz} \\ \cdots & \cdots & \cdots & \cdots \\ I_{n1x}I_{n1y}I_{n1z} & I_{n2x}I_{n2y}I_{n2z} & \cdots & I_{nnx}I_{nny}I_{nnz}\end{bmatrix} \quad (8)$$

If n parts assumed to be involved in assembling, disassembly matrix is a n rows and 3× n columns matrix. If we consider the two-dimensional assembly, then the matrix is n rows and 2×n columns matrix. Each column is composed of three parts from the left, the middle to the right. Each part corresponds to the assembly components X, Y, Z directions interfering with other parts of the disassembly. I_{ijx} expressed its elemental parts j interfere with the part i along direction $+X$. It is determined by the following rules: If part j interfere with the part i along direction $+X$ in disassembly, then I_{ijx}=1, else I_{ijx}=0.The case of part j interfering with the part i along direction $-X$ in disassembly is the same as part i interfering with the part j along direction $+X$ in disassembly, expressed by I_{jix}. By the same method, the values of I_{ijy} and I_{ijz}. can be determined.

The matrix shown above we can make *OR* operations of Boolean operator with the value from the left, the middle and the right in each row and column. Thus judging arbitrary parts along a particular direction can operate disassembly freely without interference of the other parts matrix of disassembly. In the disassembly matrix, if any row e_i, i=1,2,…,n, all the left elements I_{ijx} equal to 0, then the value of all I_{ijx} and computational results are 0 which mean that the part will not interfere with any other spare parts along +X, so it can be disassemly along the +X direction of freely. Instead, if any row e_i, i=1,2,…,n, any left elements I_{ijx} equal to 1. The value of all I_{ijx} and computational results are 1, which mean that the part will interfere with other spare parts along +X. So it can not be disassembly along the +X direction. whether the disassembly of the part can be operated freely along +Y,+Z or not can be judged by results of all the elements I_{ijy}, I_{ijz} in the disassembly matrix. In the disassembly process of assembly, the bound of assembly will be declined with the disassembly of parts and the disassembly matrix also can be simplified.

As shown below, demolished parts corresponding to the matrix of rows and columns can be deleted in the disassembly matrix by which we can get the simplified matrix of disassembly shown as formula (9):

$$I=\begin{bmatrix} I_{11x}I_{11y}I_{11z} & I_{12x}I_{12y}I_{12z} & \cdots & I_{1nx}I_{1ny}I_{1nz} \\ I_{21x}I_{21y}I_{21z} & I_{22x}I_{22y}I_{22z} & \cdots & I_{2nx}I_{2ny}I_{2nz} \\ \cdots & \cdots & \cdots & \cdots \\ I_{n1x}I_{n1y}I_{n1z} & I_{n2x}I_{n2y}I_{n2z} & \cdots & I_{nnx}I_{nny}I_{nnz} \end{bmatrix} \quad (9)$$

B. *The Procedure of Algorithm*

The algorithm steps of model as following:

Step 1: Initializing the parameter value, searching ant initial nodes space under list of established disassembly matrix and tool;

Step2: Ant choosing the initial nodes with the same probability, nodes will be deposited in the chosen sequence S_N;

Step3: According to the selected node's value dynamically simplify detachable matrix obtain the next step detachable part and feasible direction;

Step4: Calculating values of l, m, n in the probability formula to choose the next node with the probability formula, the node will be deposited in S_N, repeating this step until the whole of the road completed;

Step5: According to the evaluative formula of disassembly sequences to get the value of the S_N and then updating track; Repeating the above steps until the value of stable sequence S_N has been reached;

Step7: Output value S_N, namely, optimal sequence of disassembly/assembly;

Ⅴ. CASE STUDIES

A. *Case description*

In order validate the proposed method, the vise is introduced as follow in figure 3. It is made of 12 parts, when the small attachments are simplified to ignore.

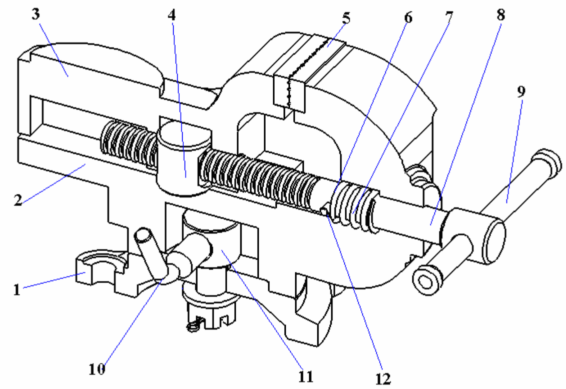

Fig. 3 the assembly view graph of vise

The meanings of numbers correspond to figure 3 as following TABLE Ⅰ.

TABLE Ⅰ
PART'S NAME CORRESPONDING TO FIG3

No.	Name
1	base
2	fixed body
3	flexible body
4	orientation block
5	vice grip
6	spring damper
7	spring
8	tommy screw
9	hand knob
10	eccentric rod
11	locking screw
12	locking stud

B. *Result Analysis*

The assembly shown in the figure is composed of 12 parts. In order to calculate the simply, we assume that tools can be used in the process of assembly as shown in TABLE Ⅱ.

TABLE Ⅱ
TOOLS AVAILABLE OF ASSEMBLY

Part No	1	2	3	4	5	6
tool	G1,G2	G1,G5	G2,G3	G5	G4	G2,G3,G6

Part No	8	9	10	11	12
tool	G1	G5	G4,G3	G2,G6	G1,G4

Through the establishment of the corresponding matrix of disassembly, the controlling parameters in algorithm are set. controlling parameters of ACS are set as following: trajectory concentration weights of ant system α=1.5, weights of disassembly tools β=2.5, weights of direction of disassembly γ=2.0, amount of ants M=30, track volatile coefficient ρ=0.8, track increment coefficient Q=1.0. Disassembly optimized results, as shown in TABLE Ⅲ.

TABLE Ⅲ
DISASSEMBLY SEQUENCE OPTIMIZED RESULTS OF ASSEMBLY

Part No	Tool	Direction
7	G3	-Y
11	G2	-Z
8	G1	+Y
1	G2	-Z
6	G3	-Y
4	G5	-Y
3	G2	-Y
5	G4	+Y
9	G5	+X
12	G1	+X
10	G4	+X
1	G1	+X

Obviously this sequence is entirely feasible. Additionally, the algorithms may be effected by the following parameter:

- Parameter α: The impact on the quality of the sequence of solutions of convergence is little, but more on the convergence rate of algorithm. From the experimental results, we know that the larger the value of α, the better the convergence of the algorithms.
- Parameter β: The impact on convergence rate of the algorithms is little, but more on the number of changes of disassembly tools in obtained the convergence of sequence. The larger the value of β, the less the number of changes of disassembly tools in obtained the convergence of sequence.
- Parameter γ: The same as β, the impact on convergence rate of the algorithms is little, but more on the number of changes of disassembly direction in obtained the convergence of sequence. The larger the value of γ, the less the number of changes of disassembly direction in obtained the convergence of sequence.
- Parameter ρ: The only impact on the convergence properties of the algorithms.
- Parameter Q: Having no impact on convergence of algorithms and the quality of sequence for convergence of Solutions.
- Parameter M: Greater impact on the convergence properties of the algorithms.

VI. CONCLUSIONS AND FUTURE WORKS

Disassembly sequence planning as a major technical facing design for disassembly, it are also an important part facing the life cycle design of product. The advantage and disadvantage of disassembly sequence not only decide the cost of the disassembly and removal efficiency, but also affected the efficiency of recovery and recycling of products. Therefore, the planning study of disassembly sequence has been the difficult and hot point for product developer and scholars who engaged in filed of product manufacture. During the process of product design facing DFA, the optimization of product disassembly sequence is very important for which directly influence the time and cost of products.

In this paper, according to the basic principles of the ant algorithm and the characteristics of disassembly, based on the disassembly of the ant algorithm is proposed to obtain a set of optimization program of disassembly and assembly sequence. When it is used to solve the optimal solutions of disassembly sequence planning, not only the sequence of parts in product was optimized, but also other information in the disassembly process was also optimized. Finally, an example is presented to show the feasibility of the method which is comparatively better than other optimization algorithm.

However, there are only six basic directions in space is considered referring to the direction of assembling, the factors, such as the stability, should be addressed in future research in the process of assembling. Furthermore, the future research efforts are required to improve the efficiency and accuracy of planning the disassembly process for the following aspects, such as the ways of acquiring the assembly information of product, the integrated interference matrix of assembly, the table of disassembly tools and the information of τ wave by human-computer interactive input.

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