Control-oriented representation method of assembly process for intelligent assembly system

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**Abstract.** This work put forward a new idea of reconfigurable control of assembly process with a modular assembly control schedule (ACS) as system input and a series of automatic assembly actions of terminal execution units as system output. Based on this, an assembly process representation mechanism for reconfigurable control of intelligent assembly system is proposed, which provides an important basis and support for the further optimization and control of assembly actions. Firstly, the concepts of process meta-action (PMA) and control meta-instruction (CMI) of assembly were proposed, and the assembly process was decomposed into multiple PMAs by PSA (Procedure-Step-Action) decomposition method. Then, oriented to the control of assembly actions, PMAs were symbolized. Finally, the assembly of a micro gear was taken as a case study, and this work has been used to schedule the assembly actions of an actual micro-assembly system.

1. **Introduction**

The object of traditional automatic assembly system is one or several changeless products or components [1], and the control of assembly process is usually realized by running program codes, which are embedded in the software. If the assembly object is changed, in addition to adjusting the hardware of the system, the control program of the assembly process must be rewritten or modified, due to the change of assembly process flow. It must be completed by the programmer, and it is difficult for the on-site process engineer to complete. As for the intelligent assembly system, it must be able to meet the assembly requirements of products or components with multiple species and variable batches. Therefore, the intelligent assembly system should be reconfigurable not only at the mechanical level but also at the control level [2]. In other words, it should be able to adjust the control of the assembly process conveniently and simply, which can be completed by the assembly process engineer.

In view of this demand, this paper put forward an idea of reconfigurable control of assembly process with a modular assembly control schedule (ACS) as system input and a series of automatic assembly actions of terminal execution units as system output, as shown in figure 1. ACS refers to a sequence that carries assembly action control information corresponding to the assembly process and can be directly used for the control of automatic assembly. It is the basis for the automatic assembly system to perform the assembly task and the bridge between the assembly task layer and the assembly control layer. When the assembly requirements change, the corresponding ACS can be adjusted quickly, and the system can meet the new assembly task requirements only by changing the input. This
is of great significance for the realization of intelligent assembly of multi-variety, small-batch and variable-batch precision micro-products or micro-components.

![Diagram of Reconfigurable Control of Intelligent Assembly System](image)

Figure 1. Reconfigurable control of intelligent assembly system.

To obtain the corresponding ACS through the assembly process flow is the basic premise to realize reconfigurable control of intelligent assembly system. Automatic assembly process is the key to guide the assembly tasks of automatic assembly system and the direct basis for compiling the corresponding ACS. Therefore, to build an effective sequence representation of the assembly process is the main task of this paper.

In the literature, several representation schemes have been proposed to represent the assembly sequences. It can be roughly divided into two categories, one is process-oriented virtual assembly planning, and the other is object-oriented product information construction. The purpose is to optimize and evaluate the assembly sequence. Liu J H and Liu Z Y respectively proposed a representation model of hierarchical assembly task Link (HATL) [3] and an approach of multi-level representation of product information [4]. But these schemes are not combined with the assembly action control, only for virtual assembly planning. Johnson P Thomas proposed a type of Petri nets to represent the different levels in the assembly hierarchy, namely the assembly plan level and the control plan level [5]. Su Q proposed and optimizing a hierarchical ASP approach, focusing on assembly precedence relations (APRs) reasoning, assembly sequence planning (ASP) [6]. Niels L and Li H Q respectively built an ontology for the definition and validation of assembly processes for evolvable assembly systems [7] and an ontology-based modelling and reasoning framework for assembly sequence planning [8]. These representation schemes were for sequence optimization, not for assembly process control. So the assembly processes were described from the perspective of the feature information of the assembly object, not the automatic assembly action of the system. Based on these efforts, an assembly process representation mechanism for reconfigurable control of intelligent assembly system is proposed in this paper.

2. Process representation of intelligent assembly

The assembly process is determined by the manner and the sequence in which the product parts are put together into a complete product. It should arrange the sequence of the assembly activities of the assembly system, and also solve the problem of task assignment of the system to the mechanical equipment. It is very important for the early design, debugging and actual operation of automatic assembly equipment, and even for the assembly-oriented product design [9]. So, the design of automatic assembly process is really important. It is usually designed by process engineers and can be well understood by users, but can’t be read and understood directly by computers. Therefore, in order to make it readable, it is necessary to symbolize the assembly process. Decomposition of automatic assembly process is the premise of its symbolization.
2.1 Decomposition of process flow

For the reason above, this paper proposed a decomposition method named Process-Step-Action (PSA) for the assembly process of intelligent assembly system. As shown in figure 2, an automatic assembly process generally includes multiple assembly tasks and sub-tasks, each of which is completed by one or several terminal execution units of the system.

The intelligent assembly system can assemble several parts into a whole efficiently and quickly with a required assembly accuracy. This process is called the automatic assembly process, which is composed of several assembly procedures. In the whole process of automatic assembly, the system continuously completes a series of assembly operations on same parts or other parts added for assist, and produces one assembly connection relationship with the assembled parts or one contact relationship with the assembly platform for fixing, which can be called an automatic assembly procedure. The completion of an automatic assembly procedure requires the cooperation of each necessary execution module of the system, which consists of a series of automatic assembly steps. The system is divided into executive modules by the assembly function, such as the robot module for loading and unloading parts, the computer module for control and display, the assembly manipulator module for assembling, the precision adjustment module for position and posture slight adjustment, the image processing module for image acquisition, processing and matching, and etc. A series of assembly operations continuously be completed by the same execution module of the system on same parts is called an automatic assembly step. The system execution module also includes one or several terminal execution units. It is the smallest function unit, such as a motion axis, that can perform an action in the automatic assembly system. According to the different control modes of the system on the terminal execution units, the automatic assembly step is divided into several smallest action units which can’t be further divided, and it is called the automatic assembly process meta-action (PMA).

The PMA is defined from the perspective of control and system input, not from the perspective of assembly action and system output. Therefore, some of the response effects of the PMAs are dynamic, such as axial motion, and some are static, such as image processing, and some include one action, and some include more than one action, such as the adjustment of precision adjustment module. The difference of control mode here refers to the difference in communication mode, communication port and communication content.

![Figure 2. Decomposition method of PSA of assembly process.](image-url)
2.2 Symbolization of PMA.
The symbolization of PMA means standardization, modularization and mathematical description. Each PMA carries specific assembly information, which is called PMA information. As follows:

\[ A(i) = \{ \text{Mec, Exe, Pos, Par, Ope, Tim, Fun, Mod, Para}\} \]

Where:
- **Mec** —— The mechanical execution module which the PMA execution unit belongs to.
- **Exe** —— The terminal execution unit which executed the PMA.
- **Pos** —— Location of static PMA or the target location of dynamic PMA.
- **Par** —— The part being operated in the PMA.
- **Ope** —— The operation of the part in PMA.
- **Tim** —— Time needed in the PMA.
- **Fun** —— The function of the PMA.
- **Mod** —— The control mode of the PMA.
- **Para** —— Parameters of the PMA which control needed.

For example:

\[ A_{22}(t) = \{ \text{Robot; Robot; Home; Part1; Held; 7.2; Robot; RobotMove; Coordinate = Cartesian; Route = MoveJ; Speed = 100; X = 0; Y = 0; Z = 0; R = 0}\} \]

The formula above means that the robot carries part 1 and moves to position \((0,0,0,0)\) in Cartesian coordinates at a speed of 100mm/s, with the goal of returning to the original position, which takes 7.2 seconds.

The PMA information contained in \(Ai(t)\) can be divided into two parts, namely external attribute information and internal control information. The former is used to describe the time-space characteristics of the occurrence of the PMA, which is used in the process optimization stage. The first six elements belong to it. The latter is used for the control of the PMA, which is the key information for the successful communication between the industrial computer and the terminal execution unit, and also the basic content of the control meta-instruction (CMI). The last three elements belong to it. Each CMI can be composed of several different level instructions and several parameters. A CMI with full information can be used to control a PMA, that is, to control the terminal execution unit to execute an action unit, as shown in Figure 3.

![CMI structure tree](image-url)  
Figure 3. Composition of Control Meta-Instruction (CMI).
According to the internal control information of PMA information, the corresponding CMI can be easily obtained, which can be used for the control of the PMA, as shown in figure 4. It is the basic module that constitutes the ACS.

| CMI | Level 1 Instruction | Level II Instruction | Level III Mode 1 | Level VI Mode 2 | Level V Para |
|-----|---------------------|---------------------|------------------|----------------|-------------|
| Ex ample: | Robot | RobotMove | Coordinate=Cartesian | Route=Move | Speed=100 | X=0 | Y=0 | Z=0 | R=0 |

Figure 4. CMI instance and its pseudo-code.

3. Case study.

3.1 Assembly system composition.

In this paper, a specific flexible micro-assembly system is taken as a case study with reconfigurability in mechanical level [10]. The device has five basic modules: SCARA robot module, coaxial alignment module, assembly manipulator module, precision adjustment platform module, and industrial computer module as shown in Figure 5. Among them, the coaxial alignment module [11] includes a CCD camera and two light sources, with two degrees of freedom in the X direction. The SCARA robot module has three degrees of freedom of rotation and two degrees of freedom of movement, with the end equipped with six positions of fixtures, holding parts by vacuum adsorption and rigid clamping. The assembly manipulator module has one degree of freedom of rotation and another one in the Z direction, and also is equipped with six positions of fixtures. The precision adjustment platform module has three degrees of freedom: X and Y directions and rotation around Z axis. Industrial computer module plays the role of manager, such as display of assembly progress on the screen and coordination of assembly pace.

The interference assembly of micro gear-piece and micro gear-shaft is taken as an example. The structure and dimensions of parts are shown in Figure 6.

Figure 4. CMI instance and its pseudo-code.

Figure 5. System configuration.

Figure 6. Micro gear parts.
3.2 Representation of assembly process flow of the micro gear.

The micro gear consists of two parts: gear-piece and gear-shaft. Due to producing a contact relationship between the gear-piece and the assembly platform and a connection relation between gear-shaft and gear-piece, the automatic assembly process can be decomposed into two automatic assembly procedures. Due to the assembly tasks contained in those assembly procedures need to be assigned to different execution modules to complete, each assembly procedure can be decomposed into multiple assembly steps according to the division of task, as shown in figure 7.

According to the different control modes of the system for each terminal execution unit, each assembly step can be decomposed into multiple PMAs. Then the initial PMA sequence can be obtained, as shown in left of figure 8, which can be symbolized and represented according to the definition of PMA information. Finally the symbolized PMA sequence was obtained, as shown in the right of figure 8.

Specific ACS for this micro gear assembly can be obtained according to the internal control information in symbolized PMA sequence, which is the key for the future work of modular and reconfigurable control of assembly process.

Figure 7. Procedure sequence and step sequence.
Figure 8. Initial PMA sequence and Symbolized PMA sequence.

4. Conclusion
In order to meet the need of intelligent assembly of multi-variety, small-batch and variable-batch precision micro-products, this paper mainly studies the problems of poor scalability, insufficient reconfigurability and insufficient response to the changes of assembly object in the current micro-assembly systems. Firstly, a reconfigurable assembly process control idea is proposed, which takes the ACS as the system input and the automatic assembly actions of the terminal execution units as the system output. Based on this, a representation mechanism of assembly process for reconfigurable control of intelligent assembly system is proposed, which provides an important basis and support for further optimization and reconfigurable control of assembly process. For automatic assembly process, PSA decomposition method is used to decompose it into multiple PMAs. Then, oriented to assembly process control, these PMAs are symbolized. Finally, the assembly of micro gear is taken as a case study, and the above methods are used to represent the assembly process flow, which paves the way for the next step of assembly sequence optimization and the transformation to ACS. There can be no doubt that ACS is more complex than assembly process flow, which involves serial and parallel actions. The future work will focus on optimization of assembly process and the realization of modular and reconfigurable control for intelligent assembly system.
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