Modeling and optimization of assembly process of flexible accelerometer based on Petri net

Zechen Li, Xin Jin, Xiayu Li and Junqi Cai

School of Mechanical Engineering, Beijing Institute of Technology, Haidian District, Beijing, 100081, China

*Corresponding author’s e-mail: zechen_lee@163.com

Abstract. With the continuous improvement of micro-machining technology, sensors such as flexible accelerometers are developing in the direction of miniaturization, integration and complexity. At present, the assembly of flexible accelerometers is mainly done by manual, which cannot meet the requirements of product consistency, and the low efficiency of the production cannot match the requirements. Therefore, based on the modular design method, this paper proposes an automatic assembly system for flexible accelerometer, then uses Petri net to display the assembly process of flexible accelerometer visually, and finds the constraints which restrict the improvement of production efficiency.

1. Introduction

As a core component in the inertial navigation system, the flexible accelerometer is used to detect the linear motion and angular motion of the carrier in space, which has been widely used in aviation, aerospace, navigation and other fields[1]. With the continuous improvement of the precision machining technology, the precision and process method of the flexible accelerometer have reached a high level, so the assembly has become a limiting factor for improving the capability of the flexible accelerometer. Nowadays the assembly of flexible accelerometers mainly relies on manual, the capability and consistency of the product are inefficient, so it is urgent to develop a flexible automotive assembly system to match the quality and quantity requirements of the flexible accelerometer in the military and civilian fields[2].

Petri net is a mathematical tool to describe and analyze the logical relationship of discrete event. It is suitable for logical modeling and has strong ability to describe. As a discrete system, an automatic assembly system for flexible accelerometer can use the Petri net to describe the assembly process graphically. Petri net has been widely used in the industrial fields. Wang[3] from Zhejiang University has optimized the target with the shortest construction period and found the lowest working group and the highest total efficiency through the timed place Petri net (TPPN). The total assembly process model is established to determine the optimal job ordering. Gao[4] from Southeast University conducts a systematic logical analysis of the aerospace engine assembly workshop and finds the optimal layout plan based on the layered colored timed Petri net.

Based on the modular design method to improve the assembly quality and efficiency, this paper proposes an automatic assembly system for flexible accelerometer[5]. Under the principle of functionality and economy, it evaluates the assembly process of the flexible accelerometer and proposes some methods of optimizing assembly system[6].
2. Method
Based on the integrity of universal function and system’s reconfigurability, this paper establishes the assembly process model of the flexible accelerometer, and completes the sequence and path planning of the assembly. The petri net is used to analysis the assembly process to find the constraints. The bottleneck problem of the assembly of the flexible accelerometer will be optimized finally to improve the quality and efficiency of the product.

2.1. Modular design method
The assembly system divides the module into the dedicated function modules $S_{w(j)}$ and the general function modules $P_i$ based on the characteristics of the assembly process. The dedicated function modules are mainly for specific processes, and the common function modules are used in the entire assembly process. The advantage of this configuration is to avoid the redundancy of functions and simplify the mechanical and electrical structure.

$$R_w = \sum_{i=1}^{n} \left( \bigcup_{j=1}^{m} P_i \right) \cap S_{w(j)}$$  \hspace{1cm} i,j = 1,2,...,m \hspace{1cm} (1)

Among them, $P_i$ is the general function module of the assembly system, $S_{w(j)}$ is the jth dedicated function module in the wth assembly unit based on the requirements; $R_w$ is the set of all functional modules in the assembly system; n is the total number of assembly units in the assembly system. The flexible automative assembly system uses flexible accelerometer as the assembly object and has reconfigurable characteristics. It is designed with small volume, low energy consumption, high efficiency, high precision, strong maneuverability, good environmental interference resistance and low pollution. The fast and high-precision assembly of flexible accelerometers is achieved by the reconfigurability of functional structures. The assembly system needs to meet the functional requirements, structural correlation principles, interface correlation criteria, common parts principles, and module standardization principles while complying with design requirements[7].

2.2. Petri net
Petri net is a formal tool for the modeling and analysis of the system proposed by Carl Adam Petri in 1962. As a meshed model of information flow, it includes two types of nodes, the place and the transition, and adds the token to the directed bipartite graph which has the place and transition. Among them, the resources and positions stored are called the place. The generation, use and consumption of resources correspond to changes in the place which are called transitions. Some black points marked in the nodes of the network are called token.

The basic Petri net mainly includes three elements $N = (P, T, F)$ and has the following constraints:

$$P \cup T \neq \emptyset \hspace{1cm} P \cap T = \emptyset$$  \hspace{1cm} (2)
$$F \subseteq (P \times T) \cup (T \times P)$$  \hspace{1cm} (3)
$$\text{dom}(F) \cup \text{cod}(F) = P \cup T$$  \hspace{1cm} (4)

Among them, $P = (P_1, P_2, ..., P_n)$ indicates the collection of the places, $R$ indicates the sets of the transitions, n, m indicate the number of the places and transitions. $F$ indicates the collection of directed arcs between the places and transitions.

3. Experiment and results
Due to the long-term lack of research on the assembly process in China, the assembly of flexible accelerometers still mainly adopts the manual method which has blindness in the formulation of the assembly process. The performance of the accelerometer is closely related to the assembly workers'
skills, operating habits, proficiency, experience and physical conditions which results to many uncertainties.

3. 1. Design requirements for the assembly system
As a typical intermediate-scale MEMS, the flexible accelerometer has the characteristics of complex structure, fragile material, high processing precision and large span (0.5mm-20mm). The gap of the assembly between the torque and the pendulum reed is only 19 μm, which makes the assembly of the flexible accelerometer more difficult. The main structure of the flexible accelerometer consists of an upper torque, a pendulum, lower torque and a clamp. The structure of the flexible accelerometer is shown in Figure 1.

![Figure 1: Structure of the flexible accelerometer](image)

The indicators of the assembly system for flexible accelerometer are as follows: 1) the coaxiality of the torque and the pendulum is better than 0.005mm; 2) the gold wire ball is welded firmly, and the correctness of the welding is 100%; 3) the assembly beat is achieved 25 sets/h; 4) automatic distribution of materials in the assembly process; 5) repeated positioning accuracy of moving parts is better than 0.002mm. Its structure is shown in Figure 2, which is mainly composed of a feeding unit, a welding unit and three assembly units.

![Figure 2: Structure diagram of the flexible accelerometer assembly system](image)

The assembly unit 1 and 2 have the same structure, which mainly complete the assembly of the torque and the pendulum. The main structure includes the assembly module, the adjustment module and the detection module. The assembly unit 3 is used to complete the assembly of the clamp. The assembly process is as follows: 1) complete the assembly of the lower torque and the pendulum, the connection is
gold wire ball welding; 2) complete the assembly of the upper torque and the pendulum, the connection is the weight pressing; 3) complete the assembly of the clamp.

3.2. Petri net modeling of assembly process

In the transition sequence in parallel, if each transition \( t_{j_1}, t_{j_2}, \ldots, t_{j_k} \) in \( \sigma = \{ t_{j_1}, t_{j_2}, \ldots, t_{j_k} \} \) occurs sequentially in state \( M \), and the time limit of each transition can be represented as \( d_{j_1}, d_{j_2}, \ldots, d_{j_k} \). The new state can be expressed as \( M' = M + A\beta(t_j) + \cdots + A\beta(t_j) \). The total time of the transition sequence which occurs in parallel can be expressed as \( t = \max(t_{j_1}, t_{j_2}, \ldots, t_{j_k}) \).

The petri net is mainly composed of \( \sum \text{Petri} = (R, D) \), which \( R = \{P, T, F; M_s\} \) represents the P/T network, \( M_s \) represents the initial identity and state, \( P \) is the collection of the places, \( T \) represents the sets of the transitions, and \( D \) represents the mapping function of the \( D \) to the non-negative rational number set. And \( D(t_j) = d_j \) is the time of the transition \( t_j \) required. The definitions of the places are shown in Table 1, and the petri net under parallel operation is shown in Figure 3.

| Place | Meaning                                      | Place | Meaning                                      | Place | Meaning                                      |
|-------|----------------------------------------------|-------|----------------------------------------------|-------|----------------------------------------------|
| \( P_1 \) | Task assignment of the loading unit         | \( P_2 \) | Task assignment of welding unit              | \( P_3 \) | Loading 1-1 completed                        |
| \( P_4 \) | Loading 1-2 completed                       | \( P_5 \) | Loading 1-3 completed                        | \( P_6 \) | Loading 1-4 completed                        |
| \( P_7 \) | Loading 1-5 completed                       | \( P_8 \) | Loading 1-6 completed                        | \( P_9 \) | Loading 2-1 completed                        |
| \( P_{10} \) | Loading 2-2 completed                       | \( P_{11} \) | Loading 2-3 completed                       | \( P_{12} \) | Loading 2-4 completed                       |
| \( P_{13} \) | Loading 2-5 completed                       | \( P_{14} \) | Loading 2-6 completed                       | \( P_{15} \) | Loading 3 completed                         |
| \( P_{16} \) | Unloading                                   | \( P_{17} \) | Loadind 1. 1 completed                      | \( P_{18} \) | Loading 1. 2 completed                      |
| \( P_{19} \) | Loading 2. 1 completed                      | \( P_{20} \) | Loading 2. 2 completed                      | \( P_{21} \) | Loading 3. 1 completed                      |
| \( P_{22} \) | State judgment                              | \( P_{23} \) | Feeding unit idle 1                         | \( P_{24} \) | Feeding unit idle 3                         |
| \( P_{25} \) | State judgment                              | \( P_{26} \) | Feeding unit idle 2                         | \( P_{27} \) | Feeding unit idle 4                         |
| \( P_{28} \) | Assembly idle                               | \( P_{29} \) | State judgment                              | \( P_{30} \) | Feeding unit idle 6                         |
| \( P_{31} \) | Assembly 1 completed                        | \( P_{32} \) | Welding 1 completed                         | \( P_{33} \) | Assembly 2 completed                        |
| \( P_{34} \) | Welding 2 completed                         | \( P_{35} \) | State judgment                              | \( P_{36} \) | State judgment                              |
4. Discussion

Based on the modular design method, the automatic assembly system for flexible accelerometer takes only 210s to assemble two sets of products in parallel operation, which greatly improves the production efficiency, and improves the utilization ratio of the feeding unit and the welding unit.

The overall optimization of the automatic assembly system for flexible accelerometer is to establish a balance between the assembly sequence, the resource allocation and the assembly time. In order to achieve the re-optimization of the assembly system, the methods of optimization based on resource constraints and time allocation can be considered.

4.1. Optimization of assembly process based on resource constraint

The resource-constrained assembly system optimization method refers to the case where at least two processes use the same resource during the assembly process of the flexible accelerometer. In this case, the relevant process sequence needs to be adjusted to a serial relationship. Taking the assembly unit 3 as an example, the finished product of the assembly unit 1 and 2 needs to be transported to the assembly unit 3 to complete the assembly of the clamp, and the resource occupation for the assembly unit 3 occurs. Due to various human intervention in the actual production process, it is highly probable that the finished product of the assembly unit 1 is assembling with the clamp, while the assembly unit 2 has completed the assembly of the finished product, but it has to stay.

In response to this situation, the assembly system can add another assembly unit 4 which has the same structure as the assembly unit 3, so that the entire assembly system is in a parallel state, and the entire assembly process only involves the occupation of the feeding unit and the welding unit.

4.2. Optimization of assembly process based on time allocation

The optimization method of the assembly system based on time constraint refers to adjusting the start time and running time of every process according to the available state of the resources and the limit of the maximum time in the assembly process. Taking the use of machine vision in the assembly of the lower torque and the pendulum as an example, the feeding unit is idle, the lower torque can be grabbed by the feeding unit to the assembly unit 2.
There are three main aspects to adjust the start time and running time of every process in the assembly system:

• Change the movement speed of the linear motion platform and the rotary platform in the assembly system;
• The speed of imaging during the detection process and the calculation time of the assembly posture deviation;
• The optimal path planning of the robot;

For the assembly of the flexible accelerometer belongs to the micro-miniature assembly, the assembly has the characteristics of fragile structure and small size. Therefore, it is obviously inappropriate to increase the speed of the moving platform to reduce the time of the assembly process. The greater acceleration and deceleration produced affects the dynamic and static performance of the parts in turn. Besides, the speed of imaging is related to the performance of CCD, light source and other detection components, which can only changes the process time to a certain extent and increases the cost. Therefore, the best way to adjust the process time of the assembly system is to find the optimal path planning of the robot.

5. Conclusion

This paper completes the design of the automatic assembly system for flexible accelerometer based on the modular design method which reduces the labor intensity of workers and improves the assembly quality. The assembly process is optimized by establishing the Petri net, and the assembly system optimization methods based on resource constraint and time allocation are proposed. The results show that the beat of the assembly system is better than the requirements, which greatly improves the efficiency of the production.

Acknowledgements

This work was financially supported by the Graduate Technological Innovation Project of Beijing Institute of Technology(2019CX10007).

References

[1] Zhang Xiaofeng, Zhang Zhijing, Jin Xin, Ye Xin, Ye Zhipeng, Li Yan. Modular design method of desktop micro-assembly system for non-silicon MEMS[J]. Journal of Beijing Institute of Technology, 2015, 35(11): 1108-1112+1134. (in chinese)
[2] Ye Xin, Zhang Zhijing, Wang Qiang, et al. Reconfigurable 12-DOF micro-assembly technology and its realization[J]. Transactions of Beijing Institute of Technology. 2009. 29(9): 775-779. (in chinese)
[3] WANG Qing, WEN Li-qing, LI Jiang-xiong, KE Ying-lin, LI Tao, ZHANG Shi-zhen. Modeling and optimization of aircraft assembly line based on Petri net[J]. Journal of Zhejiang University(Engineering Science), 2015, 49(07): 1224-1231. (in chinese)
[4] Gao Jia, Wang Wei. Analysis of Aeroengine Assembly Workshop Based on Petri Net Simulation[J]. Industrial Control Computer, 2013, 26(04): 114-116+127. (in chinese)
[5] Malarvizhi Kaniappan Chinnathai, Bugra Alkan, Robert Harrison. Convertibility Evaluation of Automated Assembly System Designs for High Variety Production[J]. Procedia CIRP, 2017, 60.
[6] Leberle U, Fleischer J. Automated Modular and Part-Flexible Feeding System for Micro Parts[J]. IJAT, 2014, 8(2): 282-290.
[7] Gao Weiguo, Xu Yanshen, Chen Yongliang, et al. Theory and methodology of generalized modular design[J]. Chinese Journal of Mechanical Engineering, 2007, 43(6): 48-54. (in chinese)