Design of an End-effector for Spacecraft Automatic Assembly Robot

Bin Zhang\textsuperscript{1,2}, Chengli Zhang\textsuperscript{1,2}, Fugui Xie\textsuperscript{3}, Wangmin Yi\textsuperscript{1,2,3}, Shaohua Meng\textsuperscript{2} and Wei Wang\textsuperscript{1,2}

\textsuperscript{1} Beijing Institute of Spacecraft Environment Engineering, Beijing, China, 100094
\textsuperscript{2} Assembly Processing Technology Center for Aerospace Product of CASC, Beijing, China, 100094
\textsuperscript{3} Tsinghua University, Beijing, China, 100084

*E-mail: zhangbin_bisee@126.com

Abstract: With the increasing of large-weight equipment on spacecraft, the traditional assembly method using hoisting manual guidance has some shortcomings, such as poor flexibility, high risk of bumping, low assembly efficiency, etc. [1]. In recent years, robot assembly system has been widely used in spacecraft assembly process. End-effector is an important part of automatic assembly robot. In this paper, an end-effector for batch equipment installation with fast connection and fast release function was designed. Through simulation analysis and experimental verification, it proves that the end-effector has good performance and can meet the application requirements. It helps to raise efficiency and reduce cost for spacecraft assembly.

1. Introduction
The traditional spacecraft assembly operations are usually based on manual operation. For the heavy equipment which cannot be afforded by hand, we usually use crane to us to install it. With the continuous improvement of spacecraft integration, more and more heavy equipment are employed on spacecraft. For the large-weight equipment outside the spacecraft cabin, the crane and other tools can be used to help operators to complete the installation. For the large-weight equipment inside the cabin or in some special locations, the space is so narrow that it is difficult to use lifting tools. The feasibility of operation is low and the risk of collision is high. In recent years, a robot-based assembly system for large-scale equipment has been developed. Robots are used to grasp the installed objects and transport them to the assembly location accurately, which can make the assembly process of large-weight equipment safer and more efficient [2-4]. End-effector is a device that directly contacts and operates with the equipment and tools. It is one of the key components of automatic assembly system, which directly affects the effect and efficiency of robot assembly work[5-6]. Spacecraft products show the characteristics of small batch and diversification, and the shape and size are not uniform. For the connecting devices used for the clamping of medium-sized equipment in spacecraft (the weight range is 20kg-150kg), they were designed separately for each equipment in the past. The connecting devices are not universal, the assembly and disassembly work is complex, the utilization rate is low, and the cost is high. Therefore, it is necessary to develop an end-effector with fast loading and unloading function.

2. Design Constraint
2.1 Requirement analysis and design scheme

There are 7 types of equipment with mass above 30 kg on a spacecraft, as shown in Table 1. These seven types of equipment need to be installed by robot assembly system. Different kinds of equipment have different interface sizes and requirements. According to past experience, seven types of end-effectors need to be designed to connect the robot assembly system and the equipment to be installed. The design work is heavy and the resources are expensive.

Table 1. List of equipment above 30kg on a spacecraft

| Equipment Type | Interface Size(L×B) | Interface Bolts | Horizontal Projection Size | Weight |
|----------------|---------------------|-----------------|---------------------------|--------|
| A1             | 377mm×148mm         | 4-M6 (10mm)     | 659mm×410mm               | 30kg   |
| A2             | 430mm×226mm         | 4-M10 (10mm)    | 696mm×480mm               | 65kg   |
| A3             | 490mm×260mm         | 4-M10 (10mm)    | 832.3mm×583mm             | 100kg  |
| A4             | 630mm×300mm         | 4-M10 (12mm)    | 974.3×700mm               | 129kg  |
| A5             | 329mm×258mm         | 4-M6 (18mm)     | 406.5mm×362mm             | 32kg   |
| A6             | 180mm×170mm         | 4-M10 (15mm)    | 426mm×333mm               | 65kg   |
| A7             | 170mm×175mm         | 4-M5 (8mm)      | 378mm×366mm               | 40kg   |

At the same time, the installation process is complex. The installation steps with traditional end-effector are as follows: 1) Connect End-effector 1 and the Robot; 2) Connect end-effector 1 and Equipment A1; 3) Grab the Equipment A1to the Spacecraft and install Equipment A1; 4) Remove End-effector 1 from Equipment A1; 5) Remove End-effector 1 from the Robot. Then repeat steps 1)-5) to install equipment 2. Repeat the steps until all the equipment are installed.

For the convenient consideration, a kind of fast connection and fast release end-effector is designed. The end-effector is divided into two parts: robot connecting part and equipment connecting part. The robot connecting part is connected to the six-dimensional force sensor on the end of the robot. The equipment connection part is connected to the equipment to be installed. And the two parts are connected by a fast connection and fast release connector. The assembly system is shown by Figure1.

For the installation requirements of various equipment with different interface sizes, the equipment connecting parts with different interface sizes are designed. These connecting parts have the same interface with the robot connecting parts, and the interface is a fast connection and fast release interface with simple operation, which is convenient for switching between different interface devices and supports a batch of equipment installation.

1. Robot;
2. Six-dimensional force sensor;
3. End-effector;
4. Equipment;
5. Robot connecting part;
6. Fast connection and fast release connector;
7. Equipment connecting part.

Figure 1. Robot assembly system for spacecraft large-weight equipment installation
2.2 Work process

The connecting parts of the end effector robot are installed on the robot. When the robot is initially installed, the locking actuator is in the initial position. The connecting parts of equipment are installed separately on each equipment to be installed, and then the robot reaches the position of the equipment to be installed, and docks the robot connecting part with the docking slot on the equipment connecting part, triggers the docking switch after docking, lights up the docking indicator on the controller, and drives the actuator to turn forward and extend to start the locking action through the locking button on the controller. After the lock is completed, the indicator light on the controller is turned on, and the connection between the robot and the equipment to be installed is completed. After the robot installs the equipment 1 to the installation position, and completes the installation operation, it drives the actuator to reverse and retract to the initial position through the release button on the controller. The lock indicator light on the controller is turned off and the release indicator light is turned on. At this time, the robot reaches the position of the equipment 2 to be installed, repeats the above actions, and completes the robot connecting part with the end-effector on the robot. The parts are connected with the connecting parts of the equipment on the equipment 2 to be installed. Repeat the above steps to complete the installation of all the equipment. The locking and loosening operation is simple and fast, which is convenient for batch installation of interface equipment of different sizes and improves the spacecraft assembly efficiency.

2.3 Interface Conditions

1) According to the Table 1, the maximum weight of the equipment is 129kg, and for the consideration of some expansion, the maximum load of the end-effector is designed to be 150kg. The safety coefficient is 3.

2) For the safety consideration, the end-effector should have enough stiffness. If under the worst condition, the maximum deformation at full load should no more than 1 mm.

The six-dimensional force sensor employed in this paper is Omega190, which can load 150 kg weight. So the interface of robot connecting part which will be docked to the six-dimensional force sensor must be designed to be matched to the interface of Omega190.

3. System Design

3.1 Structure Design

The installation of end-effector and robot can be divided into coaxial type and suspension type[7]. Coaxial means that the axis of the end effector is installed parallel to the axis of the flange of the robot. Suspension means that the axis of the end effector is installed vertically with the axis of the flange of the robot. In this paper, coaxial axis coincidence mode is chosen. The end-effector axis can coincide with the geometric axis of the equipment in order to avoid the vertical installation space of the equipment in the cabin.

The structure of the fast connection and fast release end-effector is shown by Figure 2. It is consisted by supporting structure, fast connector, connection and release actuator, equipment connecting structure, and force sensor. Fast connector is the part for fast connection and release. The connection and release actuator is the key executive part for connection and locking.
3.2 Control system
The main components of the control system include control cabinet, PLC, sensor signal processor, relay, switch lamp and other control components, as well as proximity switch, force sensor and actuator sensing and executing devices. PLC, sensor signal processor, relay and switch lamp are installed on the control cabinet, and proximity switch, force sensor and actuator are installed on the terminal of the robot. Connecting with control cabinet through 24V DC specification cable in joint.

4. Simulation analysis
The material of the main structure is 30CrMnSi, whose yield point is 800MPa, and the tensile strength is 1100MPa.

To simplify the fixed support scheme mentioned above, the finite element analysis model was obtained. Loading simulation calculation is carried out in three directions: X, Y and Z, with the maximum mass of the load is 150 kg. Y direction is the direction of vertical equipment connecting surface, and the weight is distributed to four bolt connection holes on average. The strength of end-effector is analysed and the deformation is analysed.

4.1 Strength analysis result
The stress is simulated. The result is shown by Figure 3, and the maximum stress of X, Y, and Z direction are shown in table 2. From the result of the simulation, we can see the maximum stress is 195.16MPa on Z direction, and the minimum safety coefficient is 4.1, which is larger than 3. So strength of the main structure can satisfied the requirement.

| Serial number | Simulated working condition | Maximum stress (MPa) | Safety coefficient |
|---------------|----------------------------|----------------------|-------------------|
| 1             | X                          | 189.77               | 4.2               |
| 2             | Y                          | 42.03                | 19                |
| 3             | Z                          | 195.16               | 4.1               |

Table 2. The results of strength analysis
4.2 Deformation analysis result

The deformation is simulated. The result is shown by Figure 4, and the maximum deformation of X, Y, and Z direction are shown in table 3. From the result of the simulation, we can see the maximum deformation is 0.78mm on Z direction, which is shorter than 1mm. So deformation of the main structure can satisfy the requirement.

Table 3. The results of deformation analysis

| Serial number | Simulated working condition | Maximum deformation (mm) |
|---------------|-----------------------------|--------------------------|
| 1             | X                           | 0.40                     |
| 2             | Y                           | 0.38                     |
| 3             | Z                           | 0.78                     |

5. Test verification

In order to verify the functions of the end-effector, a testing system was built, as shown by Figure 5, including KUKA KR210 Robot, Omega190 six-dimensional force sensor, end-effector design in this paper, and weight block which is simulating the equipment.

First function check was carried out, such as fast connection function check, connection locking function check, connection releasing function check, and etc., it is verified in good conditions. Then, loading test is carried out on the end-effector to simulate the actual installation of the equipment. Each connection of the end-effector and the equipment is loaded 100kg in directions of X, Y and Z, respectively. Deformation of the end-effector is measured. Through measurement, the maximum deformation is 0.2mm. It can meet the requirements of the design.
6. Conclusion
In this paper, an end-effector used for spacecraft assembly robot with fast connection and fast release function was developed in order to meet automatic installation requirements for several large-weight equipment. After design, the End-effector was manufactured, assembled and tested. It is verified in good functions, and can provide a strong basis for following research.

Reference
[1] Hu R Q, Zhang L J, Meng S H, Dong Q, Long C Y, Robotic Assembly Technology for Heavy Component of Spacecraft Based on Compliance Control, JOURNAL OF MECHANICAL ENGINEERING, 2018 54(11): 85-93
[2] Yi W M, Long C Y, Hu R Q, Design and Application of Spacecraft Assembly and Testing Robot System, Aerospace China, 2019 (2):30-33
[3] Wang J, Liu H. Design of Drilling End Effector for Aircraft Automatic Assembly, Journal of Nanjing University of Aeronautic and Astronautics, 2012 4(44):20-22
[4] Olsson T, Haage M, Kihlman H, Johansson R, Nilsson K, Robertsson A, Bjöorkman M, Isaksson R, Ossbuhr G, Brogårdh T. Cost-efficient drilling using industrial robots with high-bandwidth force feedback. Robotics and Computer-Integrated Manufacturing, 2010, 26(1): 24-38
[5] Kubela T, Pochyly A, Singule V, Flekal L. Force-torque control methodology for industrial robots applied on finishing operations. Mechatronics: Recent Technological and Scientific Advances. Berlin: Springer-Verlag, 2012. 429-437
[6] DeVlieg R, Feikert E (2008) One-up assembly with robots. In: SAE 2008 Aerospace Manufacturing and Automated Fastening Conference & Exhibition, North Charleston, SC, USA. SAE Technical Papers 2008, 44(01):297~302.
[7] Cheng D X. Mechanical Design Manual (Volume 4) [M]. 4th Edition Beijing: Chemical Industry Press, 2002.