Modeling and Simulation of mechanical equipment virtual maintenance training collaborative operation

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Abstract—Virtual maintenance technology is a useful supplement to mechanical manufacturing technology. Virtual maintenance training can improve training efficiency, reduce training cost and operating expenses. In order to realize multi person collaborative maintenance training under the maintenance simulation environment, this paper carries out the research on virtual maintenance training collaborative operation modeling and simulation. Firstly, the coordination of maintenance operation process is analyzed, and the operation tasks are reasonably and effectively decomposed according to the structure, function and relationship of maintenance objects; The logical relationship of collaborative maintenance operation is represented by collaborative network operation model; According to the mechanical equipment maintenance process and the characteristics of multi-agent, a hybrid cooperation model based on the role and multi-agent is constructed; In order to realize the concurrency control of collaborative operation, according to the logical relationship between tasks and resource constraints in the working environment, the locking method is used to control the execution of maintenance tasks; The mechanical equipment virtual training and assessment platform is constructed to realize the functions of disassembly process training, operation learning and process discussion.

1. Introduction
As an important direction of simulation technology, virtual reality technology is a collection of computer graphics, man-machine interface technology, multimedia technology, sensing technology, network technology and other technologies, which has three most remarkable technical characteristics: interactivity, immersion and fantasy\textsuperscript{[1]}. It is of great significance to the development of mechanical manufacturing. The virtual maintenance system based on virtual maintenance technology can effectively solve the problems such as site constraints, resource shortage, old methods, backward models and high costs, so as to improve training efficiency, reduce training costs and operating expenses. At the same time, it also greatly overcomes the key difficulties of real mechanical equipment support, solves the problems that seriously restrict the effectiveness of training and the improvement of crew level maintenance ability\textsuperscript{[2-3]}, which is of great significance to the formation and maintenance of mechanical equipments. At present, simulation maintenance training with computer system as the core has become an indispensable way of equipment maintenance training\textsuperscript{[4]}.

For the large and complex equipment, maintenance operation usually needs more than one person at the same time. Collaborative maintenance can not only improve maintenance efficiency, but also improve the accuracy of decision-making. Collaborative maintenance mainly realizes the functions of
disassembly process training, disassembly operation learning, disassembly process discussion, by the collaborative methods of virtual simulation platform, video, voice, text. In order to realize the functions of simultaneous roaming, independent maintenance and cooperative maintenance in the maintenance simulation environment, this paper carries out the modeling and simulation of virtual maintenance training cooperative work, constructs the maintenance operating work model based on multi-agent, and studies the concurrency mechanism of cooperative work.

2. Overview of maintenance collaboration

In daily life, when human beings encounter complex problems or large-scale tasks that cannot be carried out or solved independently, they usually need several people's cooperation, which is called synergism. Synergetic means the science of cooperation, which is gradually applied to the fields of physics, mechanics, medicine, mechanical engineering, economy, sociology and so on. Synergetic studies the complex phenomena of the system from the overall perspective of the system, which makes the research more comprehensive and scientific[5-6].

Computer supported cooperative work (CSCW) is the collaborative work of the interconnection between users in different departments and regions by using computer network technology[7]. CSCW provides a computer and network support environment for the group composed of several collaborators to carry out organized group activities for the same task. In order to realize the collaborative maintenance operation of a certain type of equipment virtual maintenance training, it is necessary to equipment modeling and simulate to form multiple maintenance operation user scenarios. This needs the states of main components in each user scenario participating in the collaboration are consistent, so to support multiple people's simultaneous maintenance roaming, independent maintenance and collaborative maintenance in the maintenance 3D simulation environment. The following functions should be considered: (1) reasonable decomposition of maintenance tasks; (2) maintenance personnel role setting; (3) Scene consistency; (4) Collaborative perception; (5) Multipoint trigger.

In view of the above functions, the virtual maintenance simulation training system supported by CSCW constructed in this paper adopts distributed structure. In the simulation environment, the management of heterogeneous scenarios depends on the server, and it is very important to maintain the consistency of scenarios. The consistency of heterogeneous scenarios is that the parent scenario with complex equipment as the maintenance object is controlled to be consistent under the three training modes of maintenance roaming, independent maintenance and collaborative maintenance, and the maintenance sub scenario is controlled to be consistent under the three kind of training modes. In the equipment maintenance simulation training environment, the disassembly of the smallest replaceable unit by the maintenance team will be perceived, when the constraint condition is judged to be triggered, the trigger message will be sent to the server, and the server will distribute the message to the trained users to keep the coordinated maintenance scenario consistent. Synergistic maintenance scenarios are consistent through message distribution.

3. Collaborative analysis of maintenance process

3.1 Maintenance process elements

After receiving the maintenance task, the work content should be clarified at first, which means to determine the maintenance task and analyze it in detail. The content of maintenance operation analysis mainly includes three aspects:

(1) Determine the attributes of maintenance operation, including requirements for the maintenance operation environment, demands for the special support equipment and maintenance support time constraints;

(2) The decomposition of maintenance tasks: Firstly, the maintenance tasks are decomposed into a series of interrelated maintenance events, then each maintenance event is decomposed into several
maintenance operations, and finally be determined as the basic maintenance events with a certain sequence relationship:

(3) Determine the demand for support resources, including the quantity and functional demand of equipment or spare parts for each basic maintenance operation, as well as the demand for the technical level and quantity of staff.

Maintenance operation analysis process: firstly, determine a maintenance operation from the maintenance scheme as the input of the analysis process, identify the attribute and time of the work, then decompose the maintenance operation into basic maintenance events in order, and finally determine the information such as maintenance equipment requirements, technical data requirements and personnel requirements of each basic maintenance event.

3.2 Research on decomposition method of maintenance operation

From the perspective of management, the breakdown structure of maintenance operation is a hierarchical, systematic and structured maintenance management scope and maintenance operation scope. Equipment maintenance operation decomposition can be regarded as a tree hierarchy system with the equipment to be repaired as the object. Maintenance operation decomposition is the basis of its process analysis, because only by reasonably and effectively decomposing the operation tasks, can we reasonably and effectively manage the human resources arrangement, maintenance production plan, spare parts supply, technical management, maintenance operation regulation and other aspects.

The decomposition of maintenance operation is based on the analysis and reasoning of maintenance tasks. The maintenance unit comprehensively considers the personnel and technical conditions of the unit, and usually uses the maintenance function flow chart and product function hierarchy block diagram to describe the operation decomposition information of maintenance products according to the structure, function and mutual relationship of maintenance objects. Firstly, the maintenance task is divided into several maintenance events, and then each maintenance event is divided into maintenance operations. Finally, each operation is divided into simple maintenance actions, namely basic maintenance operations. If it is necessary to further analyze and calculate the maintenance operation and its time, the completion process of basic maintenance operation can be subdivided into maintenance actions in combination with the concept of actions in human factors engineering. Maintenance actions include grasping, moving and reaching, which will not be detailed here. For the parts in complex system, the adjacency matrix and reachability matrix can be used to describe or calculate the system structure by using the methods in system engineering.

4. Logical relationship representation of collaborative maintenance

4.1 Serial operation model

According to the decomposition method of maintenance operations described in the previous section, maintenance tasks are composed of multiple maintenance operations. The basic maintenance operations in serial maintenance operations do not have the relationship of superposition or disconnection, and there is a certain sequence in the execution process, that is, the latter operation can be started only when the previous operation is completed.

The total time of maintenance events is the sum of the basic maintenance operation time: \[ T = T_1 + T_2 + \cdots + T_m = \sum_{i=1}^{m} T_i \]

4.2 Parallel collaboration model

Parallel operation refers to the situation that multiple operation tasks are carried out simultaneously in maintenance events. Usually, multi person cooperation is used to work on complex maintenance tasks at the same time. There is no fixed sequence between maintenance operations or basic maintenance operations. The operation of staff is not limited to a maintenance task. Different operations can be carried out separately according to needs.
Therefore, the maintenance time of parallel maintenance events is represented by the maximum of all operation time.

Calculation formula of parallel maintenance operation time:

\[ T = \max \{ T_1, T_2, \ldots, T_m \} \]

### 4.3 Collaborative network work model

Network work is a description of the combination of serial work and parallel work. As a more complex work mode, it includes both serial work events and parallel work events. Different maintenance events in the model can have different start times, and there may be restriction or trigger relationships between them. Program Review Technique (PERT) chart uses arrows, line segments and nodes to represent the work flow, which can well represent the network operation model, as shown in the figure below.

![Figure 1 PERT chart of network operation model](image)

Maintenance operation time:

\[ T = \max \{ t_1 + t_2, t_3, t_4, t_7, \ldots, t_6 + t_8 \} \]

### 5. Construction of hybrid collaborative model

#### 5.1 Role-based modeling

Cooperative members usually have their own domain knowledge and are independent of each other. The coordination among maintenance participating members is the basis for realizing the cooperative work process. The cooperation model between maintenance agents is one of the important factors to establish an effective work model.

As an extension and extension of object-oriented modeling method, role-based modeling method has good results in showing the dynamic relationship between object and object, object and subject, and subject and subject. The role modeling process can be summarized into the following four parts:

1. Define maintenance tasks and decompose them until a series of corresponding basic maintenance operations are obtained. In collaborative maintenance tasks, different roles can get the same operation tasks due to the existence of collaboration relationship;
2. Due to the existence of multiple cooperative tasks, each role may obtain one or more maintenance tasks and be assigned to the corresponding basic maintenance tasks;
3. According to the constraint relationship and resource conditions between works, the basic maintenance operations are combined to form the corresponding basic maintenance operation flow.
4. In collaborative maintenance operation, all roles share resources in the environment, and they cooperate to complete maintenance tasks. Therefore, access conflicts are likely to occur during maintenance operations. Therefore, negotiation and communication are very important, and dialogue mechanism is indispensable.

#### 5.2 Multi-agent based maintenance operating cooperation model

The research of multi-agent system is to solve the problem of how to make multiple agents work together in the field of distributed artificial intelligence. Each agent in the system is an independent and interactive agent with autonomous knowledge and objectives. They can produce different
solutions to deal with the changes of the environment, and coordinate and cooperate with other agents according to the communication protocol.

Equipment maintenance operation is a distributed complex process, in which each element has a certain degree of independence, such as maintenance personnel, tools and equipment have their own attributes and operation characteristics. At the same time, they are closely linked, constitute an indispensable part of maintenance operation, and cooperate to complete maintenance tasks. The elements of maintenance operation process accord with the basic characteristics of agent, such as autonomy, interaction and sociality. Therefore, according to the characteristics of equipment maintenance operation process and multi-agent, this paper constructs the multi-agent model of maintenance operation: task agent, equipment agent, personnel agent and process agent. The specific description is as follows:

(1) The role of task agent is to manage all information related to tasks and assign maintenance tasks. In the process of collaborative maintenance, task allocation plays a vital role in the smooth progress of subsequent works. In order to improve the collaboration effect in maintenance operations and meet the requirements of switching roles and operating resources in the dynamic environment of collaborative work, a dynamic allocation strategy is adopted. In the process of collaborative work, tasks can be reassigned and adjusted at any time according to the change of work task status and the needs of users for resource operation authority.

(2) Equipment agent is the agent of maintenance spare parts, tools and equipment, including equipment attribute parameters, service status and other information. The agent connects with the corresponding device through the interface, and can also pass the work task request to the device.

(3) The personnel agent manages the personnel information involved in the maintenance process, and sets the specific operation permissions of the operators.

(4) The operation agent is determined according to the specific maintenance task, corresponds to the specific operation, and manages the relevant data and production scheduling process. In addition to the interface with people and tools, process agent also includes reasoning knowledge base for analyzing, processing and optimizing operation data.

Figure 2 shows the maintenance operating cooperation model based on multi-agent.

5.3 Hybrid collaboration model based on role and Multi-Agent
Based on the above, a hybrid collaboration model based on role and multi-agent is constructed. The work process is described as follows:

(1) The agent submitting the maintenance task automatically obtains the administrator role permission. The administrator can assign different roles to other agents. Users with different role characteristics have different permissions. These permissions control the user's access to resources and operation of data.
(2) In the collaborative maintenance environment, the agent of the manager role can actively select the work agent in the environment to build a collaborative work group according to the maintenance task information and role settings;

(3) The agent in the role group analyzes the maintenance task and task status, and dynamically divides the maintenance task into several work groups. Each work group designs the collaborative operation scheme through the visualization technology scheme;

(4) According to the changes of the current task environment, the related transactions are processed in parallel among the work groups and processed cooperatively within the work group; Each work group shall submit a processing result as a proposal for the implementation of the work task scheme;

(5) Finally, each cooperative work group shall submit the proposed comprehensive plan to determine the maintenance operation process.

6. Research on concurrency mechanism of collaborative maintenance

Generally, cooperative work mode can be divided into distributed and non-distributed modes, and can be divided into synchronous mode and asynchronous mode respectively. In the process of cooperative operation, the time and operation method of each basic maintenance operation are formulated by different maintenance personnel, and the cooperative operators are usually independent of each other. In this way, parallel conflicts may occur in the whole operation process. Therefore, it is necessary to establish a constraint mechanism to limit the operation of each member.

The collaborative maintenance process is defined as a maintenance task operation set $S$. According to the specific requirements of the maintenance process, the maintenance task is divided into multiple basic maintenance operations with certain relationship constraints. The staff in various roles participating in the cooperation to complete each basic maintenance operation, so as to complete the whole maintenance task. In this paper, a directed graph is used to visually represent the logical relationship between operations, and then a relational adjacency matrix $M_{n \times n}$ ($n$ is the number of collaborative repair works) is established, set the initial value of all elements to 0. First, the work set is represented as: $S = \{S_i|S_i \in S, i = 1, \cdots, n\}$, $S_i, S_j$ represents the $i$-th and $j$-th basic maintenance operations in the set respectively, $I_i, I_j$ is used as the marks for the start of the operation, $O_i, O_j$ is used as the marks for the end of the operation, and the logical sequence is expressed as: $I_i \rightarrow S_i \rightarrow O_i$; $I_j \rightarrow S_j \rightarrow O_j$.

When the basic maintenance operation $S_i$ is completed, the basic maintenance operation $S_j$ can be executed, that is, $S_i$ is the precursor condition of $S_j$, which is recorded as: $S_i > S_j$. At this time, the value of element $a_{ij}$ in $M_{n \times n}$ is recorded as 1; Similarly, when $S_i$ is the successor operation of $S_j$, it is expressed as $S_i < S_j$, at this time, the value of element $a_{ij}$ in $M_{n \times n}$ is recorded as 0.

When there is no time or logical relationship between $S_i$ and $S_j$, it can be expressed by symbols that $O_i$ and $I_j$ intersect, and $O_j$ and $I_i$ also intersect, that is, the two maintenance operations can be performed at the same time. Set the maintenance operations referred to by $a_m$ and $a_l$ as $S_m$ and $S_l$ respectively, if the element in line $i$ of $M_{n \times n}$ conforms to the relationship described below: $ROW_i = \{a_0, \cdots, a_i, 0, \cdots, a_m, 0, \cdots | a_i = a_m = \cdots = 1\}$

Then, the relationship between $S_i, S_m$ and $S_l$ is that $S_m$. $S_l$ is the precursor task of maintenance operation $S_i$, which determines whether $S_i$ can start.

In the process of collaborative maintenance, the execution of a work operation is likely to be affected and determined by its predecessor task or related task in terms of time, resources and logic. The affected maintenance operation is also called subsequent task. In this paper, concurrency control uses the locking method to control the execution of maintenance tasks according to the logical relationship between tasks, resource constraints in the working environment and other influencing factors, so as to coordinate and unify the collaborative maintenance process. The specific locking mechanism is designed as follows. When the current user is preparing to perform a basic maintenance work, he needs to submit a request to lock the basic maintenance work to the system first. The system queries the lock information record and determines whether the work is currently locked. If the job is
currently locked, the request will be rejected. If it is not locked, the system will also check whether there is a submitted lock request information in the message queue. If so, the request will be retained and the current user will be placed in the waiting queue, that is, the lock operation cannot be completed immediately. If the system accepts the lock request, it will search for subsequent works according to the logical relationship between tasks represented by the adjacency matrix, and then lock the current maintenance work and all subsequent maintenance work tasks at the same time. After the execution of a maintenance work, the locks related to the operation, including subsequent works, are released. Then, select a user from the work execution request queue whose lock is released and allow it to execute. According to the operation data records, the system judges the type of operation that has been performed, and maintains the consistency of the interactive operation contents including subsequent works. If any conflict is found, it will be handled according to certain rules and fed back to the current user.

7. Conclusion
The typical functions of virtual maintenance training system are shown in Figure 3.

![Figure 3 Typical functions of virtual maintenance training system](image)

Aiming at the difficult problem of mechanical equipment maintenance training, this paper develops the mechanical equipment virtual maintenance training system through advanced technologies such as computer simulation and virtual reality, combined with the experience and results of real mechanical equipment training, studies the collaborative operation modeling and simulation methods, and explores new ways and methods of training based on reality and VR. By simulating the common maintenance methods of equipment, a virtual equipment training and assessment platform is constructed by introducing realistic fault situation. On the one hand, the virtual maintenance training system described in this paper can provide a new training method for mechanical equipment maintenance personnel in advance. On the other hand, it can improve the virtual prototype modeling technology of complex equipment, and lay a foundation for improving the maintenance support ability of equipment users and repair factories at all levels.

References
[1] Jiang Chenhao. Design and implementation of virtual CAP1400 powerplant based on Unity3D[D]. Shanghai: Shanghai Jiao Tong University, 2016.
[2] Li Ping, Xie Yundeng, Xie Zhihong. Research on development of virtual teaching system on armored equipment[J]. Computer Era,2018(7):9-12.
[3] Luo Yidan, Wang Nansong. Design and realization of equipment virtual maintenance training system. [J]. Computer Measurement & Control, 2019,27(7):155-158.
[4] Song Guohe, Chen Tongjun, Zhang Zhongwen. Associated debugging virtual training system of certain type complex weapon equipment[J]. Ordnance Industry Automation, 2016, 36(2) : 14-16.

[5] Gao Juan. Principle and simulation example of artificial neural network (2nd edition) [M]. Machinery Industry Press, China, 2013: 209-226.

[6] Shen Zonghui. Research and application of deep synergetic neural network based on synergetics[D]. Xian: University of Electronic Science and Technology of China, 2017.

[7] Wang Yanzheng Han Jie Zhang Zhigang, etc. Research on collaborative process and design method of complex optical remote sensor based on CSCW[J]. Aerospace Manufacturing Technology, 2020 (4) : 24-28.