Development and application of lifting and levelling system for space station

Wang Pengfei¹, ², Zhang Xiaodong¹, ², Xing Shuai¹, ², Liu Tonghui¹, ², Zhang Chengli¹, ²

¹Beijing Institute of Spacecraft Environment Engineering, Beijing, 100094;
²Beijing Engineering Research Center of the Intelligent Assembly Technology and Equipment for Aerospace Product, Beijing, 100094
wangepengfeimisha@163.com

Abstract. In this paper, the characteristics of the hoisting assembly process of the space station are analysed. The adjusting parameters of suspension under different eccentric conditions are explored. The scheme of the hoisting levelling system during the hoisting process of the space station is put forward, and various levelling means are given. Through collecting and analysing the geometric parameters of the distance from the horizontal plane during the hoisting process, the relative position and posture of the space station and the horizontal plane under the current state are obtained. Through theoretical calculation and analysis model, the levelling control software is compiled, and the automatic levelling of the space station is realized. The feasibility and accuracy of the design scheme are verified by laboratory results and actual levelling analysis. The controllability, stability, convenience and safety of the space station hoisting operation are improved.

1. Preface
The space station in China includes the core module, the experimental module I and the experimental module II. The basic configuration of the space station is composed of rendezvous, docking and the transposition module. The final space station was identified as a combination of three 20-ton class sections. The space application capacity is increased to approximately 20t. During the development of space station, the hoisting process is numerous and very critical. There are a large number of cabin sections, the overall vertical lifting of the cabin combination, and the docking of the cabin and the docking of the cabin and tooling under different working conditions.

The crane in the assembly and implementation site of the spacecraft hoisting operation is the power source for lifting. Under the existing assembly conditions, the attitude of the spacecraft hoisting process is completely dependent on the eccentricity of the cabin and the adjustment ability of the spreader; it mainly relies on the skills of the final assembly operator. At this stage, the spacecraft hoisting mode is a special spreader that is matched with the spacecraft. The levelling method of the spacecraft is to observe the tilting condition of the spacecraft by hand and judge the size and direction of the eccentricity according to experience, and adjust the level of the cabin by adjusting the size and position of the weight or adjusting the size of the lock. When the level meets certain requirements, the spacecraft will be lifted or docked. Unstable operation, excessive dependence on people and experience judgment are the main shortcomings of current lifting, which seriously restricts the operability of large cabin docking and the success of docking.
Figure 1(a). The Section Docking of Japanese JAXA freight spacecraft.

From the figure 1, it can be seen that the hoisting of large spacecraft depends only on manual observation of the spacecraft's level to adjust, which will cause repeated adjustment of the level of the spacecraft during the hoisting process. The phenomenon seriously affects the operational feasibility and the reliability of hoisting, and there are hidden dangers of hoisting safety.

In order to satisfy the reliability and one-time success of large spacecraft docking in the space station, it is urgent to introduce leveling control means in the process of cabin hoisting to complete the automatic leveling control of spacecraft by means of automatic solution.

2. Analysis of the overall requirements of levelling system

During the assembly of the space station, the horizontal leveling of the cabin is mainly the vertical docking of the cabin and the vertical docking between different cabins. The number of space station cabins is large, and the working conditions of vertical docking are more than 20 kinds. The structure of the spreader used in the docking process of the actual space station cabin is shown in figure 2.

Figure 2. Large-scale lifting of space station.

Space station products are usually docked by lifting at 4 o'clock during the lifting process. The length adjustment of the spreader is realized by adding a "flower basket screw" to the spreader during the lifting process. In the case that the cabin cannot be lifted at 4 o'clock, the spreader is disassembled, and the cabin is lifted and docked by means of lifting at 2 o'clock. In this state, the adjustment of one direction is realized by adding a "flower basket screw" on the spreader, and the horizontal adjustment of the other direction is realized by increasing the weight, thereby, finally achieving the level of the docking process cabin. The adjustment of the spreader ensures the success of the docking. However, the existing docking process has the following disadvantages through the above analysis. Main disadvantages are as follows:
1) The size and position of counterweight and the adjusting length of "flower basket screw" can only be judged qualitatively and adjusted by experience.

2) The level of hoisting docking surface needs repeated hoisting to accurately leveling, with high operational risk and large adjustment workload.

3) The eccentricity of the cabin is complex, the eccentricity values are uncertain and the process parameters are unstable.

In view of the shortcomings of the existing docking process, it is necessary to carry out in-depth research on leveling mechanism and leveling method, which can solve the problem of docking and leveling of space station cabin, improve the controllability, stability, convenience and safety of cabin hoisting. Therefore, the hoisting leveling system developed needs to meet the following functions.

1) The horizontal attitude of the hoisting cabin is monitored and the adjustment parameters of the cabin during hoisting are quantitatively analyzed.

2) After quantitative analysis, the actual hoisting level of the cabin is less than 5 mm/4 m.

3) After introducing the leveling system, the average leveling time of the cabin can be completed in 20 minutes.

4) The software of hoisting leveling system is convenient to use and easy to operate.

5) The leveling process can achieve the adjustment accuracy of less than 2 mm.

3. Analysis of the adjustment scheme

The lifting leveling jig of super-large spacecraft is used to complete leveling task by coordinating and controlling the length change of the sling. It is a space cooperative flexible parallel configuration equipment, which has the characteristics of flexible parallel robot. Because of the use of flexible cables instead of rigid connecting rods as driving elements, flexible parallel robots overcome the shortcomings of traditional rigid parallel robots in working space and moment of inertia, and it has the characteristics of simple structure, large workspace, easy disassembly and reconstruction, fast movement speed and strong bearing capacity.

According to the structure form of the space station hoisting system, the three-dimensional model of the cable-driven parallel mechanism of the space station is established. The suspension structure can be divided into two flexible parallel mechanisms, the upper and the lower, as shown in figure 3, figure 4 and figure 5.

The upper parallel mechanism consists of fixed platform A, inclined sling and moving platform B. The lower parallel mechanism consists of moving platform B, vertical sling and moving platform C. The position and posture of moving platform B or C can be changed by adjusting the parallel mechanism of upper and lower cables, so as to achieve the purpose of leveling.

Figure 3. Modeling of Space Station Lifting System.
3.1. Upper parallel spreader leveling

The inclined cable leveling method: At first, it is necessary to ensure that the length of the four inclined slings remains unchanged. By adjusting the four inclined slings of the parallel adjustment platform on the space station hoisting system, only three oblique slings need to be adjusted during the adjustment process, and the other one is kept constant. And the straight line of the four oblique slings is compared with a point, wherein the intersection point is constant under the hanging point on a vertical straight line, and at the same time, the lengths of the four straight slings under the space station hoisting system are equal, that is, the space station hoisting system platform is guaranteed B is parallel to platform C.

According to the schematic diagram of the inclined line of the space station hoisting system, through calculation, the two coordinate components \( x_0, y_0 \) of the centroid in the centroid coordinate system are obtained. By adjusting the length of the cable, the coordinate component of the lifting point in the coordinate system \( C-x_1y_1z_1 \) is adjusted to \( x_0, y_0 \). During the adjustment process, the vertical sling length \( h_2 \) is kept unchanged, and one of the slings \( l_1 \) is kept unchanged, the adjustment lengths \( \Delta l_2, \Delta l_3, \Delta l_4 \) of the remaining three oblique slings can be derived from the geometric relationship.

3.2. Lower parallel spreader leveling

Lower parallel vertical rope leveling method: the length of the four inclined slings above the space station hoisting system is the same, but it is required that the straight line of the four oblique slings intersect at a point, where point A is constant below the hanging point in the vertical on the straight line. The model achieves the leveling of the cabin by adjusting the length of the four slings under the space station hoisting system. Initially, the length of the four slings is kept constant, and only the length of three of them is adjusted during the adjustment. After reaching the level, the space station hoisting system is not parallel to the cabin.

Because of the size parameters of each link of the spreader system are known, by calculating the three coordinate components \( x_0, y_0, z_0 \) of the centroid in the centroid coordinate system, the rotation angles \( \alpha, \beta \) of the space station hoisting system in two directions can be obtained. Keeping the length of the four inclined slings above the space station hoisting system unchanged, while keeping the length \( l'1 \) of one of the vertical slings unchanged, the length of the other three vertical slings \( \Delta l'2, \Delta l'3, \Delta l'4 \) can be obtained by geometric relationship.

3.3. Weight Compensation system

Balance compensation square adjustment: the length of the four inclined slings above the space station hoisting system is the same, but it is required that the straight line of the four oblique slings intersect at a point, where point A is constant below the hanging point in the vertical on the straight line. First, by adjusting the length of the four slings under the space station hoisting system, the length of the slings

4
is the same and the length is kept the same. By adding a counterweight, the coordinates of the eccentricity of the cabin can be measured and calculated. Therefore, the quality and position of the weight to be added on the platform B or the platform C can be obtained to compensate for the eccentricity of the cabin and to make the cabin level.

3.4. Summary
In summary: by analyzing the structure of the space station hoisting system, the corresponding leveling principle is obtained. The cabin leveling can be realized by adjusting the length of the inclined sling, the length of the vertical sling, and adding the weight. In the actual operation process, different leveling schemes can be selected according to the convenience of operation, and the cabin docking process can be safe, reliable.

1) Adjust the length of the diagonal strap: By adjusting the length of the inclined sling to adjust the attitude of the platform B, the platform B can be leveled, so that the cabin reaches a level.

2) Adjusting the length of the vertical sling: By adjusting the length of the vertical sling to adjust the attitude of the platform C cabin, the cabin level can be made.

3) Adding weight: By adding a counterweight to the platform B or the platform C, the posture of the cabin is adjusted to make the cabin level.

4. System design
4.1. Overall scheme of motion control system
After the modification of the space station spreader system, the spreader adjustment system adds an angle measuring sensor to realize the flatness information of the lifting process of the cabin in real time. For the entire operating system, you first need to set the initial conditions, and then need to carry out the first lifting; after measuring the required data, By adjusting the length of the basket screw again, the cabin is lifted again to achieve cabin leveling.

Figure 6. The schematic after the modification of the space station hoisting system.

4.2. Visualization software design scheme
The software system is developed based on the matlab programming language under windows system. By directly adopting the advanced computing language of professional data calculation and numerical analysis, the simplification and accuracy of programming is realized.

In the process of using the space station leveling control software system, the parameters of the space station hoisting leveling process are obtained through a series of processes such as data acquisition, analysis, transfer and processing in the hoisting process. The attitude of the cabin is collected in real time; the user is allowed to monitor the lifting and leveling process. The software uses simple and friendly human-computer interaction interface to display measurement data and calculation result data in real time. It is used to measure the lifting posture of the hoisting product and monitor the lifting process in real time, which can effectively assist and guide the operator to complete the lifting operation. Its leveling interface is shown in figure 7.
5. System performance verification

5.1. Laboratory Model Verification
The test verification model was built by using aluminum profiles, slings and other materials to verify the rationality of the adjustment principle. A test verification model as shown in Figure 8 was built to verify the accuracy of the leveling spreader length adjustment algorithm.

| Cross Beam Weight | Adjusting the length of suspension chain | Distance between lifting points | Chain weight | Upper chain length |
|-------------------|-----------------------------------------|-------------------------------|--------------|-------------------|
| 9.6kg             | 1320mm                                  | 1800mm                        | 2kg          | 1500mm            |

According to the specific parameters of the spreader used in the laboratory, the adjustment parameters of the spreader under different loads are analyzed, and the adjustment parameters of the spreader are obtained by the calculation software. After the test, the calculation result is correct, and the simulation software can be applied to the docking process of the space station cabin. The specific test process parameters are shown in table 2.
Table 2 Test model leveling parameter table

| Counterweight position | Centroid coordinates | Chain length | Regulation quantity | Post conditional state |
|------------------------|----------------------|--------------|---------------------|------------------------|
| Xaxis-2kg*500mm        | (73.529mm, -73.529)  | 1320mm       | l₁-52mm, l₂, l₃, l₄-52mm | level                 |
| Yaxis-2kg*500mm        |                      |              |                     |                        |
| Xaxis-5kg*500mm        | (-127.55mm, -102.04mm) | 1320mm       | l₁-83.48mm, l₂+10.25mm, l₃, l₄-93.73mm | level                 |
| Yaxis-5kg*400mm        |                      |              |                     |                        |

5.2. Physical verification of space station cranes

After verification by the experimental model, it is proved that the adjustment theory is correct and the software analysis is reliable. The test of the specific working condition can be carried out on the space station cabin. The test state is shown in figure 9. The parameters of the space station spreader are shown in table 3. The specific test parameters are shown in table 4.

Table 3 Space Station Lifting Parameters Table

| Cross hanger quality | Adjusting the length of numerical suspension chain | Distance between lifting points | Chain weight | Upper chain length |
|----------------------|----------------------------------------------------|---------------------------------|--------------|--------------------|
| 2910kg               | 6942mm                                             | 4900mm                          | 4810kg       | 1977mm             |

Table 4 Simulated parameters table of suspension leveling for space station

| First lifting parameter | 538mm | 506mm | 511mm | 541mm | Maximum difference: 35mm |
|-------------------------|-------|-------|-------|-------|-------------------------|
| adjustment              | +37.5mm | -5.5mm | 0     | +43mm | /                       |
| Adjusted distance from ground distance parameter | 557mm | 555mm | 553mm | 556mm | Maximum difference: 35mm |

Through the verification of the space station hoisting system, it is proved that the theoretical calculation model of the space station is correct, and the calculation control software is reasonable, which can meet the leveling function of the space station cabin during the hoisting process. The relevant performance of the leveling system meets all the requirements through the test verification, the performance of the leveling system is shown in table 5.

Table 5 The performance of the leveling system

| entry name               | Requirement index | measured value |
|--------------------------|-------------------|----------------|
| Regulating range         | ±200mm            | ±250mm         |
| Internal accuracy of 4m  | Accuracy is better than 5mm | 4mm          |
| Computation accuracy     | Accuracy is better than 1mm | 0.1mm        |
| Leveling time            | ≤20min            | 15min          |

6. Concluding remarks

According to the characteristics of space station hoisting leveling, this paper presents a scheme of visual and accurate hoisting safety monitoring system. Through the collection and analysis of hoisting process data, the horizontal position and posture of the cabin can be obtained. The real-time monitoring of the hoisting process can be realized by real-time acquisition of the level information of the cabin through angle sensor, and quantitative guidance and assistant operation of spacecraft cabin hoisting can be achieved. The hoisting leveling system has strong versatility, which can be used for hoisting leveling and process analysis of similar products. It will play an important role in improving the safety of production in enterprises. In the future, the system can integrate stress sensors, at the
same time, it can adjust lifting gear with electric adjusting device to realize the automatic leveling design of the whole lifting system.

References
[1] Zhou Jianping General conception of space station project in China Manned Spacelight.2013,19(2):1-10
[2] Wang Yongzhi Launching manned space station project and promoting the development of Chinese manned space. engineering Manned Spacelight. .2011, 17(1):1-4
[3] Du Ruizhao,Hu Ruiqin,Xing Shuai,He Yun Analysis of Application of Hydraulic Positioner in Spacecraft Hoisting Journal of Jianghan University Natural Science Edition.2015,43(6):566-570
[4] Dong Yaohui Research on flexible assembly method of aerospace products based on Digitalization Chinese Aerospace Science and Technology Corporation Digital Manufacturing Forum. 2011
[5] Fan Rongqian Key technology research on visual measurement based on machine vision Chongqing University, Chongqing, China, 2014
[6] Zhu Weijie, YU Xiangzhen Design of self-adaptive reverse radar based on ultrasonic ranging Auto Electric Parts.2009(4):15-17
[7] Park F C, Martin B J Robot Sensor calibration solving AX=XB on the euclidean group IEEE Transactions on Robotics & Automation, 2002, 10(5):717-721
[8] Geng Yongfeng, Chen Feng 6-6 rope traction parallel lifting equipment pose space and azimuth space research Science and technology information. 2007 (20): 28-29
[9] Li Chenggang, Wang Huaming, Zhu Jianying Dynamics analysis of 2-DOF spherical parallel mechanism Transactions of Nanjing University of Aeronautics&Astronautics, 2009, 26(2): 95-100
[10] Murray M Optimised assembly mode reconfiguration of the 5-DOF Gantry-Tau using mixed-integerprogramming Meccanica,2011,46(1):101-111
[11] EVERIS T, JACOB M. A System for in-space Assembly IEEE International Conference on Intelligent Robots and Systems,2012,(3):2356-2361
[12] HUNT K H Structural kinematics of in-parallel-actuated robot-arms Journal of Mechanism Transmissions, and Automation in Design,1983,105(12):705-712
[13] SOKOLOV A,XIROUCHAKIS P Dynamics analysis of a 3-DOF parallel manipulator with R-P-S joint structure Mechanism and Machine Theory,2007,42(5):541-557
[14] HU B,LU Y New approach for analyzing the stiffness of 3-PRS parallel manipulator Journal of Mechanical Engineering,2010,46(1):24-29