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Research Article

Research on Key Technologies of Unit-Based CNC Machine Tool Assembly Design

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Assembly is the part that produces the maximum workload and consumed time during product design and manufacturing process. CNC machine tool is the key basic equipment in manufacturing industry and research on assembly design technologies of CNC machine tool has theoretical significance and practical value. This study established a simplified ASRG for CNC machine tool. The connection between parts, semantic information of transmission, and geometric constraint information were quantified to assembly connection strength to depict the assembling difficulty level. The transmissibility based on trust relationship was applied on the assembly connection strength. Assembly unit partition based on assembly connection strength was conducted, and interferential assembly units were identified and revised. The assembly sequence planning and optimization of parts in each assembly unit and between assembly units was conducted using genetic algorithm. With certain type of high speed CNC turning center, as an example, this paper explored into the assembly modeling, assembly unit partition, and assembly sequence planning and optimization and realized the optimized assembly sequence of headstock of CNC machine tool.

1. Introduction

CNC machine tool is key basic equipment in manufacturing industry and a carrier of advanced manufacturing technology. CNC machine tool manufacturing enterprises must improve the product quality and shorten the product design and manufacturing cycle in order to occupy vantage ground in fierce market competition. Assembly refers to the connection and formation of a group of scattered parts following a rational technological process and requirements, which form products with specific functions. Assembly is the part that produces the maximum workload and consumed time during product design and manufacturing process, which directly affects the quality and reliability of final products. Efficient assembly performance is of great significance to improve assembly efficiency, reduce assembly costs, and ensure assembly quality of products.

Assembly is the main line throughout entire product development process, involving design, manufacturing, maintenance, recycling, and other aspects of product lifecycle. Assembly automation is always a "bottleneck" of manufacturing industry automation. With increasing complexity of products, it is needed to develop new methods and techniques to increase assembly efficiency and quality. Thus, research on the technologies of CNC machine tool assembly design is of great theoretical significance and practical value.

2. Literature Review

Assembly design refers to the process from structural design and detailed design of products to final assembly model of products according to conceptual design. Research of unit-based assembly design mainly comprises three parts: assembly modeling, assembly unit partition, and assembly sequence planning.

2.1. Assembly Modeling. Assembly model is a key component of product information model and a premise to realize assembly design. A complete assembly model should support all assembly-related activities in the processes of product design, manufacturing, maintenance, and recycling. It should be able to transmit the assembly information completely and correctly in product lifecycle. In assembly model, the integrity and rationality of assembly information determine whether an assembly sequence can be correctly generated.

Blanchot and Daidie [1] introduced the adjustment of a numerical model simulating a riveted link using different approaches and presented the simulation of riveting process and its influence on the riveted link behaviour. Gu et al. [2] represented subassemblies, assembly states, and assembly tasks as Boolean characteristic functions and proposed symbolic OBDD (ordered binary decision diagram) scheme for all feasible assembly sequences. Xu et al. [3] simplified assembly resource, established a matrix of polychromatic sets, and set up a dynamic assembly model based on the theory of polychromatic sets. Guo et al. [4] explored into the layered assembly model under the complex constraint condition and proposed a layered constraint assembly model based on the attributes of assembly objects.

2.2. Assembly Unit Partition. As the diversity and complexity of product assembly structure and process, the assembly sequence planning is complex. The partition of complex products into assembly units with fewer parts and taking assembly unit as the study object could effectively overcome the issue of "combinatorial explosion" and reduce the difficulty of assembly sequence planning.

Gottipolu and Ghosh [5] described an approach for generation, representation, and selection of assembly sequence alternatives, in which the geometric and mobility constraints extracted directly from the CAD model of the assembly were translated into two types of unidirectional matrices, the contact, and the translational functions. Ko et al. [6] presented an assembly-decomposition model to improve product quality and used mixed-integer programming to partition the liaison graph of a product assembly with the consideration of defect rates in components and assembly tasks. Wu [7] proposed the connection intensity to express the tightness of assembly, used the fuzzy clustering for parts clustering, and established the identification of subassembly units and partition method. Wang and Liu [8] quantified the constraints of assembly units and proposed the decision-making diagram of assembly unit based on fuzzy analytic hierarchy process.

2.3. Assembly Sequence Planning. The research on assembly sequence planning can be divided into two main categories: (1) according to constraint condition, the feasible assembly sequence is generated through reasoning and optimization. (2) Using the modern optimization methods, feasible assembly sequence is generated and simultaneously filtered.

Wang et al. [9] coupled the solution space generation and disassembly solution optimization into one technical framework, represented all assembly/disassembly sequences in the DFIG (disassembly feasibility information graph) model, and proposed an integrated methodology for mechanical assembly planning. Sinanoğlu and Börklü [10] proposed an approach for the development of a process for the determination of geometric feasibility whose binary vector representation corresponds to assembly states. Zhong et al. [11] presented a determination system of assembly units for the hull structure in order to shorten construction cycle time and construction quality in shipbuilding and introduced the assessment model by fuzzy synthetic evaluation. Wang et al. [12] suggested assembly sequences merging based on assembly unit partitioning to reduce the searching space of assembly sequence planning of complex products and comprehensively took into account the assembly design constraints and the assembly process constraints.

With the research object of the headstock of HTC2550hs CNC turning center, this paper conducted assembly modeling, assembly unit partition, assembly sequence planning, and other tasks. In Section 3, the simplified assembly semantic relation graph (ASRG) for CNC machine tool was created and the assembly relationship among parts was quantified into assembly connection strength. Section 4 proposed the transmissibility of assembly connection strength. The assembly unit partition of CNC machine tool was realized. Section 5 adopted genetic algorithm for optimized assembly sequence of parts in assembly units and each assembly unit, respectively. Finally, the concurrent assembly sequence was generated. Section 6 took the headstock of HTC2550hs CNC turning center as the example and verified the technique of concurrent assembly sequence planning. Section 7 provided a conclusion of the research.

3. Assembly Modeling Based on Assembly Semantics

The assembly model of product is the foundation of assembly sequence planning. The more the complete the information included in a model is, the higher the efficiency of assembly sequence planning is. Meanwhile, the assembly modeling becomes more difficult. In the field of assembly design, designers tend to express the assembly relationship among parts by assembly semantics. The basic concept of assembly modeling based on assembly semantics is to integrate the assembly engineering semantic analysis method with object-oriented techniques, which can be used in the assembly modeling, the expression of assembly relationship, and the product model description.

3.1. Assembly Semantics. Assembly units contain rich assembly design information, which comprises assembly semantics. Assembly semantics are the abstract expressions of assembly relationship between assembly units and parts during assembly design, which embody the information such as positioning constraints and engineering constraints between assembly units and parts as well as the two assembly objects corresponding to semantics.

According to the commonly existed assembly needs such as axial restraint, connection, and transmission among assembly units, common assembly semantics in assembly design are extracted and divided into four categories: connection semantics, transmission semantics, coordinating semantics, and user-defined semantics. Connection semantics are mainly used to depict the assembly relationship among parts with connection, which generally requires auxiliary tools for assembly. Transmission semantics are mainly to depict the assembly relationship among parts with transmission relation, which generally does not need auxiliary tools for assembly. Coordinating semantics are mainly to depict the assembly relation related to axial restraint, which does not need auxiliary tools or only needs simple tools. User-defined semantics are mainly to realize the extension of assembly semantics, which are defined and extended by users.

3.2. Assembly Semantic Relation Graph Model. To simplify the assembly modeling of complex product and support assembly sequence planning, this paper used assembly semantic relation graph (ASRG) to depict the assembly structure of products. Related concepts and descriptions were as follows:

(a) function parts: parts in assembly units with connectors removed;

(b) ASRG: with assembly semantics and connector information included in edges of undirected graph, ASRG uses the undirected graph to describe the assembly connectivity of function parts in assembly units and defines the graph as a quaternion:

$$\mathrm{ASRG} = \langle V, E, A_V, A_E \rangle , \quad (1)$$

where $V = \{P_1, P_2, \dots, P_n\}$ is the set of nodes in the assembly relationship diagram, showing the function parts of products. n is the number of parts; $E = \{E_1, E_2, \dots, E_m\}$ is the set of edges in the assembly relationship diagram, and each edge corresponds to one assembly relationship, m is the number of assembly relationship; A_V represents the attribute set of nodes to describe the information of function parts; A_E represents the attribute set of edges to describe the assembly information of function parts.

Figure 1 shows the ASRG model between two parts. Edge attributes of P_i and P_j mainly include assembly semantics, connector, and geometric constraint information. ASRG separates assembly information of products from parts information so that assembly information only contains labeling information of parts. When attribute information of parts is changed, it does not influence original assembly relationship while simplifying expressions of assembly relationship and reducing the node number in graph and modeling difficulty.

3.3. Weights of Edges in ASRG. To describe the importance of assembly relationship and the difficulty of assembly, this paper defined assembly connection strength as the summation of assembly connection strength of connector information, semantic information of transmission, and geometric constraint information.

According to the difficulty of assembly/disassembly, connectors and transmission semantics parts, and evaluated assembly connection strength of geometric constraint information are shown by fuzzy hierarchical approach. These numerical values aim to exhibit certain difficulty. When there were several assembly characteristics among parts, the connection strength should be calculated, respectively, and sums should be calculated. Thus, weights of edges of ASRG could be calculated by the following formula:

$$R(i,j) = \begin{cases} \sum_{k=1}^{3} w_k r_k(i,j) & i \neq j \\ 1 & i = j, \end{cases} \quad (2)$$

where $R(i,j) = R(j,i)$, $i, j \in \{1, 2, \dots, n\}$ is weights of edges between i and j among parts; w_k is the weight of kth evaluation value of assembly connection strength; $r_k(i,j)$ is the kth evaluation value of assembly connection strength.

4. Assembly Unit Partition Based on Connection Strength

CNC machine tool products have more complex process of assembly sequence planning than normal mechanical products. The complex product is partitioned into the assembly unit containing fewer parts, which can effectively overcome the issue of "combinatorial explosion" and remarkably reduce the difficulty of assembly sequence planning. This research proposed the transmissibility of assembly connection strength and realized the assembly unit partition of CNC machine tool. This paper used assembly relationship interference matrix for interference checking and revision of the produced assembly unit, thereby obtaining assembly unit with mutual noninterference in the assembly.

4.1. Assembly Unit Partition. A product is normally formed by several parts. The complexity of assembly relationship among parts could greatly influence the assembly performance. This research quantifies the assembly difficulty among parts to assembly connection strength and proposed the transmissibility of assembly connection strength to realize assembly unit partition based on connection strength.

4.1.1. Number of Assembly Unit Partition. Assembly unit is a relatively independent structural unit to realize one or several functions. Assembly unit is a prerequisite to produce simple assembly planning tasks. This paper assumed that each unit is assembled concurrently and after the assembly all units are assembled into a final product on the main assembly line. It was also assumed that each unit does not show delaying in assembly process. With the goal of reducing assembly time, the number of optimal unit partition was obtained by formula (3). N_m was rounded and taken as the number of optimal assembly unit partition. Consider

$$N_m \leq \sqrt{N_p}, \quad (3)$$

where N_p is the total number of parts of a product and N_m is the number of unit partition of a product.

4.1.2. Basic Parts of Assembly Unit. Basic part is the important function part for an assembly unit. The selection of different basic part could reach different assembly units. According to the assembly connection matrix, the connection number of parts with other parts could be used as the basis to identify

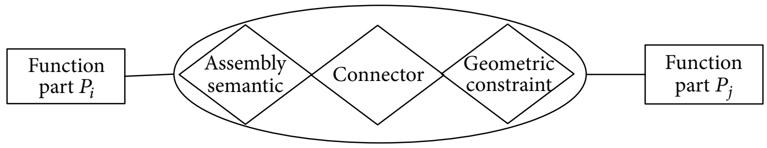

Figure 1: Assembly semantic relation graph model.

basic part. In this paper, the sum of edge weight of connected with part i in ASRG was taken as the importance degree of part i in the assembly. The importance degree could be calculated by the following formula:

$$W(i) = \sum_{j=1}^{n} R(i, j), \tag{4}$$

where $R(i, j)$ is the edge weight of ASRG.

After the calculation of importance degree of all parts is finished, N_m parts with the maximum importance degree were taken as basic parts for assembly unit partition.

4.1.3. Assembly Connection Strength. The assembly relationship graph among parts is similar with the trust network diagram among users in recommender systems of e-commerce [13]. The transmissibility of similarity was introduced into the assembly unit partition in this research so that assembly connection strength among parts could be transferred.

The transmission rules of assembly connection strength can be defined as follows: assume that there are m paths between part A and part B in ASRG, and nodes on the ith path between A and B are, respectively, $N_{i1}, \ldots, N_{ik}$; assume k is the number of nodes between A and B. If in a path there is basic part, the assembly connection strength between A and B was denoted by 0; if in a path there is not basic part, the assembly connection strength between A and B was calculated by the following formulas:

$$\begin{aligned} AI_i(A, B) &= \operatorname{Min}\left[R(A, N_{i1}), R(N_{i1}, N_{i2}), \ldots, R(N_{ik}, B)\right] * \beta_i \\ AI(A, B) &= \operatorname{Max}\left[AI_1(A, B), AI_2(A, B), \ldots, AI_m(A, B)\right], \end{aligned} \tag{5}$$

where $i = 1, 2, \ldots, m$; $R(A, N_{ik})$ is the edge weight of part A and part N_{ik} in ASRG; $AI_i(A, B)$ is the assembly connection strength between part A and part B on ith path; $AI(A, B)$ the assembly connection strength between part A and part B; β_i is an attenuation factor of assembly connection strength on ith path, which decreases with the increase of present transfer path. The calculation is as follows:

$$\beta_i = \frac{L - T_i + 1}{L}, \tag{6}$$

where L is the threshold of the length of transmission path, denoted as 5; T_i is the length of the ith transmission path, denoted as the number of edges.

According to the above process, assembly connection strength of part i and each basic part were identified. Next, based on the assembly connection strength, function parts were put in the unit where the basic part with the largest of assembly connection strength was in. With the cyclic operation, all parts were partitioned in the unit where basic parts were in. In this way, the partition of assembly unit was realized.

4.2. Interference Checking and Assembly Unit Correction. Since the factors like assembly precedence constraint and geometric constraints were not considered in assembly unit partition, interference may happen during assembling. Thus, in order to improve the accuracy of assembly unit partition, this paper generated assembly unit interference judgment matrix through assembly relationship interference matrix for interference checking and correction of partitioned assembly unit.

4.2.1. Assembly Relationship Interference Matrix. Let $E = \{e_1, e_2, \ldots, e_n\}$ be the set of assembly relationship. If assembly relationship e_i after the preferential assembly interfere with the assembly relationship e_j, it is denoted that assembly relationship e_i interferes assembly relationship e_j. e_i is called the assembly relationship that produces assembly interference. e_j is called the interfered assembly relationship [14]. Assembly relationship interference exhibits the priority of two assembly relationships. Assembly relationship interference matrix is used to express assembly interference, denoted as $I(R)$. In the matrix, if $r_{ij} = 1$, e_i after the priority assembly interferes e_j; if $r_{ij} = 0$, no assembly interference occurs between e_i and e_j; if $r_{ij} = 0$ and $r_{ji} = 1$, e_i is prior to e_j. If the row of e_i has all values as zero, e_i can be assembled prior to other assembly relationships.

In the assembly process, the composition parts of the product were only assembled with adjacent parts rather with all rest parts. Therefore, most interferences of assembly relationship exist in adjacent assembly relationships. However, due to the complexity of product structure and assembly process, some nonadjacent assembly relationships might be interfered. The interference information could be obtained through the interference extension of assembly relationship.

4.2.2. Assembly Unit Interference Judgment Matrix. With the assembly unit interference judgment matrix for interference checking and correction of each assembly unit, assembly units with no interference could be obtained. Through the following 3 steps, the assembly unit interference judgment matrix can be obtained:

(1) m assembly relationships $EU = \{e_1, e_2, \ldots, e_m\}$ in unit U were extracted;

(2) each line of elements corresponding to $e_1, e_2, \ldots, e_m$ was extracted from the assembly relationship interference matrix to form the intermediary matrix MU;

(3) each line of elements corresponding to $e_1, e_2, \ldots, e_m$ in MU was taken as zero to obtain the assembly unit interference judgment matrix CU.

If the corresponding line of assembly relationship e_i ($1 \le i \le m$) in assembly unit interference judgment matrix CU has 1, it indicates that assembly relationship e_i will interrupt the assembly of other units; that is, there is interference between assembly unit U and other units. The assembly relationship that produced interference was dissembled. The newly formed assembly unit did not create interference in the process of assembly. Disassembled parts could be adjusted to other units or partitioned into new units if needed.

5. Assembly Sequence Planning Based on Genetic Algorithm

The solutions of assembly sequence planning could be divided into two categories: serial assembly and concurrent assembly. Concurrent assembly could increase the parallelism of assembly, improve assembly efficiency, reduce assembly costs, and could not trigger "combinatorial explosion." Thus, it fits the assembly sequence planning of complex products. Genetic algorithm generates satisfactory effects in the research of combinatorial optimization. Assembly sequence planning is a typical combinatorial optimization issue. Therefore, this paper used genetic algorithm in optimized assembly sequence of parts in assembly units and each assembly unit and then generated concurrent assembly sequence.

5.1. Chromosome Coding of Assembly Sequence. The assembly sequence planning is under the umbrella of combinatorial optimization and suitable for the coding approach of combinatorial optimization. Therefore, this research used order-sensitive codes for the coding of parts. For assembly sequence planning of N parts, the chromosome was divided into N segments and each segment is the corresponding code of parts. In order to facilitate the coding, part number in the assembly unit was arranged from small to large and then was coded.

5.2. Ways to Generate Initial Population. Generally speaking, units in the initial population are randomly generated. In this paper, the automatic generation was used to generate initial population. y = Randperm (n) in MATLAB was used for population initialization to obtain a nonrepeated random structure including integers from 1 to n as a valid chromosome.

5.3. Fitness Function Design of Assembly Sequence. According to the feasibility of assembly sequence and the incidence of the strengths and weaknesses, indicators with the maximum influence and easy access to information were used to establish fitness function. This research mainly constructed the fitness functions from three aspects including the geometric feasibility of assembly sequence, stability of assembly units, and the position of basic parts in assembly sequence.

(1) Geometric Feasibility. Geometric feasibility requires no interference during disassembly. This research used integrated interference matrix [15] to derive the feasible disassembly direction of any part in the assembly unit. It was assumed that an assembly unit $A = \{1, 2, \ldots, n\}$ comprised n parts, and its corresponding integrated interference matrix was a matrix I_A with n rows and $6n$ columns, as shown in the following formula:

$$I_A = \begin{bmatrix} I_{11x} I_{11y} I_{11z} I_{11x'} I_{11y'} I_{11z'} & I_{12x} I_{12y} I_{12z} I_{12x'} I_{12y'} I_{12z'} & \cdots & I_{1nx} I_{1ny} I_{1nz} I_{1nx'} I_{1ny'} I_{1nz'} \\ I_{21x} I_{21y} I_{21z} I_{21x'} I_{21y'} I_{21z'} & I_{22x} I_{22y} I_{22z} I_{22x'} I_{22y'} I_{22z'} & \cdots & I_{2nx} I_{2ny} I_{2nz} I_{2nx'} I_{2ny'} I_{2nz'} \\ \vdots & \vdots & \cdots & \vdots \\ I_{n1x} I_{n1y} I_{n1z} I_{n1x'} I_{n1y'} I_{n1z'} & I_{n2x} I_{n2y} I_{n2z} I_{n2x'} I_{n2y'} I_{n2z'} & \cdots & I_{mx} I_{my} I_{mz} I_{mx'} I_{my'} I_{mz'} \end{bmatrix}. \quad (7)$$

If at one direction d, part i is not interfered by any part during disassembly, then $I_{id} = 0$, which indicated that part i met the geometric feasibility of disassembly and the disassembly was activated. If, at one direction d, part i is interfered by any part during disassembly, then $I_{id} = 1$, which exhibited that parts did not meet the geometric feasibility and the disassembly was not feasible. When part i was successfully disassembled, all elements at the ith row in integrated interference matrix I_A were 0, indicating that part i did not produce interference with other parts. formula (8) could evaluate the geometric feasibility of assembly sequence:

$$f_1 = \frac{N(N-1)}{2} - M, \quad (8)$$

where N is the total number of parts in assembly unit and M is the times of an assembly sequence that generated interferences during assembly.

(2) Stability of Assembly Unit. The stability connection matrix C was used to quantify the stability of feasible assembly sequence. C_{ij} represented the connection relation between part i and part j. When a stable connection relation between part i and part j was observed, let $C_{ij} = 2$; when a contact

connection relation between part i and part j was observed, let $C_{ij} = 1$; when there was no connection relation between part i and part j, let $C_{ij} = 0$. The stable connection in this research refers to connection relations with mandatory constraints such as screw joint, interference fit, and pinned connection. Hence, formula (9) was used to evaluate the stability of assembly sequence:

$$f_2 = \sum_{i=1}^{N-1} K_i, \tag{9}$$

where N is the total number of parts in an assembly unit and K_i is a quantified connection relation between part i and part $i+1$. When a stable connection existed, $K_i = 2$; when a contact connection existed, $K_i = 1$; when no connection relation existed, $K_i = 0$.

(3) Position of Basic Parts. The basic part is the key function part in assembly unit and should be firstly assembled during the assembly process. In initial population, number 1 part in each assembly sequence is not necessarily a basic part. Therefore, the assembly sequence with the basic part in the very first place should be distinguished from that with the basic part not in the first place. In this research, formula (10) was used to evaluate the position of basic parts in assembly sequence:

$$f_3 = N - P, \tag{10}$$

where N is the total number of parts of assembly unit and P is the position of basic parts in assembly sequence.

(4) Fitness Function. According to the analysis on the above evaluation indexes, a fitness function of genetic algorithm was designed for assembly sequence planning, as shown in the following formula:

$$F(S) = \omega_1 f_1 + \omega_2 f_2 + \omega_3 f_3, \tag{11}$$

where S is the assembly sequence in the population; ω_1 is the weight coefficient of geometric feasibility; ω_2 is the weight coefficient of assembly unit stability; and ω_3 is the weight coefficient of positions of basic parts.

5.4. Genetic Manipulation. Genetic algorithm simulates the evolutionary mechanism of "survival of the fittest" in the living nature through genetic manipulation. The mission of genetic manipulation is to apply certain operations on individuals in the population according to their fitness (fitness evaluation) to environment, thereby realizing the evolutionary process of survival of the fittest. Common genetic manipulation approaches include selection, intersection, and mutation.

Selection operation refers to the selection of individuals with better fitness to produce new population. For assembly sequence planning, this research provided three approaches: roulette selection, linear ranking selection, and tournament selection. Crossover operation is used to simulate genetic recombination in the genetic evolution. In the assembly sequence planning of this paper, single-point crossover, two-point, and multipoint crossover, as well as uniform crossover, were applied. Mutation is used to mimic the variation of biological heredity in the evolutionary process. In this paper, switched mutation and inserted mutation were provided.

5.5. Control Parameters and Termination Criterion of Genetic Algorithm. In order to ensure that genetic algorithm could reach the optimal solution along the optimal research track, the control parameter should be rationally selected, which mainly included the population size N, encoding length L, crossover probability P_c, mutation probability P_m, and termination condition.

For the assembly sequence planning in this research, encoding length L is the number of parts in the assembly unit. The population size N doubled the number of parts in assembly unit; that is, $N = 2L$. Crossover probability P_c controls the utilization frequency of crossover operation. Generally, $P_c = 0.6$~1.0. Mutation probability P_m controls the utilization frequency of mutation. Generally, $P_m = 0.005$~0.01. The termination condition of genetic algorithm in this paper is when a specific algebra was run on genetic algorithm, the calculation was terminated. Besides, optimal individuals in the current population were taken as the optimal solutions.

6. Case Study

With the example of headstock of HTC2550hs CNC turning center, this paper illustrated the technologies of concurrent assembly sequence planning.

6.1. Assembly Modeling of Headstock of CNC Machine Tool. After the removal of connectors in headstock, there were 43 function parts. The assembly relationship among function parts of the headstock was analyzed to establish ASRG of CNC machine tool. Parts were expressed by numbers, as shown in Figure 2.

As the headstock had a large number of function parts and ASRG was complex, this paper used Graphviz to establish ASRG. The function parts of headstock were expressed by numbers. The established ASRG is shown in Figure 3. The assembly relationship information among function parts of headstock was analyzed. The analytic hierarchy process (AHP) was used to generate weights of connection semantics information, semantic information of transmission, and geometric constraint information. The corresponding weights were, respectively, $w_1 = w_2 = 0.43$, and $w_3 = 0.14$. Next, edge weights in ASRG were calculated according to formula (2).

In Figure 3, as function parts were distinguished from connectors, there were only 43 nodes in this model. In addition, the assembly relationship information was added in edges. Edge information in ASRG could be revised according to needs so that ASRG has good maintainability.

6.2. Assembly Unit Partition of Headstock of CNC Machine Tool

6.2.1. Selection of Basic Parts in Assembly Unit. The total number of function parts of this headstock was 43. According

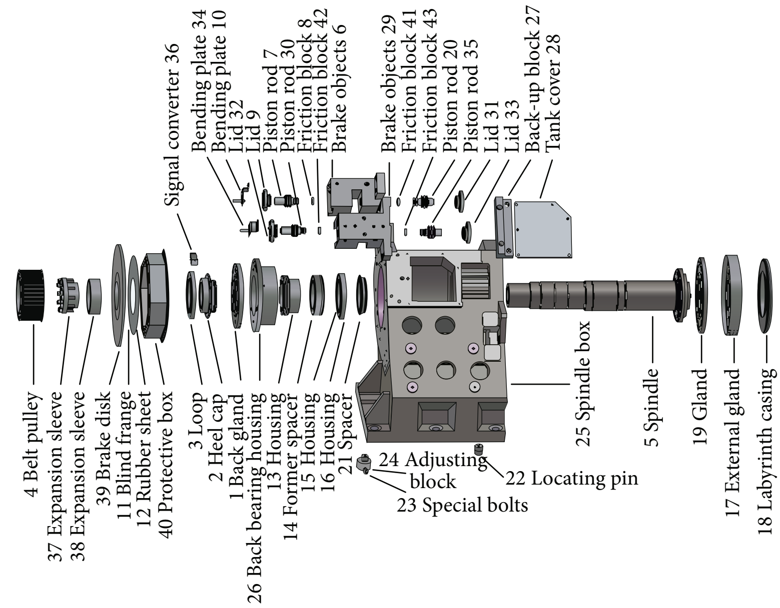

Figure 2: Explosive view of headstock.

to formula (3), $N_m \leq 6.56$, so the number of optimal unit partition was $N_m = 6$. According to edge weight in ASRG, formula (4) was used to calculate the importance degree of each part in the assembly. The result was shown in Table 1.

6 parts with the largest importance degrees were taken as the basic parts of assembly unit partition. In Table 1, part {25, 29, 6, 5, 40, 4} had the largest importance degree so that they were selected as the basic parts of assembly unit.

6.2.2. Assembly Unit Partition. The assembly connection strength between part i and other basic parts was calculated and part i was put in the unit containing basic part with the largest connection strength to accomplish the assembly unit partition. Result of assembly unit partition was shown in Table 2 and Figure 4.

6.2.3. Interference Checking and Assembly Unit Correction. Interference checking based on the above partition results was carried out. The interference judgment matrix of assembly unit 1 was shown as follows:

$$CU_1 = \begin{array}{c} \\ e_1 \\ e_2 \\ e_4 \\ e_{39} \\ e_{40} \\ e_{41} \\ e_{42} \\ e_{45} \\ e_{46} \\ e_{47} \end{array} \begin{array}{c} \begin{array}{ccccccccccc} e_1e_2e_3e_4e_5 & & \cdots & & & \cdots & & \cdots & & & e_{51}e_{52}e_{53} \end{array} \\ \left[\begin{array}{ccccccccccc} 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00100 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00001 & 00100 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \\ 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 00000 & 000 \end{array}\right] \end{array}. \tag{12}$$

By the analysis of interference judgment matrix in each assembly unit, it was found that part 2, 17, 18, and 19 would trigger assembly interference among units. After the disassembly, the assembly unit without interference was obtained. In addition, part 39 shared an assembly relationship with part 2. When part 2 was disassembled, part 39 was also disassembled.

Elements of the assembly relationship between part 19 and part 5 in the interference matrix were 0. The assembly was prioritized and it was placed in the unit where the spindle 5 was. Part 2 and part 39 had bolted connections with the

Table 1: The importance degree of each part in the assembly.

Part number	Importance degree	Part number	Importance degree	Part number	Importance degree	Part number	Importance degree
1	0.796	12	0.88	23	0.426	34	0.426
2	0.622	13	0.14	24	0.852	35	0.566
3	0.734	14	0.14	25	4.566	36	0.398
4	1.182	15	0.112	26	1.052	37	0.622
5	1.862	16	0.112	27	0.88	38	0.622
6	2.208	17	0.566	28	0.482	39	0.482
7	0.566	18	0.482	29	2.606	40	1.446
8	0.482	19	0.824	30	0.566	41	0.482
9	0.51	20	0.566	31	0.51	42	0.482
10	0.426	21	0.168	32	0.51	43	0.482
11	0.88	22	0.426	33	0.51		

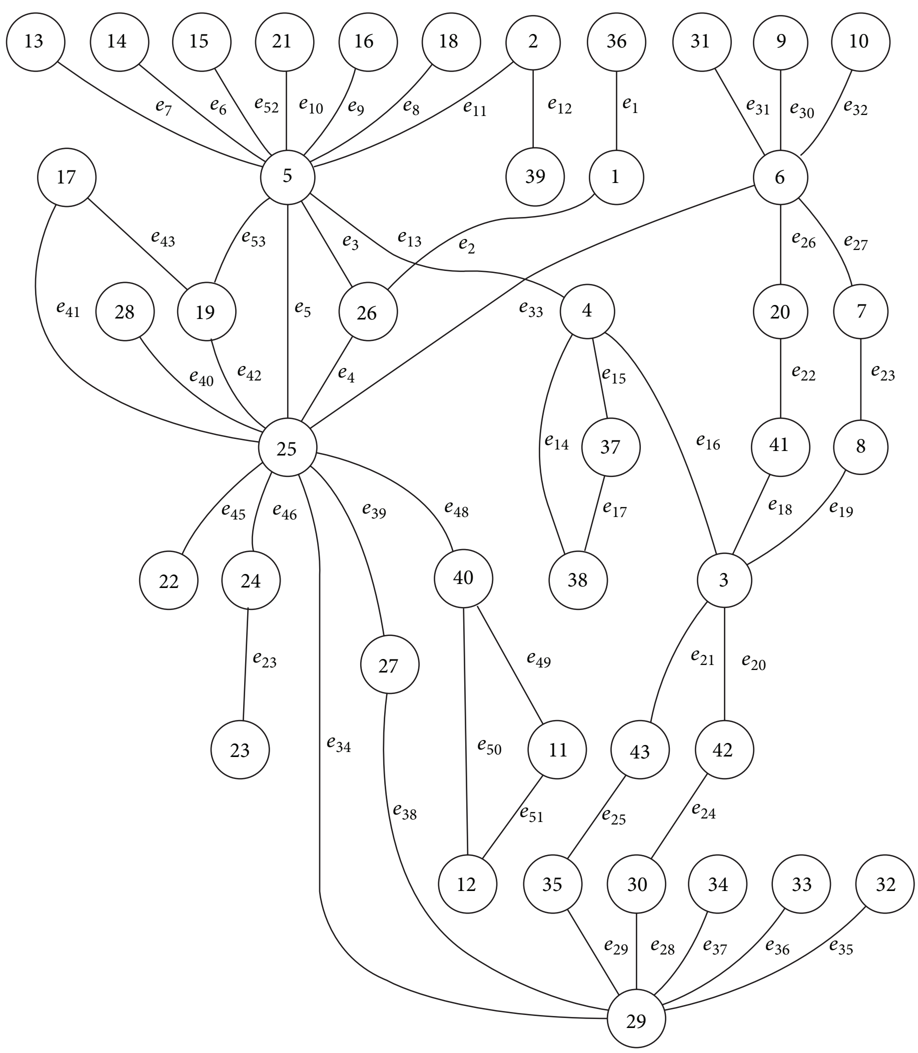

Figure 3: ASRG of headstock.

Table 2: Results of assembly unit partition.

Unit number	Basic part number	Results of assembly unit partition
1	25	1, 17, 19, 22, 23, 24, 26, 27, 28, 36
2	29	30, 32, 33, 34, 35, 42, 43
3	6	7, 9, 8, 10, 20, 31, 41
4	5	2, 13, 14, 15, 16, 18, 21, 39
5	40	11, 12
6	4	3, 37, 38

relatively intensive connection strength. Elements of assembly relationship in the interference matrix were 0, which could prioritize assembly. Therefore, an independent unit was formed. As the assembly connection strength between part 17, part 18, and basic parts in other unit was small, the partition was not conducted for independent assembly. Results of modified unit partition were shown in Table 3 and Figure 5.

6.3. Assembly Sequence Planning and Optimization for CNC Machine Tool

6.3.1. Case of Optimized Assembly Sequence. Assembly unit 3 was the braking part of headstock and contained 8 function parts. The corresponding part number was {6, 7, 8, 9, 10, 20, 31, 41} as shown in Figure 6.

The interference relationship between parts in an assembly unit at directions ($\pm X$, $\pm Y$, $\pm Z$) during disassembly and other parts was analyzed. An integrated interference matrix I_A was constructed as follows:

$$I_A = \begin{array}{c} \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 20 \\ 31 \\ 41 \end{array} \begin{array}{c} \begin{array}{cccccccc} 6 & 7 & 8 & 9 & 10 & 20 & 31 & 41 \end{array} \\ \begin{bmatrix} 000000 & 011111 & 000010 & 011111 & 000100 & 111011 & 111011 & 000010 \\ 111011 & 000000 & 100000 & 011111 & 010100 & 100000 & 100000 & 100000 \\ 010000 & 000100 & 000000 & 000000 & 000100 & 100000 & 000000 & 100000 \\ 111011 & 111011 & 000000 & 000000 & 000100 & 100000 & 100000 & 100000 \\ 100000 & 100000 & 100000 & 100000 & 000000 & 100000 & 100000 & 100000 \\ 011111 & 000100 & 000100 & 001000 & 000100 & 000000 & 111011 & 000100 \\ 011111 & 000100 & 000100 & 000100 & 000100 & 011111 & 000000 & 000100 \\ 010000 & 000100 & 000100 & 000100 & 000100 & 100000 & 000000 & 000000 \end{bmatrix} \end{array}. \quad (13)$$

The stability of the connectivity among parts in the assembly unit was analyzed and a stability connection matrix C was constructed as follows:

$$C = \begin{array}{c} \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 20 \\ 31 \\ 41 \end{array} \begin{array}{c} \begin{array}{cccccccc} 6 & 7 & 8 & 9 & 10 & 20 & 31 & 41 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & 2 & 2 & 1 & 2 & 0 \\ 1 & 0 & 2 & 1 & 0 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 2 \\ 2 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \end{bmatrix} \end{array}. \quad (14)$$

The initial population was produced by the random approach and the control parameter of genetic algorithm was set as follows: encoding length $L = 8$, population size $N = 16$, crossover probability $P_c = 0.8$, mutation probability $P_m = 0.01$, generation gen $= 100$, and genetic manipulation was, respectively, selected by roulette. This study conducted two-point crossover, switched mutation, and reverse operation. Part 6 of assembly unit 3 was a basic part. Weights of geometric feasibility, assembly unit stability, and positions of basic parts in the fitness calculation formula (11) were, respectively, $\omega_1 = 0.4$, $\omega_2 = 0.2$, and $\omega_3 = 0.4$.

Run the program in MATLAB to solve the optimal assembly sequence of assembly unit 3. Figure 7 was the fitness variation diagram of genetic algorithm optimization. According to the calculation result, the last generation of maximum fitness was 15.2, and the corresponding optimal assembly sequence was as follows:

$$6 \longrightarrow 8 \longrightarrow 7 \longrightarrow 9 \longrightarrow 41 \longrightarrow 20 \longrightarrow 31 \longrightarrow 10. \quad (15)$$

During the assembly process, basic parts should be first assembled and plate cover parts should be assembled after shaft parts. According to the optimized assembly sequence results in assembly unit 3, braking part 6 was a basic part and was firstly assembled. Cover 9 and cover 31 were assembled after the piston rod. Thus, it could be found that the assembly sequence solved from genetic algorithm was rational and feasible.

For assembly units with the number of parts larger than 5, the genetic algorithm was used for optimized assembly sequence, and assembly sequences of other units were obtained according to experiences. The result was shown in Table 4.

Similar to the optimized assembly sequencing of parts in the assembly unit, integrated interference matrix and stability connection matrix among assembly units were constructed. Assembly unit 1 was taken as the basic unit so that the assembly sequence of each assembly unit could be obtained, as shown in the following order:

$$\begin{aligned} &\text{Unit 1} \longrightarrow \text{Unit 4} \longrightarrow \text{Unit 7} \longrightarrow \text{Unit 5} \longrightarrow \text{Unit 6} \\ &\quad \longrightarrow \text{Unit 8} \longrightarrow \text{Unit 9} \longrightarrow \text{Unit 2} \longrightarrow \text{Unit 3}. \end{aligned} \quad (16)$$

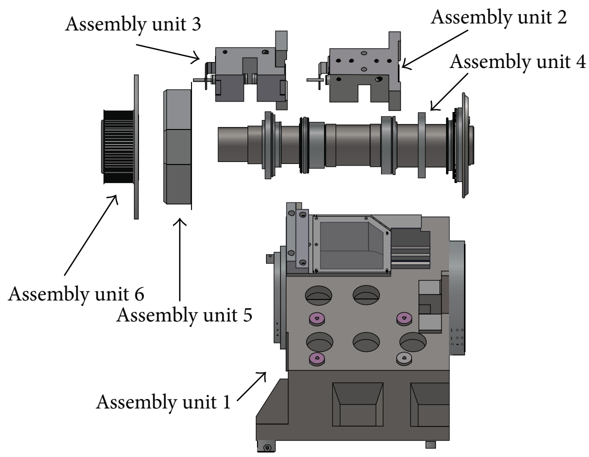

FIGURE 4: Result of assembly unit partition.

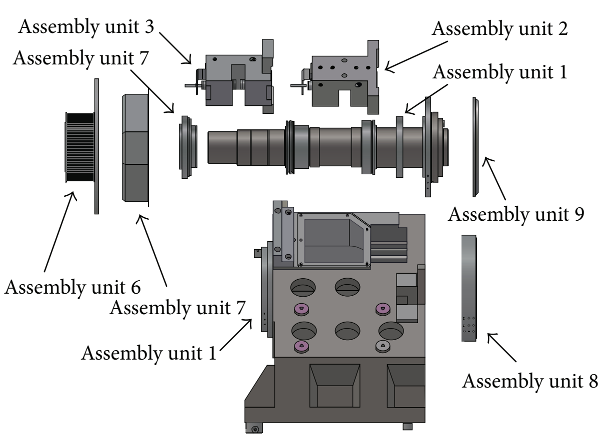

FIGURE 5: Result of modified assembly unit partition.

TABLE 3: Results of modified unit partition.

Unit number	Result of modified assembly unit partition
1	1, 22, 23, 24, 25, 26, 27, 28, 36
2	29, 30, 32, 33, 34, 35, 42, 43
3	6, 7, 8, 9, 10, 20, 31, 41
4	5, 13, 14, 15, 16, 19, 21
5	11, 12, 40
6	3, 4, 37, 38
7	2, 39
8	17
9	18

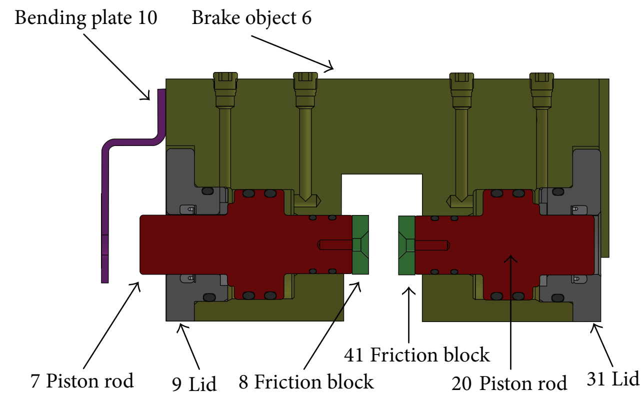

FIGURE 6: Section view of braking part.

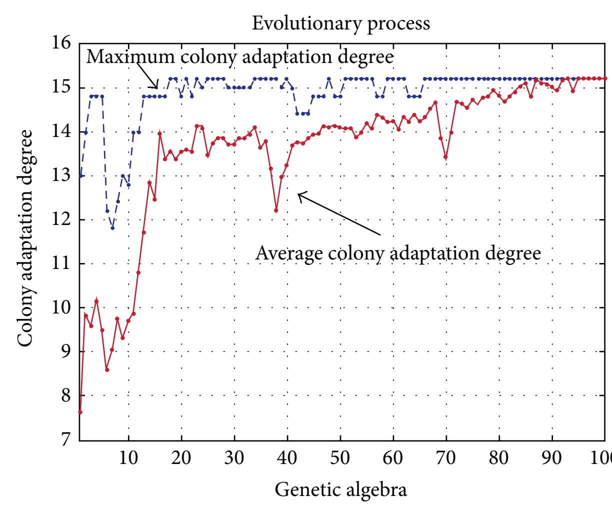

FIGURE 7: Fitness variation diagram.

TABLE 4: Assembly sequence planning of each unit.

Assembly unit number	Assembly sequence
1	25 → 27 → 26 → 1 → 36 → 28 → 24 → 22 → 23
2	29 → 42 → 30 → 32 → 43 → 35 → 33 → 34
3	6 → 8 → 7 → 9 → 41 → 20 → 31 → 10
4	5 → 19 → 21 → 16 → 15 → 14 → 13
5	40 → 12 → 11
6	4 → 3 → 38 → 37
7	39 → 2
8	17
9	18

6.3.2. Expression of Assembly Sequence. As a fishbone diagram can simply, directly, and flexibly express the assembly sequence, product hierarchies and other information, this paper used the fishbone diagram to express concurrent assembly sequence. Among them, fish head demonstrated the final product of assembly. Big bones connected with the fish spine represented each assembly unit. Small bones connected with big bones represented parts. Positions of big bones and small bones in the figure reflected the assembly sequence. The concurrent assembly sequence of headstock was shown in Figure 8.

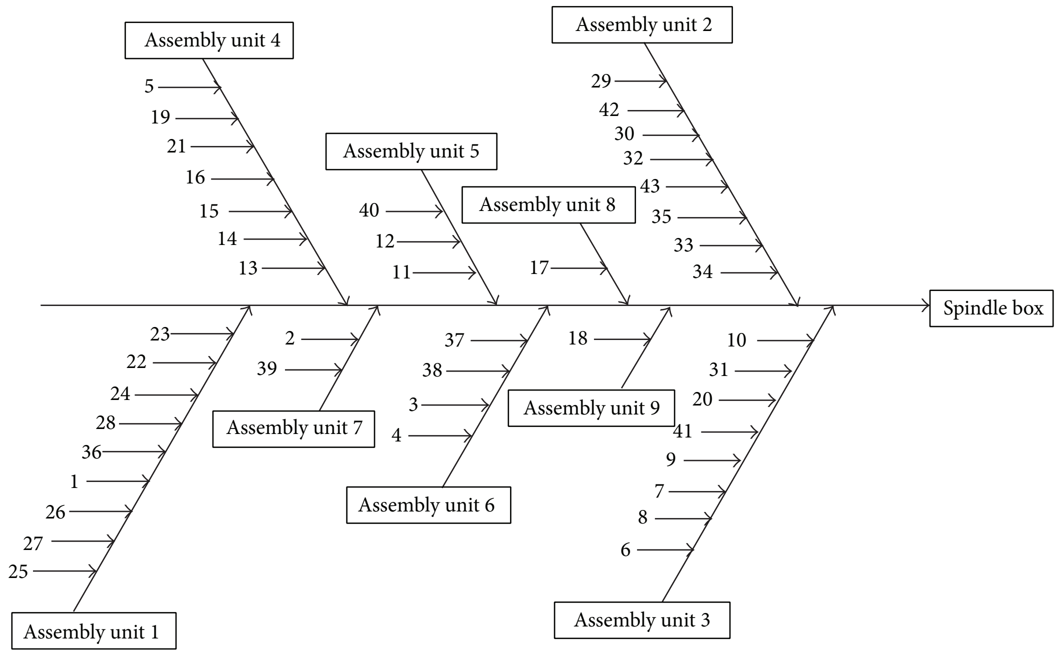

Figure 8: Expression of headstock assembly sequence.

7. Conclusions

In an era of global economic integration, to occupy a vantage ground in fierce market competition, enterprises must enhance their product innovation capability, improve product quality and performance, also shorten the product design and manufacturing cycle, and reduce costs. In modern manufacturing industry, the workload of product in the assembling stage is very heavy, producing high costs and hard to realize assembly automation. Therefore, new methods and technologies are in urgent need to support the product assembly design. On the basis of related research of assembly design, this paper explored into assembly modeling, assembly unit partition and optimized assembly sequence of CNC machine tool. In this way, the assembly design efficiency of product was improved. This research reached the following conclusions.

(1) By distinguishing connectors from function parts, a simplified ASRG was established and semantic information of assembly was added in the edges of assembly model. The study on assembly modeling cases of headstock of CNC machine tool showed that the model efficiently expressed the assembly relationship among parts.

(2) According to the transmissibility of assembly connection strength, the assembly connection strength among parts was calculated so that the information of nonadjacent parts could be utilized. The assembly unit partition based on the connection strength changed the previous partition methods by experiences so as to quantify the partition of assembly unit. In addition, through interference checking and correction of assembly unit, the rationality and accuracy of assembly unit partition were improved.

(3) According to needs of assembly sequence planning, generations of coding approach, fitness function, genetic operator, control parameters, and initial population of genetic algorithm were designed. Through case analysis of headstock of CNC machine tool, the effectiveness of using genetic algorithm for assembly sequence planning and optimization was verified.

This research actively explored into the assembly modeling, assembly unit partition, assembly sequence planning and optimization, and other aspects of CNC machine tool, realized the optimized assembly sequence of CNC machine tool, and provided theoretical basis and technical supports for the improvement of assembly quality and efficiency of CNC machine tool.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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