

Research to Assembly Scheme for Satellite Deck Based on Robot Flexibility Control Principle

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Abstract. Deck assembly is critical quality control point in final satellite assembly process, and cable extrusion and structure collision problems in assembly process will affect development quality and progress of satellite directly. Aimed at problems existing in deck assembly process, assembly project scheme for satellite deck based on robot flexibility control principle is proposed in this paper. Scheme is introduced firstly; secondly, key technologies on end force perception and flexible docking control in the scheme are studied; then, implementation process of assembly scheme for satellite deck is described in detail; finally, actual application case of assembly scheme is given. Result shows that compared with traditional assembly scheme, assembly scheme for satellite deck based on robot flexibility control principle has obvious advantages in work efficiency, reliability and universality aspects etc.

1. Introduction

Docking assembly of the deck is critical quality control point in final satellite assembly process, and important safety control point. Satellite deck generally has 2 kinds of assembly modes: the first one is process that high-mass deck assembly is finished with the help of 4-6 DOF pure mechanical deck overturn trailer vehicles; the second one is process that small-mass deck assembly is finished by relying on manual lifting and support of operators completely. It is difficult to control assembly accuracy of traditional deck assembly mode, and in the mode, assembly efficiency is relatively low, and especially in docking assembly under full- capsule state, cable and equipment bruise or locating pin bush clamping stagnation may appear easily, which affects development quality and progress of satellite to a certain extent.

Industrial robot is one of main equipment in flexible assembly. Foreign robot assembly is widely used in the fields of aviation, aerospace, weapon and missile etc., and is in the leading position in technical research^[1]. The theoretical research on robot assembly in large spacecraft component has also been widely carried out in China^[2-6]. However, there are few studies on project implementation scheme of large spacecraft component assembly.

Combining with investigation to domestic and overseas satellite assembly mode, this paper proposes assembly project scheme for satellite deck based on robot flexibility control principle to overcome several disadvantages in assembly docking process, such as operation instability, excessive human factor dependency and experience-based judgment etc., reduce collision, bruise and clamping stagnation risks in docking assembly process, and improve assembly quality and safety of docking assembly link.



2. Project scheme

Auxiliary assembly system based on robot flexibility control principle is shown in Figure 1, and mainly consists of mobile platform, industrial robot, end effector and six-dimensional force sensor etc. Main functions of each part are as follows: mobile platform is used for rapid transport of industrial robot at different final assembly stations and support and fixation to robot; industrial robot and supporting control cabinet are used to finish adjustment to pose required and docking in deck assembly process; end effector provides mechanical interfaces with six-dimensional force sensor, acceleration sensor and deck, and realizes accurate positioning and reliable clamping simultaneously; six-dimensional force sensor is important sensor of intelligent robot, and it can detect all force information of three-dimensional space (Cartesian coordinate system) simultaneously, i.e. 3 force components and 3 moment components.

Project scheme is a kind of assembly scheme with participation of people. Operator shall finish state confirmation before deck assembly and in assembly process, robot will replace docking overturn function of original overturn trailer vehicle, and support function of original overturn trailer vehicle is realized through relatively light and simple support structures.

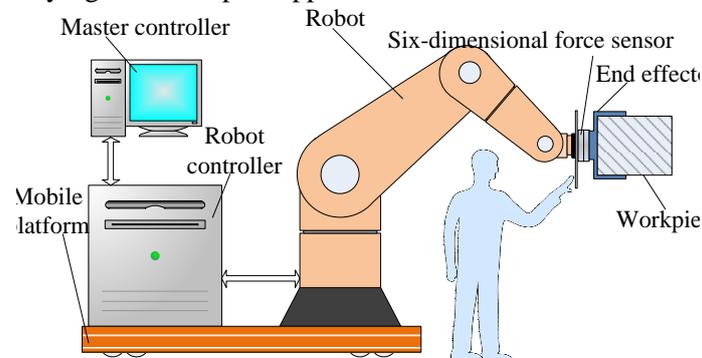


Figure 1. Diagram on System Composition

3. Flexibility control principle

3.1. End force perception

Six-dimensional force sensor is generally installed between robot and load, load gravity is imposed to six-dimensional force sensor, and to obtain acting force of the external to load through six-dimensional force sensor, effect on gravity of load and inertia force must be made. If there is no external force imposed to load, information on force and moment measured by six-dimensional force sensor is completely caused by load gravity. Under the condition, multigroup measured data of six-dimensional force sensor can be obtained by controlling robot to make load under different space postures, and least square method shall be utilized then to solve load weight and gravity center coordinate^[3,7].

Schematic diagram on effect of load gravity in six-dimensional force sensor coordinate system is shown in Figure 2, six-dimensional force sensor coordinate system is space rectangular coordinate system with 3 coordinate axes, i.e., X, Y and Z, and load gravity is G , coordinate of load centroid in six-dimensional force sensor coordinate system is (x, y, z) , and acting component force of load gravity G in X, Y and Z respectively is G_x, G_y, G_z , and applied moment of load gravity G to X, Y and Z respectively is M_{gx}, M_{gy}, M_{gz} , and according to relationship between force and moment, there is:

$$\begin{cases} M_{gx} = G_z \times y - G_y \times z \\ M_{gy} = G_x \times z - G_z \times x \\ M_{gz} = G_y \times x - G_x \times y \end{cases} \quad (1)$$

Measure and obtain multigroup six-dimensional force sensor data by selecting numerous different load poses, to solve and obtain coordinate of load centroid in six-dimensional force sensor coordinate system, (x, y, z) and size of load gravity G .

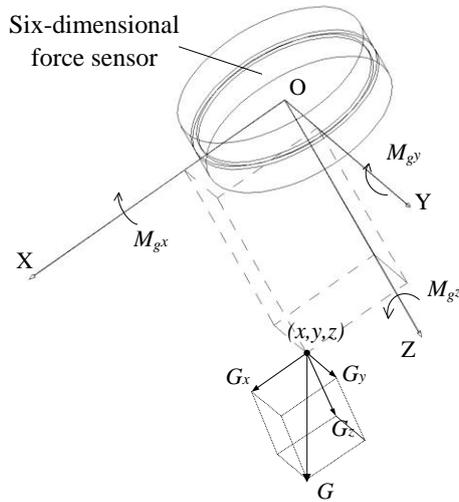


Figure 2. Schematic Diagram on Effect of Load Gravity in Six-dimensional Force Sensor Coordinate System

Assumed that 3 force components measured by six-dimensional force sensor under the condition that external force is imposed to load are F_x, F_y, F_z , and 3 moment components are M_x, M_y, M_z .

In flexibility control process, direction of load gravity in six-dimensional force sensor coordinate system changes with change of posture at end of mechanical arm. Through calibration to placement posture of mechanical arm, included angles, α, β, γ , between gravity direction and axis X, Y and Z of six-dimensional force sensor coordinate system can be obtained in real time through mechanical arm control system, and projections of load gravity in 3 coordinate axes of six-dimensional force sensor coordinate system can be calculated as follows:

$$\begin{cases} G_x = G \times \cos \alpha \\ G_y = G \times \cos \beta \\ G_z = G \times \cos \gamma \end{cases} \quad (2)$$

G_x, G_y, G_z are parts generated because of load gravity in force component F_x, F_y, F_z measured by six-dimensional force sensor, and substitute them and load gravity coordinate obtained, (x, y, z) into formula (1), to obtain M_{gx}, M_{gy}, M_{gz} , which are parts generated because of load gravity in moment component data M_x, M_y, M_z measured by six-dimensional force sensor, thus obtaining:

Components of external force in 3 coordinate axes are:

$$\begin{cases} F_{ex} = F_x - G_x \\ F_{ey} = F_y - G_y \\ F_{ez} = F_z - G_z \end{cases} \quad (3)$$

Components of external moment in 3 coordinate axes are:

$$\begin{cases} M_{ex} = M_x - M_{gx} \\ M_{ey} = M_y - M_{gy} \\ M_{ez} = M_z - M_{gz} \end{cases} \quad (4)$$

3.2. Flexible docking control

Schematic diagram on flexible docking is shown in Figure 3. When 2 docking surfaces approach to each other under unparallel condition, point contact or line contact will occur firstly, keep that contact force is within safety range, and adjust pose of workpiece installed according to force and moment information generated through contact to make 2 installation surfaces approach to each other continuously and turn to parallel until it is impossible to make approach under the premise that safety contact force is guaranteed, which means that installation surface docking is finished.

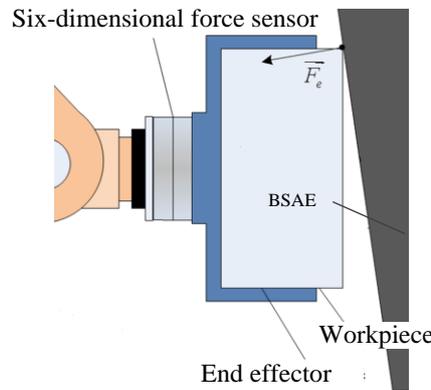


Figure 3. Schematic Diagram on Adjustment to Flexible Docking Pose of Mechanical Arm

Considering actual installation demand, in docking adjustment, in direction perpendicular to installation surface, it is required that contact force shall be kept within safety range, and in direction parallel to installation surface, workpiece shall still move along installation surface. Define robot base coordinate system in installation surface, which is recorded as BASE, and define axis Z perpendicular to installation surface with external direction being BASE, and after contact between workpiece and installation surface, external force imposed to workpiece, \vec{F}_e , is perpendicular to installation surface. Flexible docking control flow chart of mechanical arm is shown in Figure 4. In control, information on external force/ moment imposed to load is obtained in real time, and judgment control is made according to different external effect information:

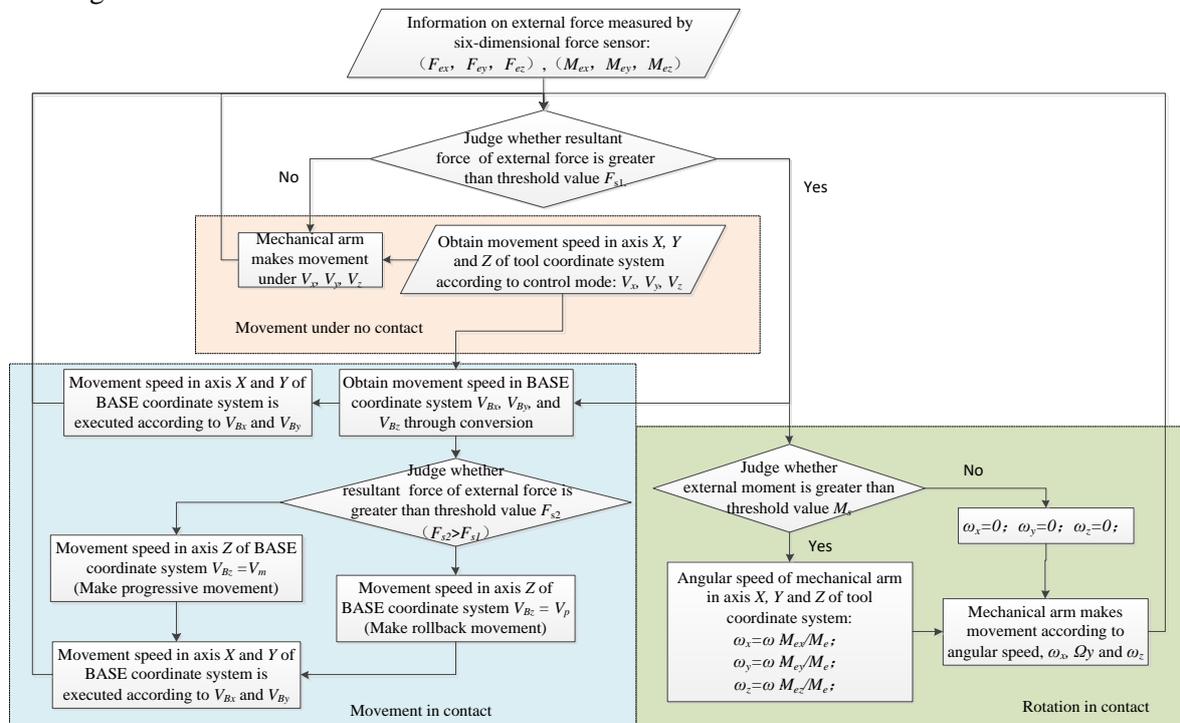


Figure 4. Flexible Docking Control Flow Chart of Mechanical Arm

3.2.1. *Movement under no contact*: judge whether resultant force $|\vec{F}_e|$ of external force is greater than threshold value F_{s1} preset, and if $|\vec{F}_e| < F_{s1}$, it is considered that there is no contact, and control movement of mechanical arm towards installation surface according to control strategy in free space; if $|\vec{F}_e| > F_{s1}$, it is considered that there is contact, control mechanical arm according to control strategy for force/position to realize flexible docking of workpiece.

3.2.2. *Movement in contact*: if $|\vec{F}_e| > F_{s1}$, it is considered that there is contact, and speed of BASE coordinate system in axis X , Y and Z shall be controlled independently. Convert coordinate system speed of robot tool for input control to component of BASE coordinate system in axis X and Y to obtain speed of BASE coordinate system in axis X and Y . Speed of BASE coordinate system in axis Z shall be fed back and controlled according to size of contact force. When $|\vec{F}_e| > F_{s2}$, workpiece will make rollback movement, and when $|\vec{F}_e| < F_{s2}$, workpiece will make progressive movement.

3.2.3. *Rotation in contact*: if $|\vec{F}_e| > F_{s1}$, it is considered that there is contact, and judge whether external moment $|\vec{M}_e|$ is greater than threshold value preset, M_s ; if $|\vec{M}_e| < M_s$, it is considered that no rotation is required, and if $|\vec{M}_e| > M_s$, then convert angular speed component of mechanical arm according to moment component, and adjust posture of workpiece.

4. Implementation flow

Logic control chart on robot auxiliary assembly flow system is shown in Figure 5.

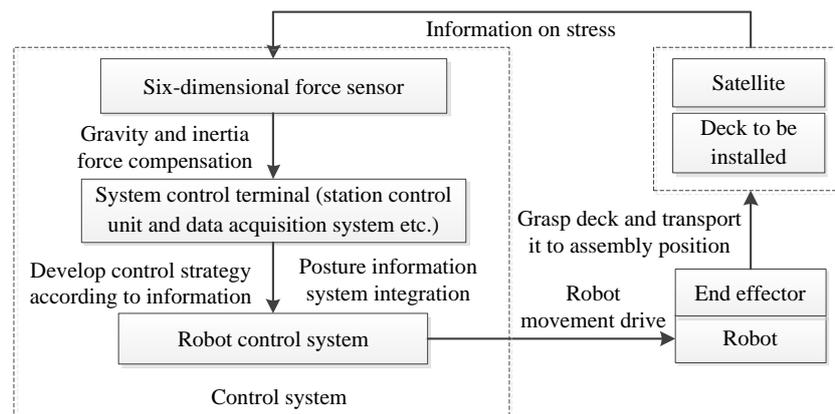


Figure 5. Logical Relationship Chart on Assembly Flow System

Utilize robot and six-dimensional force sensor to finish mass detection of deck at different poses, transmit mass detection data to upper computer through Ethernet and upper computer calculates weight of deck to be installed and centroid position, which means obtaining gravity compensation parameter of deck to be installed correctly.

Make manual traction to realize movement of end effector towards target location, large six-dimensional force sensor measures external force imposed to deck in real time, and develop mixed control strategy for force/ displacement to form control command.

Lower computer gains mixed control strategy for force/ displacement of upper computer and control command through RSI (Robot Sensor Interface), and robot drives motor to make movement according to direction of force/ moment imposed. Control robot to make continuous and compliant movement through real-time measurement feedback, to realize compliant force control in movement process.

Above process is coarse positioning process on large stroke (away from satellite) of deck to be installed. When deck to be installed approaches to target location, switch movement mode of robot to fine adjustment mode, so that robot can be operated under lower speed. Compliant force control mode will be adopted for compliant assembly of deck until docking requirements are met.

5. Application case and effect

5.1. Key point design

Compared with large-batch production line assembly, satellite deck assembly is characterized by small batch, and uncertain assembly station etc. Therefore, assembly scheme for satellite deck based on robot flexibility control principle must adapt to different assembly sites and working conditions of different assembly. In practical project application, following problems must be considered:

- Support structure used to match with robot must be light and convenient, and reduce demand to site space as much as possible;
- Robot must be provided with movable working platform, which is convenient for adjustment to relative pose relationship between robot and satellite;
- Height of movable working platform shall be proper, and ensure that movement envelope of robot can cover opening and closing route of deck;
- Choose model of sensor according to the maximum force and the maximum moment born by 6 DOF sensors in deck assembly process, and the maximum force and the maximum moment value of sensor must be greater than 1.2 times of practical application condition;
- In flexible docking process, line speed of deck in movement cannot exceed 6mm/s, and angular speed in rotation cannot exceed 1 %s, and ensure that operator has enough response time to stop robot under accident.

5.2. Application case

At present, assembly scheme for satellite deck based on robot flexibility control principle has been successfully applied to satellite. Full load weight m_1 of deck is 80Kg roughly, and the maximum size of deck cannot exceed 1500mm×1000mm. Design simple support structure as shown in Figure 6 by combining with practical application condition. Support structure consists of 2 parts, respectively being overturn support and holder. Overturn support is directly connected to deck, and robot finishes opening and closing of deck by grasping end effector on overturn support; holder can support overturn support and deck. Total weight m_2 of overturn support and holder does not exceed 20Kg, and load force arm L of centroid of composite solid constituted with deck to 6 DOF sensors does not exceed 500mm. Therefore, the maximum moment M imposed to 6 DOF sensors is as follows:

$$M=(m_1+m_2)\times L < (80+20)\times 0.5=500\text{Nm} \quad (5)$$

Model of 6 DOF sensors is determined as Omega190 of ATI Company (SI-3600-700, the maximum force is 3600Kg and the maximum moment is 700Nm). Model of robot is determined as KUKA-210 (the maximum bearing is 210Kg). Final assembly process of deck is shown in Figure 7.

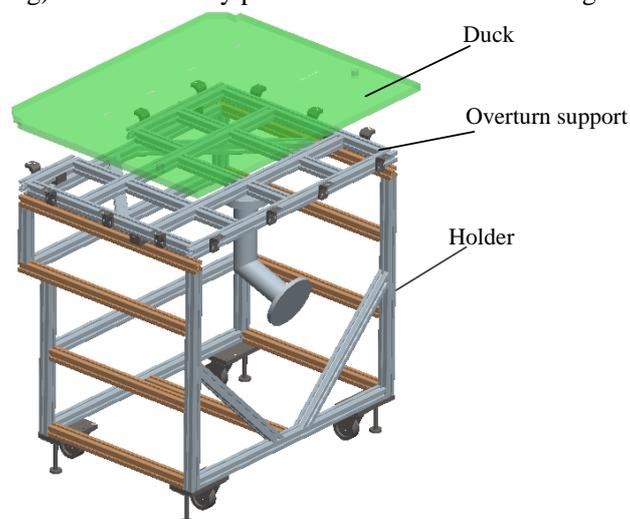


Figure 6. Schematic Diagram on Support Structure

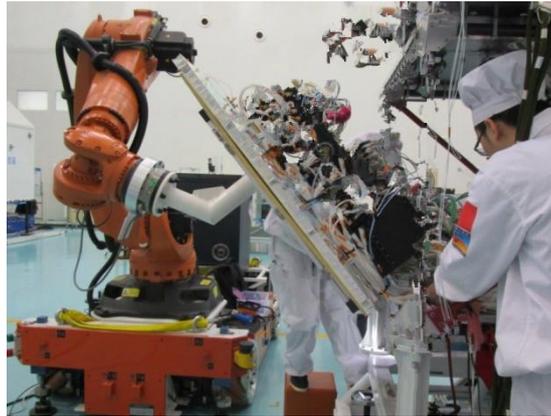


Figure 7. Assembly Process of Deck

5.3. Application effect

Compared with traditional deck assembly method, robot auxiliary assembly scheme has obvious advantages in work efficiency, reliability and universality aspects etc., which is shown in Table 1.

Table 1. Advantage of Robot Assembly Scheme

Aspect	Traditional method	Robot Assembly
Work efficiency	4-5 operators are required in deck overturn docking process, and operation time is 0.5~1 hour with low work efficiency.	3-4 operators are required in deck overturn docking process, and operation time is 0.5 hour roughly and work efficiency is improved obviously.
Reliability	Assembly process is rigid assembly, which may cause deck bruise and dowel clamping stagnation easily, and has high requirement to skill level of operator, with relatively bad reliability.	Assembly process is flexible docking, which avoids dowel clamping stagnation basically, and has low dependency to operator with high reliability.
Universality	Overturn trailer vehicle is developed through customization and can only be used for certain satellite.	Robots are general goods, and can be used for assembly process of other satellite.

6. Conclusion

Aimed at problems existing in satellite deck assembly process, assembly scheme for satellite deck based on robot flexibility control principle is proposed in this paper, and in virtue of end force perception and flexibility control technology of robot, high-efficiency and high-reliability installation of satellite deck can be realized. Assembly scheme for satellite deck based on robot flexibility control principle has certain universality, which can provide reference for assembly process of other similar large spacecraft component.

7. Reference

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