Design and Application of Satellite Automatic Angle Measurement System Based on Robot

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Abstract: In order to achieve the on-orbit performance of the satellite, the installation positions of some instruments on the satellite are measured when the satellite is integrated on the ground, to ensure the installation position and the accuracy meet the design requirements. With the development of aerospace industry, more and more satellites have the characteristics of difficult development, short development time and heavy position measurement task. In view of the mass produce of satellites, an automatic angle measurement scheme based on robots is designed and applied. Giving full play to the advantages of automation and high measurement efficiency of robots, this system effectively improves the measurement efficiency and reducing the occupancy of personnel.

1. Introduction
Some instruments such as sensors, inertial devices, thrusters, antennas, cameras and etc. have strict requirements of the installation position on spacecrafts. After installation, it is necessary to measure and adjust the installation position to ensure its on-orbit performance. The measurement and adjustment of the installation position accuracy is the alignment of spacecraft, which is an important guarantee for the reliable operation of satellites and on-board instruments[1-3]. In traditional measurement methods, the non-contact large-scale measurement system consisting of several theodolites is used to measure the accuracy of satellite assembly. Theodolite measurement system is a space angle intersection measurement system composed of several high precision electronic theodolites. The hardware equipment of theodolite measurement system is mainly composed of high precision electronic theodolite and reference ruler, interface, on-line cable, computer and so on. It adopts manual operation method. The batch production of satellites have short development cycle and heavy development task. There are a large number of instruments on the satellite which have the requirement of installation position accuracy. It is necessary to replace manual measurement by automatic method to improve measurement efficiency and shorten development cycle[4].

2. Principle and status of satellite precision measurement
Before the measurement, the whole satellite coordinate system is established, that is, the reference cubic prism is installed on the star, and the transformation relationship between the reference cubic prism coordinate system and the coordinate system established by the satellite-rocket interface is obtained by
the theodolite station arrangement. When measuring instruments on the satellite, the vector angle and
dimensions of the instrument in the whole satellite coordinate system are obtained through the
transformation relationship between the cubic prism coordinate system on the instrument and the
reference cubic prism coordinate system[5,6].

Theodolite angle measurement is to measure the angle between the mirror normal lines of cubic
prisms on different instruments, as shown in Figure 1.

![Figure 1. Principle diagram of satellite theodolite angle measurement](image)

L1 and L2 represent two different instruments. It is necessary to measure the angle between mirror
normal N3, N4 and L1 of cubic prism L2. In the measurement, firstly, theodolite T1 and T2 are
collimated with the mirror of L1 and aiming at each other to obtain the angle vectors of the normal lines
N1 and N2 of the cubic prism in the measuring coordinate system, then theodolite T2 and T2', T2', T2
are collimated with the mirror of the cubic prism L2 respectively, and the angle vectors of the normal
lines N3 and N4 of the cubic prism in the measuring coordinate system are obtained. Finally, the angle
between mirror normal N3, N4 and L1 of cubic prism L2 is obtained by matrix transformation.

The photograph of the angle measurement of the instrument on the satellite by manual manipulation
of theodolites is shown in Figure 2. The manual measurement method is inefficient, so it is necessary to
find an automatic method.

![Figure 2. Manual manipulation of theodolite angle measurement](image)
3. Automatic Angle Measurement Scheme for Satellite

3.1 Measurement System

The composition of the angle measurement system based on industrial robots is shown in Figure 3, which includes industrial robots, laser tracker, theodolite, end-effector, tracking target, vision-guided camera, AGV vehicle, cubic prism of the equipment measured on board.

The system uses robots to carry theodolites to measure the angle of instruments with high position precision on board. The robots can move to all the instruments on board by using AGV vehicle, so as to accomplish the omnidirectional measurement for all the instruments on the satellite. Laser tracker is used as the global guidance and precision control device in the system. Theodolite is the position measurement. The end-effector is used to fix and support the theodolite and the tracking target. The tracking target is used to establish the relationship between laser tracker and the end-effector. Through the end-effector, the relationship of theodolite, robot and laser tracker can be obtained. The vision-guided camera is used to read the collimated light in theodolite instead of human eyes.

Firstly, the relationship between theodolite coordinate system, the robot tool coordinate system and the laser tracking target is established by calibration. Secondly, the coordinate system of the tracker and the robot and spacecraft coordinate system need to be calibrated and unified. According to the theoretical position of the instrument to be measured in the satellite coordinate system. With the help of the real-time tracking, positioning and guiding technology of laser tracker, the theodolite can automatically and accurately collimate the measured equipment. Finally, the collimation information of theodolite at various positions is unified into the coordinate system of tracker to realize the automatic measurement of the attitude information of spacecraft equipment.

3.2 Measurement Scheme and Process

According to the measurement principle, the system needs four steps to complete the measurement: acquisition of theoretical position information, system calibration, model driven auto-collimation and coordinate system construction.

1) Acquisition of theoretical position information of equipment to be measured

The theoretical position values of the cubic prism attitude information of all the instruments to be measured are obtained from three-dimensional model, and it is used to drive the robot measurement system to the theoretical position.

2) System calibration

Before measurement, each subsystem needs to be calibrated, which includes three parts: calibration and rapid construction of satellite mechanical coordinate system, calibration and rapid construction of robot body coordinate system, and calibration of theodolite coordinate system at the end of robot. The
calibration of satellite mechanical coordinate system is to establish the relative relationship between the satellite mechanical coordinate system and the fixed target on the satellite supporting equipment, so as to facilitate the rapid establishment of the relative orientation relationship between the satellite and the laser tracker in the measurement field. The robot body coordinate system calibration is to establish the relative relationship between the robot body coordinate system and the fixed target on the robot base. It is convenient to quickly establish the relative orientation relationship between the robot and the laser tracker and calibrate the robot in the field. Calibration of theodolite coordinate system at the end of robot is to determine the relative orientation relationship between theodolite coordinate system and flange coordinate system at the end of robot and laser tracking target respectively.

3) Automated collimation

After completing the overall calibration of the system, it is necessary to import the theoretical position and orientation information of the cubic prism in the satellite mechanical coordinate system into the measurement software. The robot can be driven to carry theodolite to achieve rough alignment of the equipment under test by three-dimensional model transformation operation, and then the automatic and precise alignment of the equipment under test can be achieved by combining the technology of vision-guided alignment.

4) Reconstruction of instrument coordinate system

The normal vector of the cubic prism obtained by collimating is in the theodolite's coordinate system. However, for the collimation of different cubic prisms, the orientations of theodolite's coordinate system are different. In order to determine the relative attitude matrix between different cubic prisms, the results of collimation at different positions will be unified in the same coordinate system to complete the reconstruction of instrument coordinate system.

4. Verification

The system is integrated and tested, and the indicators of the system are verified by experiments. Cubic prisms with orthogonal planes whose values were obtained by metrology testing are employed. The two orthogonal planes of Cubic prisms distributed in different positions and attitudes are measured by this automatic measuring system based on robot. The angle between the two planes is calculated according to the measuring datum. The measurement errors are obtained by comparing with the standard values of the cubic prisms. As shown in Table 1, the test results show that the measurement error of the system is better than 15", and it has high measurement accuracy, which can meet the requirements of the satellite.

| Planes          | Angles of the normal vector (°) | Angles of the two planes by measuring (°) | Angles of the two planes by metrology (°) | Error (") |
|-----------------|---------------------------------|------------------------------------------|-------------------------------------------|-----------|
| CP1-P21         | 0.495958 0.8283879 0.26038228   | 89.99745                                 | 89.9992                                   | 6.3       |
| CP1-P22         | -0.85738 0.5146662 0.0040613    |                                          |                                          |           |
| CP2-P11         | 0.476782 0.8019360 0.3596843    | 89.99608                                 | 89.9993                                   | 11.6      |
| CP2-P12         | -0.85761 0.5142100 0.0096010    |                                          |                                          |           |
| CP3-P11         | 0.515287 0.8570135 0.00268953   | 89.99608                                 | 89.9995°                                 | 12.3      |
| CP3-P22         | -0.84285 0.5074933 -0.1790332   |                                          |                                          |           |

* * In this table, CP is short for Cubic Prism.
* * In this table, P is short for Plane.
5. Application
The robot-based automatic measurement system is applied to the installation position angle measurement of instruments on the satellite. The application picture is shown in Figure 4. According to the statistics of measuring process time, the measuring time of a single cubic prism on the instrument is less than 15 minutes based on the automatic measuring system of industrial robots. The measuring time is at least 30 minutes by traditional manual method with 3 persons. Therefore, the efficiency is increased[7].

![Figure 4. Application of automatic angle measurement system based on robot for satellite](image)

6. Conclusion
In this paper, an automatic angle measurement system based on robots is designed, which is aimed at to be instead of the manual manipulation of theodolites. After design, the system is integrated and applied on the instrument position measurement for satellite. The measurement efficiency is improved and the occupancy of personnel is reduced.

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