Research on the Development of Spacecraft Assembly Tooling based on JACK

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Abstract. With the rapid development of space industry in China, the configuration of spacecrafts becomes increasingly complex. During the process of the assembly of spacecrafts, such problems as narrow operation space, complex assembly path, and multiple work coupling operations are often encountered. The conditions are not suitable for the trial of the tooling, thus a strict requirement for the design of the tooling is highly demanded. This paper takes a certain model under a specific working condition as an example. By the sequence of the preliminary design of tooling configuration, JACK human factors simulation, iterative optimization of configuration design, tooling simulation application, and practical application in field, the development of tooling can be realized from beginning to end through this tooling development mode. Consequently, the assembly task of the specific model can be carried out successfully.

1. Introduction

For a certain type of spacecraft, the operators are required to enter the interior of the rocket fairing through the tower platform to complete some assembly operations such as pulling out the electrical connector before launching the rocket. It is difficult for the operators to enter the cabin with small cross section area, poor height operation and long extension distance. Therefore, it is necessary to develop special operation tooling to complete the assembly operation. Regular tooling needs to be tested after completion, and then some improvements should be made according to the situation of the trials. However, the trial of this tooling needs the coordination of rocket, spacecraft and rocket tower to complete. Considering that rockets and spacecrafts are developed by different contractors, and the final site is the rocket launch site, there are no conditions for trial verification of tooling under real conditions. Therefore, the one-time successful development of the tooling is of great significance.

In order to better complete the development of the tooling, JACK is introduced to simulate and analyze ergonomics in the process of tooling design. A preliminary trial of the tooling has been completed by building the simulated working environment, and the tooling has been successfully applied before the launch of the rocket. The general assembly works smoothly, which ensures the completion of the task for this model.
2. The working condition of tooling
In the rocket launch site, after the docking of a spacecraft with the rocket, the spacecraft is located inside the rocket fairing, and the main activity area of the operator is the movable platform of the tower. The height difference between the operating platform and the movable platform is about 1.2 meters. The position relationship of the tower platform, the rocket fairing and the spacecraft is shown in Figure 1.

![Figure 1. Position relationship of rocket fairing, spacecraft and tower platform.](image)

The fixed interface of the tooling is the mobile platform, and the rocket fairing and spacecraft cannot provide a fixed interface. Operators can enter the fairing by means of tooling, climbing up about 0.8 meters upward in the direction of height, and extending to complete the operation of pulling off the electrical connectors on spacecrafts.

3. Preliminary configuration design of tooling
The initial configuration of the job tooling is shown in Figure 2, which mainly contains two parts, i.e., cover pedal and telescopic frame. The pedals and the telescopic frames are connected by the rotating shaft and the connecting rod. The connecting rod not only plays a supporting role, but also can be used as a guardrail. The tooling is installed to tower platform at field application, and the expansion frame is expanded. When the telescopic frame is completed within the hood, the operator is required to unlock the telescopic rod and stretch it up. After the telescopic rod is limited, the electric connector can be pulled out and so on. The use of the cover tooling is shown in Figure 2.

![Figure 2. Schematic diagram of job tooling configuration.](image)
4. Man-machine efficiency analysis of assembly operation
JACK is a human factor engineering analysis software of SIEMENS Industrial Software Co., Ltd. originally developed by the human modeling and simulation center of University of Pennsylvania, it is an advanced simulation software that integrates the main functions of 3D simulation, digital human modeling, ergonomics analysis, and so on.

Ergonomics, is also known as ergonomics and ergonomics. It is based on the physiological and psychological characteristics of human beings. From the view of system engineering, ergonomics analyzes the interaction between man and machine, man and environment, and machinery and environment. It provides theory and method to design the engineering system that is simple, powerful, safe and comfortable, and contributes to the best condition of human machine environment coordination. The core of human engineering is people-oriented, focusing on improving human performance and preventing human error. As far as possible to ensure safe and comfortable personnel in the system, the optimization of overall performance of man machine environment system is under unified consideration [2].

4.1. Simulation environment creation
In the design period of this tooling, the simulation work is carried out by the fully simulating the application of the tooling and the operation of the operator, and then each risk point can be identified, the tooling can be improved, and the best approach to the fairing can be proposed. The flowchart of the simulation process is shown in Figure 3. In the actual simulation process, the typical process simulation screenshots are shown in Figure 4.

![Figure 3. The flowchart of the simulation process.](image)
4.2. **Analysis of operation accessibility**

During the operation process of the operator, with the reachable domain analysis tool of JACK, the maximum comfort reachable area of shoulder and waist joint motion is generated. As shown in Figure 5, the purple transparent area is the reachable area of the operator's left hand at this location. The green transparent area is the reachable area of the operator's right hand at this location. From the graph, we can see that the reachable area of both hands can cover the required operation position.

![Figure 5. Operation accessibility analysis of virtual operator operation.](image)

4.3. **Analysis of operation visibility**

In the process of operation, people work in a narrow and closed space. The visual field of JACK is used to analyze the field of vision of operators. The field of view from the perspective of operators is shown in Figure 6. From the graph, we can see that the operator's field of vision can cover the working area.

![Figure 6. Visual accessibility evaluation of workers.](image)
4.4. Lower back analysis
Because of the small opening of the fairing, the operator is required to crawl through the opening of the cowl. Through the analysis and monitoring of the lower back of operator during the whole simulation process, it is found that when the operator is in the state of Figure 7, the lower back needs to undertake the most stress, but it’s still at normal level, and it is of no harm to the operator. Detailed information is shown in Figure 8. [DMH] represents the effect of each joint torque on each muscle. [Muscle Tensions] represents the size of the muscle tension. [L4/L5 Moments] represents the torque on behalf of the L4/L5 joint, and this torque is the sum of the torque to the spine, which includes muscle force, ligament force and interosseous pressure.

![Figure 7](image1.png)

**Figure 7.** The maximum state of the operator's lower back under pressure.

![Figure 8](image2.png)

**Figure 8.** The analysis data of the operator under the maximum pressure.

4.5. Static strength prediction
Through the monitoring of the static strength of the operator during the whole simulation process, it is found that the trunk bending strength of the operator is the highest in Figure 9, which may cause some danger to the staff. Thus, the operator can't keep this position for a long time. The specific analysis is shown in Figure 10. The percent capable shows the percentage of workers who can work under this postural strength. Angle values indicates the bending angle of elbow, shoulder, humorous, buttocks,
muscles, ankles, and the side, front and back bending angle of the torso. Torque Values represents its joint torque. Mean strengths indicates that the average strength of the workers at all working intensities.

Figure 9. The maximum bending strength of the torso in this condition.

Figure 10. Static strength data of the operator.

5. Optimization design proposals and simulation application of tooling

5.1. Optimization proposal of tooling
According to the JACK simulation results, it is concluded that the proposals of the tooling are as follows.

1) The fitting of the fairing is relatively matched with the interface of the cabin, but the following two points are still needed to pay attention to.

When the ladder extends directly into the fairing, it will expand again, which may interfere with the fairing (see Figure 5). It is recommended that the ladder should be expanded outside and then place the fairing again obliquely or the extended frame should be shortened.

When the operator (height: 155cm, weight: 55kg) pull out the electrical connector, the height of the operation plane of the staircase is not satisfied with the requirement (see Figure 6). It is suggested that the staircase should be raised to a higher level, about 120mm.

2) When working in the fairing, the operators have better accessibility and visibility, and can accomplish related tasks easily.

3) During the whole simulation process, the operators’ posture is naturally normal. Although the operator needs to bear greater strength at some places, the duration is not long, and it will not cause any damage to the operator.
5.2. *Simulation application of tooling*

The relationship of bracket, fairing and reentry module assembly is simulated with shear lift truck and fairing. The elevator platform is the tower platform, and the dimension requirement of height direction can be met by adjusting the lifting platform. By changing the position of the lift truck, the axis of the lift truck coincides with the axis of the operation port. By modifying the size between the simulated bracket and the spacecraft, the test state can meet the interface requirements. Afterwards, the entry fixture is placed on the scissors lift truck to complete the simulation operation. The scheme diagram of the simulation application is shown in Figure 11.

![Figure 11. Simulation application of job tooling.](image)

6. *Conclusion*

This work is based on the case of a spacecraft assembly. The application process of the tooling is modeled and simulated with JACK software. The interference between the tooling and the surrounding environment, the accessibility of operation, the polarity of the field of vision, the force on the back and the prediction of the static strength are analyzed. According to the ergonomics principle, suggestions for improvement of tooling configuration and operation process are put forward. Meanwhile, video animation of the simulation process is generated to guide the operation of operators. The optimization of the tooling according to the improvement proposal is successfully applied to the assembly operation before the launch of the model spacecraft, ensuring the successful completion of the model task.

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