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Introduction of measurement and control technology of FAST

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ABSTRACT

Five-hundred-meter Aperture Spherical radio Telescope (FAST) is a Chinese mega-science project to build the largest single dish radio telescope in the world.

Being the most sensitive single dish radio telescope. It was completed and put into use in September 2016. Its innovative engineering concept and design pave a new road to realize a huge single dish in the most effective way. The idea of sitting a large spherical dish in a karst depression is rooted in Arecibo telescope. FAST is an Arecibo-type antenna with three outstanding aspects: the karst depression used as the site, which is large to host the 500-meter telescope and deep to allow a zenith angle of 40 degrees; the active main reflector correcting for spherical aberration on the ground to achieve a full polarization and a wide band without involving complex feed systems; and the light-weight feed cabin driven by cables and servomechanism plus a parallel robot as a secondary adjustable system to move with high precision. The common feature of the latter two innovations is the transformation of large scale rigid structures into large scale flexible structures. To realize precise real-time control, the challenge of measurement and control technology is very challenging. This review intends to introduce the implementation methods, the recent progress, results, problems and future development of FAST measurement and control.

Keywords: Radio Telescope, FAST, Measurement and Control

1. BACKGROUND INTRODUCTION

The Five-hundred-meter Aperture Spherical radio Telescope (FAST) is a Chinese mega-science project funded by the National Development and Reform Commission (NDRC).The project investment is 1 billion 180 million, the construction period is 5.5 years, the construction is completed in September 25, 2016, and it is now entering the debugging stage. The innovative engineering concept of FAST creates a new model for building a giant radio telescope with low cost. It is the most powerful single aperture radio telescope in the world. It will maintain the status of the world's first-class equipment in the next 20~30 years. It is of great significance to improve the research level and international status in the field of astronomy in China[1-4]. Figure 1 is a FAST photo.

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Fig.1 FAST photo

The basic structure of radio telescope has three main parts -- reflector, receiver and pointing device. The radio signals from space celestial bodies are extremely weak. To read the information on the edge of the universe needs large aperture telescopes. Astronomical telescopes are developing towards the trend of large-scale and giant. Due to the deformation caused by self weight and wind load, the maximum diameter of the traditional telescopic telescope can reach 100-150 meters. Before 2016, the Arecibo telescope is the largest single dish radio telescope in the world. Its 305 meter aperture reflector is a fixed spherical structure, which can't be adjusted with the moving of the observation target, which limits the observation ability of the telescope.

Fig.2 Green Bank Telescope, USA Arecibo Radio Telescope, USA

FAST has three outstanding aspects: the unique the largest, round and deep Qiannan karst depression as the site; The second is active reflector during observation the surface will deform into paraboloid to correct spherical aberration on the ground to achieve full polarization and a wide bandwidth so we can use conventional feeding technology; Third, light cable drive feed support technology. If FAST adopts Arecibo technology to realize the cabin suspension it will be some ten thousand tons steel material in the air which is no practical. The quite light focus cabin is only have weight 30 tons. This structure will shake on the wind impact, so secondary adjustable system inside be used to carry the feed. The core of innovation is the active reflector technology and the light focus cabin.

Active reflector technology: the FAST reflector is composed of cable net supporting structure, reflector unit and actuator. See Figure 2, The triangular reflector unit is laid on the main cable net, and the actuators are fixed on the depressions, connecting the main cables with the down link cables, and controlling the deformation of the main network. The 500 meter caliber ball crown is initially stretched into spherical surface, and the 300 meter aperture instantaneous paraboloid is formed by 2226 actuators stretching and pulling down to control the main cable net to gather electromagnetic wave to realize the tracking observation.. Figure 3 is the structure of the reflector and the working principle.

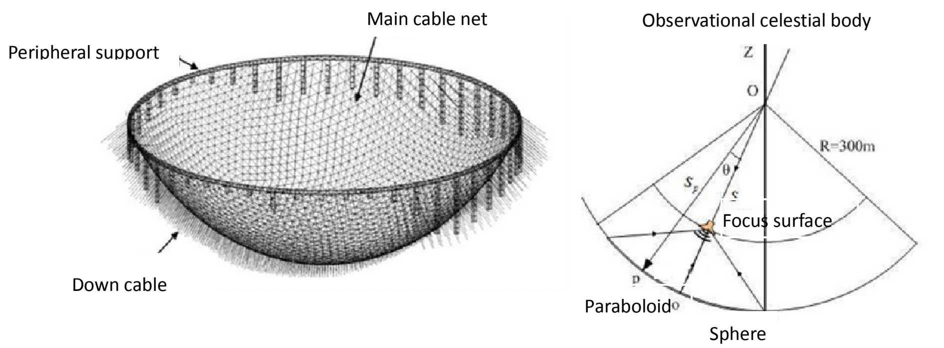


Fig.3 Reflection surface structure and working principle diagram

Light cable drive feed support technology: The feed support system consists of six supporting towers, six lasso and drive, a feed cabin and one cabin platform. The core task of the feed support is to drag the feed to the focus of the instantaneous parabolic. It was be formed of the active reflector. The feed cabin is suspended on 6 towers by 6 cables, and the feed cabin is located rough positioning by adjusting the length of the cable. The 6 leg parallel robot in the feed cabin can drive the precise position control of the different band receivers. The multi cabin receiver will be installed in the feed cabin, which will cover the working frequency of 70MHz-3GHz. The cabin platform provides a maintenance port for the feed cabin.

FAST consists of several parts, including site, active reflector, feed support, measurement and control, receiver and terminal, and observation base.

The two core innovation generalities are real time transformation. The maximum observation frequency of the FAST telescope is 3GHz. The location accuracy of reflector node adjustment is 5mm, and the measurement accuracy is 2mm. The location accuracy of the feed cabin's real-time positioning is up to 10mm, and the accuracy of measurement is 3mm. Near the kilometer scale, the 300 meter height difference, many nodes flexible cable control to achieve the real-time positioning requirements of millimeter level, is very challenging for the measurement and control system. Our team had nowhere to turn for research reference or inspiration. it's hard to find data from other projects.

The FAST measurement and control system includes four parts: telescope central control, time benchmarks and position datum, active reflector measurement and control, feed support measurement and control. This review intends to introduce the implementation methods, the recent progress, results, problems and future development of FAST measurement and control.

2. TELESCOPE CENTRAL CONTROL

The telescope's central control connection and coordination of all subsystems include active reflector, feed support, measurement and control, receiver and health monitoring, so as to make it run in an orderly and efficient way. The main functions are observing task management and sending out, storing feedback data, providing convenient data access interface, monitoring system status and fault response[5].

After the telescope is built, all functions of the central control have been realized and can be well coordinated with the telescope.

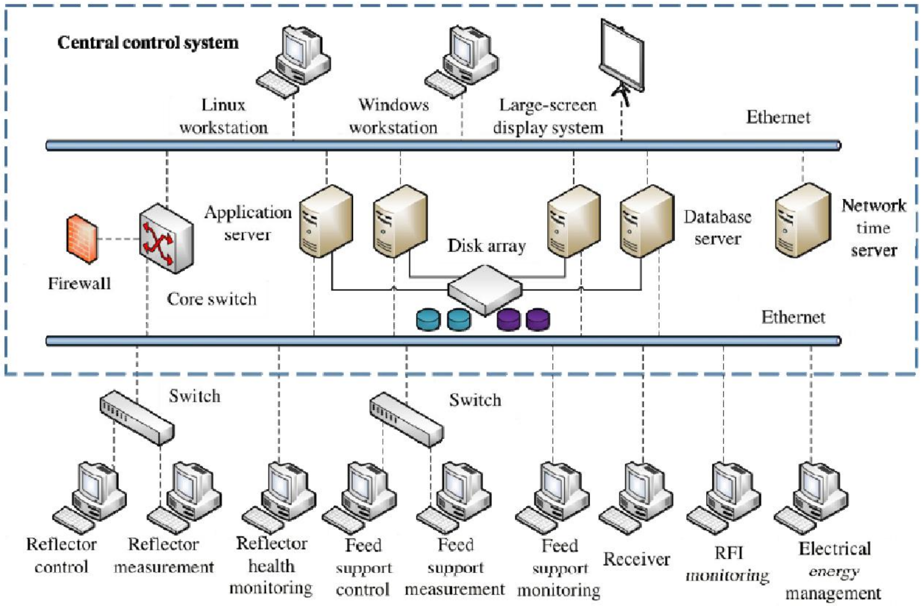


Fig.4 Hardware connection of central control

3. TIME BENCHMARKS AND POSITION DATUM

There is no rigid connection between the focus of FAST's reflector and the receiver，therefore the movement of the feed cabin and the deformation of the reflector are independent. When they change and move in the three-dimensional space, it is necessary to keep the relative relationship unchanged and need the common time datum and the measurement control relative to the same inertial coordinate system.

3.1 Time Benchmarks

The network time server consists of high precision GPS timing receiver, high precision clock oscillator, industrial mainboard, LAN and serial port, which are integrated into a standard 1U case. The system is based on embedded Linux with satellite timing and computer time synchronization function. Central control system and other subsystems use LAN port time synchronization by NTP, the time precision is about 1 millisecond.

3.2 Position Datum

In order to coordinate the operation of active reflector and feed support, establishing a set of stable inertial reference frame is the most basic requirement to achieve high precision control.

23 measurement control points have been built in the depression, , as shown in Figure 5. The measurement control point

is the concrete column, the bottom diameter is large and the base extends to the base rock, which provides a stable foundation for the base pier; the upper diameter is small and is worn out from the reflector panel to reduce the impact on the structure of the panel. The pier is a double-layer structure, and the outer layer protects the inner pier from wind, sunlight and vibration; the outer upper platform is separated from the inner layer for personnel operation. Three measuring equipment or targets can be installed at the top of each pier, and there is a leveling point at the bottom and top of each pier to monitor the change of pier.

The height of the piers is 6.8-20.6m. The 23 piers consist of 3 rings, the inner ring, the central ring and the outer ring. The diameter of the inner ring (JD1~JD5) is about 40 meters; the diameter of the middle ring (JD6~JD11) is about 200 meters; the outer ring (JD12~JD23) is about 400 meters in diameter; and the JD24 is outside the reflector on the top of the hill.

Measurement control network requirements: Astronomical Orientation Accuracy of 0.5 ", JD1~JD11 point accuracy 1.0mm, JD12~JD23 point accuracy 1.5mm. After the completion of the pier construction, three phase measurements were carried out.

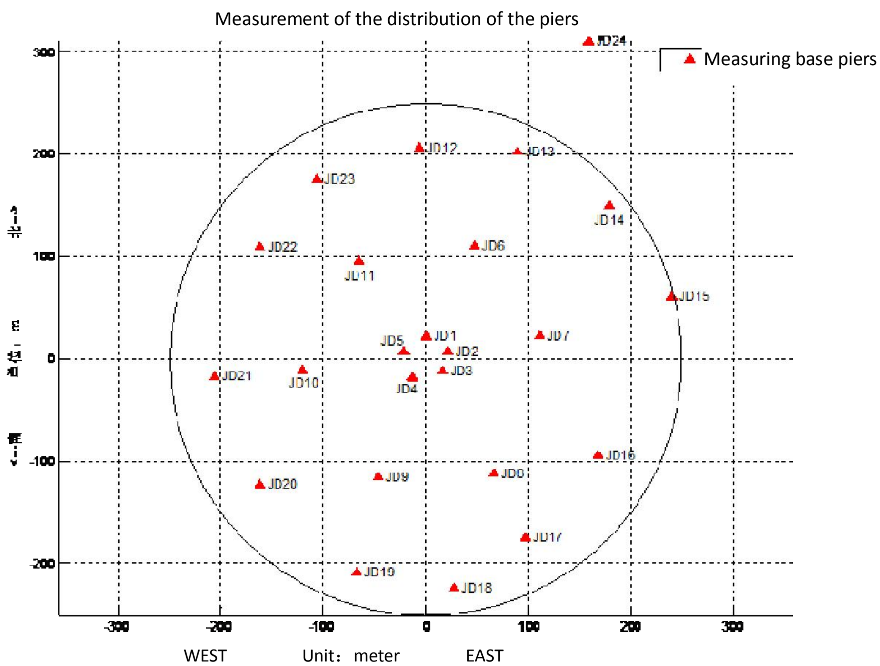


Fig.5 Piers distribution map

- **Astronomical Orientation**

The JD9 base pier is chosen as the measuring station, and the JD4 pier is taken as the target point. It is measured in 7 periods, and the true northern position angle of the reference edge is measured.The astronomical azimuth measurement is carried out using the Polaris arbitrary time angle method, and the three measurements are made. In November 2015, the first time, middle error: 0.17 "; second in February 2016, middle error: + 0.19"; third times in April 2016, middle error: 0.18 "; meet the requirement of precision.

- **Position coordinate measurement of base piers**

Measuring the location of piers by separate height and level measurements. Elevation using leveling. A two-dimensional network measurement method is used for the horizontal measurement. Based on the average of three measurement data, the measurement results are analyzed. The accuracy is shown in Table 1, figure 6-8.

Table 1. coordinate measurement accuracy of piers (mm)

	I	II	III
X axis	0.2226	0.1488	0.2237
Y axis	0.2723	0.1734	0.1898
Z axis	0.3435	0.2124	0.1869

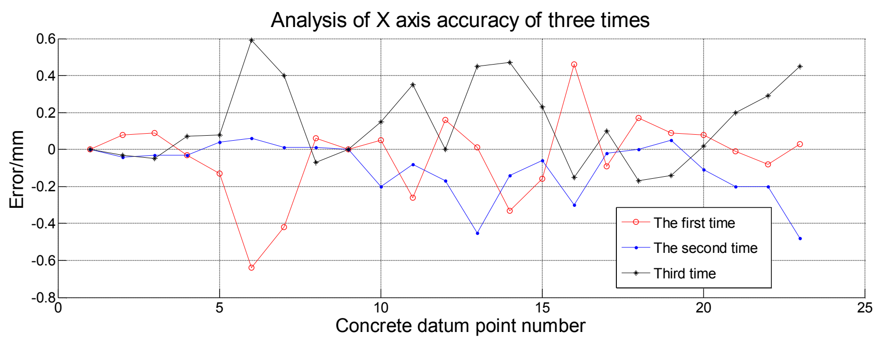


Fig.6 Analysis of x axis

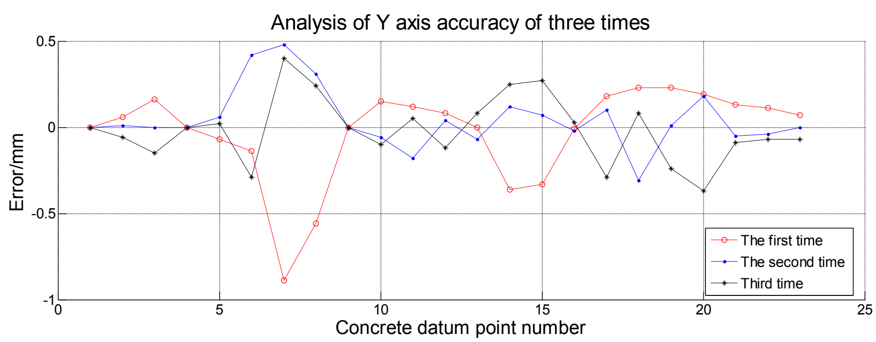


Fig.7 Analysis of y axis

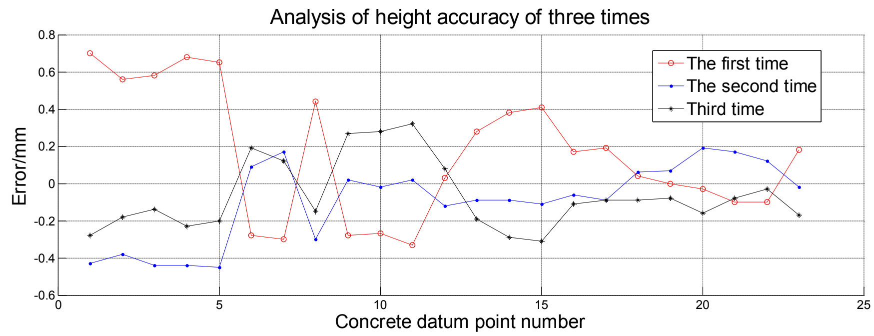


Fig.8 Analysis of z axis

4. ACTIVE REFLECTOR MEASUREMENT AND CONTROL

4.1 Active reflector control

The active reflector control system is divided into three layers: the master control room server, the relay room PLC and the terminal actuators. The central control indoor installation reflector control server, the OPC communication server, the operator station, etc. are connected by the Ethernet protocol to the controllers of the 12 relay rooms by the Ethernet protocol, as shown in Figure 9. Each relay room is equipped with a SIEMENS CPU315-2 PN/DP and 4 DP network modules CP342-5, CPU has dual Ethernet ports, CPU connects with 4 PROFIBUS-DP protocol buses. Each PROFIBUS-DP protocol bus can connect 64 actuators through optical fiber, as shown in Figure 10. The system has been matched with normal operation.

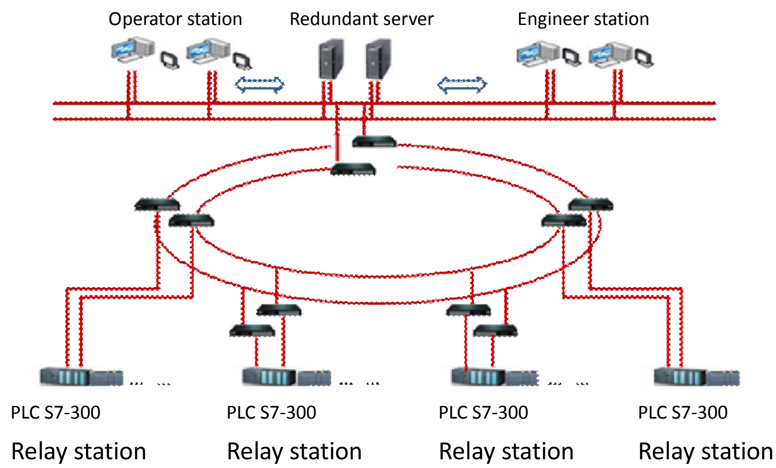


Fig.9 Hardware connection of the active reflector control system

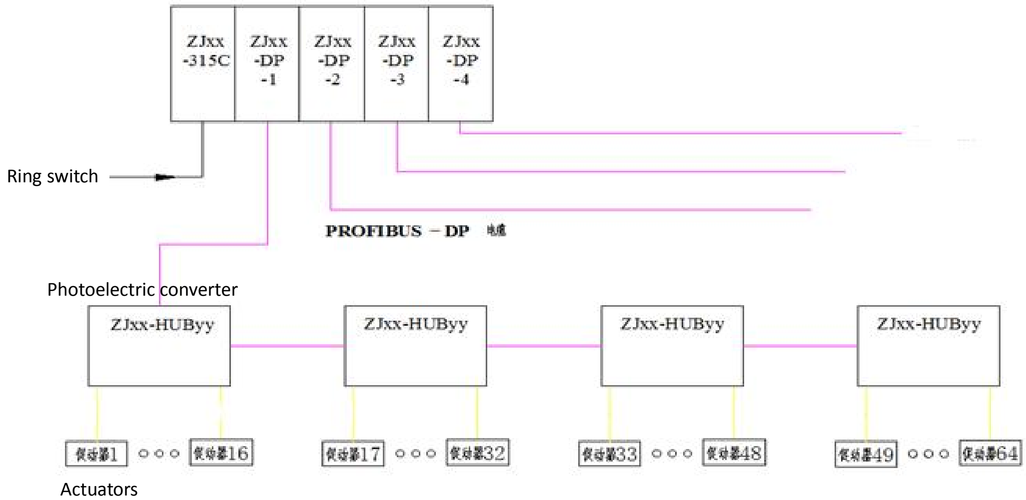


Fig.10 Hardware connection of the active reflector control system in the relay room

4.2 Active reflector measurement

During the observation, the precision measurement of about 700 nodes in the illuminating area is required within 10 minutes, the precision is RMS 2 mm. The high precision measurement for 2225 nodes within the range of 500 meters is required when the calibration is measured, and the precision is RMS 1.5 mm.

The reflector measurement system is mainly composed of total station, target and base piers. 10 total stations are placed on the JD-1~JD-5 pier, and 2 stations are placed at each point. The target is mounted on the reflector node, that is, the joint of the triangle panel. At the time of observation, the total station monitors the position of the targets in the illumination area.

Figure 11 is the measurement result of tension to sphere in November 2017. The distance difference between the measured point and the theoretical point to the sphere center of the reflector is calculated. Using this distance difference to analyze spherical accuracy, the error RMS1.5mm meets the requirements.

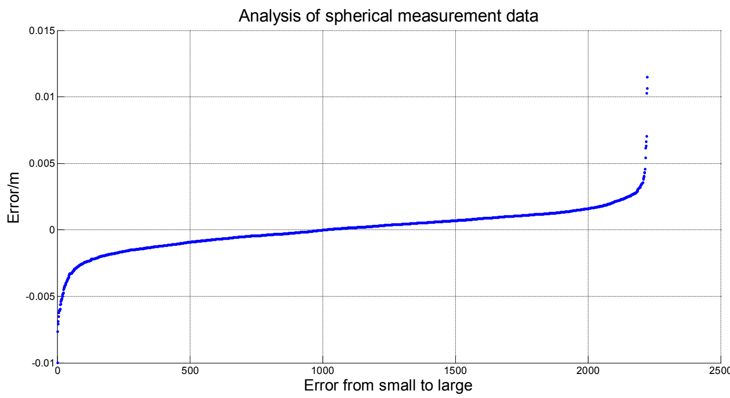


Fig.11 Analysis of data error of spherical measurement

Active reflector survey strategy: The center point of the reflector is the starting point, and the nodes in the illuminated area are partitioned with different horizontal angle ranges, so that the number of points measured in each station is basically the same, as shown in Figure 12.

Using this partition method, the AZ and EL angle distributions of the total station are small, which is helpful to improve the measurement speed. The experimental data in September 2017 showed that the accuracy of paraboloid was not RMS4.0mm, as shown in figures 13 and 14.

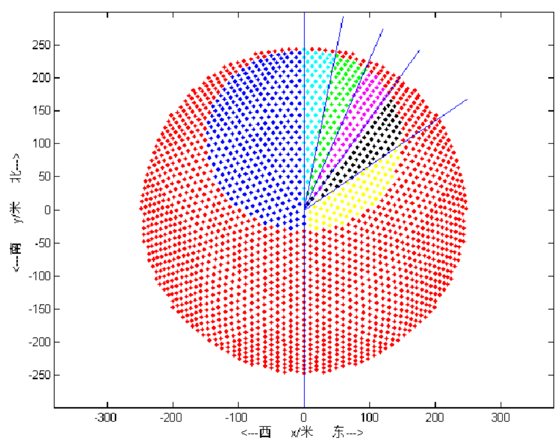
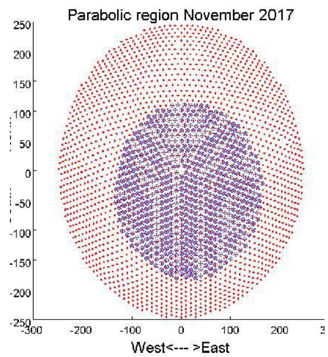


Fig.12 A schematic diagram of an active reflector measurement strategy



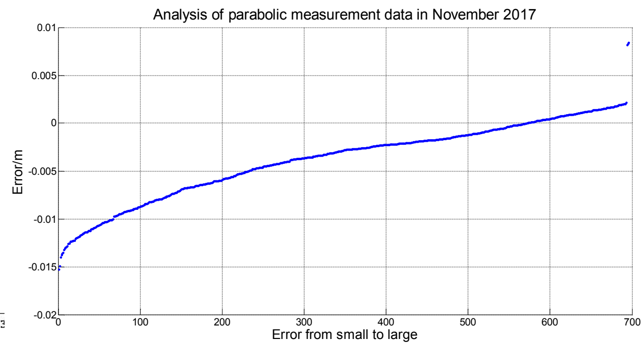


Fig.13 Parabolic position

Fig.14 Analysis of parabolic data error

5. FEED SUPPORT MEASUREMENT AND CONTROL

The telescope has a calibre of 500 m. If a rigid mechanism is used as a driving chain, the weight of the feed support mechanism will reach 10000t, the cost is extremely expensive and it is almost impossible to accomplish in engineering.

In order to avoid the high cost of using the rigid structure of the Arecibo telescope and further increase the working space of the telescope, the design of the feed support of FAST adopts the 2 stage adjustment mechanism. 6 supporting towers are distributed in the circle of 600 meters in diameter. The focus cabin is suspended in the air with 6 support cables. The length of the support cable is changed by the driving device, and the focus cabin is moved in the large workspace of the 100 meter scale.

A-B axis and Stewart platform parallel robots are installed in the feed cabin. The cable support and the A-B axis are used as the first positioning mechanism to realize the coarse positioning of the feed cabin. The Stewart platform robot, as a fine tuning mechanism, can compensate for the errors caused by the coarse positioning error of feed tanks and other factors in real time.

5.1 Feed support control

The FAST telescope uses the cable parallel connection as the first stage positioning mechanism. The flexibility of cable leads to the easy oscillation of the system. The focus cabin weighs 30 tons, and the first natural frequency of the system is between 0.18Hz~0.22Hz, and the damping ratio of flexible steel cable is only 0.2%[6]. Once the focus cabin vibrates, the decay rate is slow and long, in addition to the influence of the position and posture precision, because of the effect of large inertia, it may also have permanent damage to the mechanical structure of the system. How to suppress the effect of vibration on the accuracy and structure of telescopes is a key[7].

According to the requirement of observation frequency band, the maximum spatial position error of the first level cable drive control is 48mm, and the space position error of the antenna phase center of the receiver is 10mm.

The feed support control system can be divided into 3 levels in Architecture: management level, field level and control level, as shown in Figure 15.The management level communication protocol is TCP/IP Ethernet, which is responsible for the sending and uploading of the system operation instructions. The field level communication protocol is POWERLINK real time Industrial Ethernet. The whole control system is responsible for sending the target value of motion planning to cable driven system, feed cabin system and so on. At the same time, the other subsystems upload their key data to the whole control system. The field bus network is adopted in the cable driven and feed cabin system, which mainly controls the internal execution mechanism of each subsystem in the field. The control system adopts cascade vibration suppression method to suppress vibration.

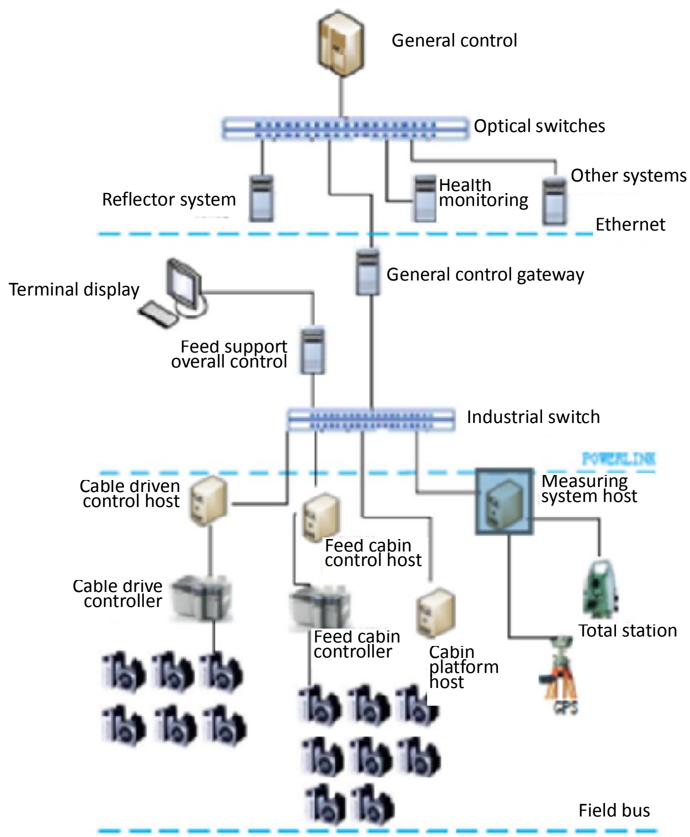


Fig.15 Hardware connection of the feed support control

5.2 Feed support measurement

On the 100 meter scale, a light cable system is used to adjust the focus cabin in real time. The cabin is exactly located at the focus position. Feed support measurement system requires multi-objective, large scale, high precision and high efficiency dynamic non-contact measurement.

The feed cabin is composed of a star frame, a AB axis and two fine tuning mechanisms, as shown in Figure 16 ; the two fine tuning mechanism, which is a six bar parallel mechanism, contains a few parts of the upper platform, the lower platform and the branch rod, and the upper platform is fixed with the AB axis.

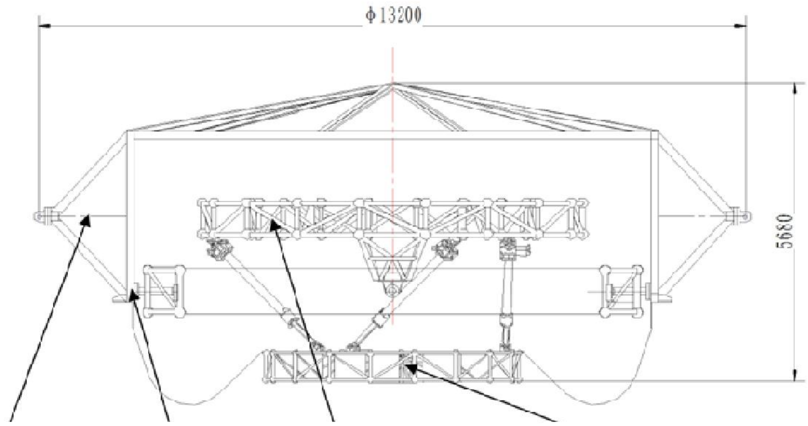


Fig.16 the structure diagram of the focus cabin

The cable driving measurement mainly completes the pose measurement of the FAST feed cabin star frame. Combined with structural calibration data, the position and attitude of AB axis can be calculated. The center position of the AB axis is required to reach a precision of + 17mm.

The key of cable driven measurement is reliability. The total station and GNSS are used to complete a cable driven measurement task. When the total station can not work under bad weather conditions, it can rely on GPS-RTK measurement technology to achieve safe landing of the feed cabin.

4 total station (1 redundant) are mounted on the outer ring piers (JD12, JD16, JD18, JD22), and the targets are mounted on the star frame for tracking measurement. 8 GNSS antennas, 6 stations mounted on top of star shaped frames as mobile stations, and 2 stations mounted on JD24 as reference stations. Under the control of the feed support measurement system software, the two kinds of measuring equipment complete a cable driving measurement with the cooperative work, and obtain the center position coordinates of the AB axis. The measurement results are shown in Figure 17.

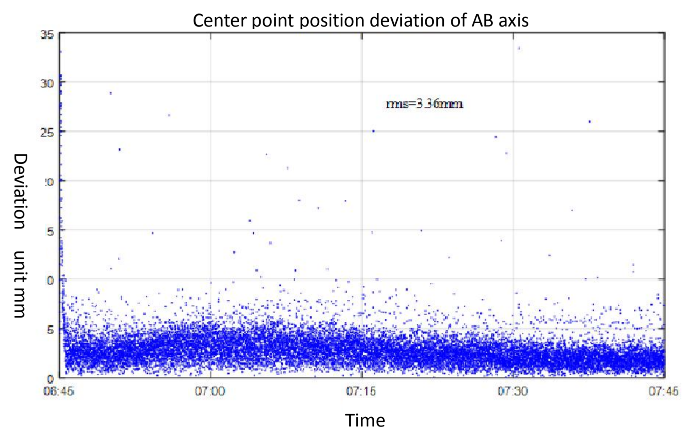


Fig.17 Analysis of the position deviation of the center point of AB axis

The fine-tuning mechanism's lower platform, which carries the feed receiver and the subsidiary mechanism, requires precise positioning of the feed phase center with a precision of 3mm.

The precision adjustment platform measurement system is mainly composed of the base pier, the total station and the target. The target is mounted on the lower platform through the adapter plate, and the prism normals point to the corresponding total station. The total station is installed on JD7, JD8, JD9 and JD11. The total station on JD8 is redundant, and the total station tracking the target for position measurement. According to the measured data and the calibration data of the feed cabin structure size, the feed phase center coordinates are solved. The results of the tracking observation are shown in Figure 18.

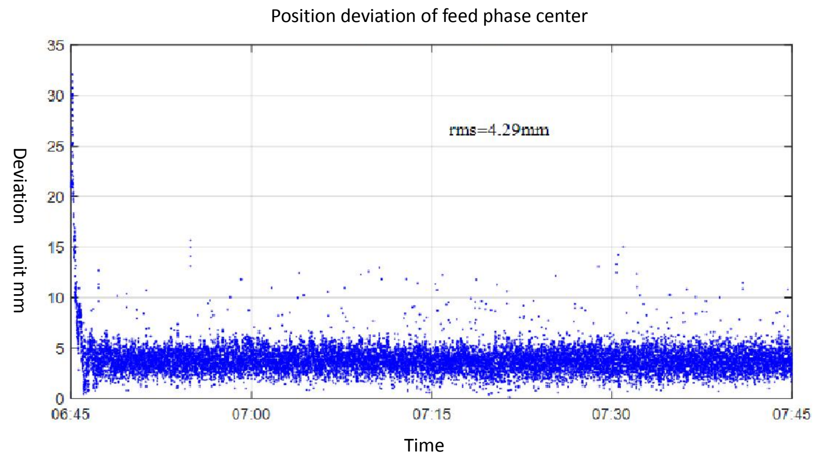


Fig.18 Analysis of the position deviation of the central point of the feed phase

The accuracy of the first order cable drive control system is 3.36mm far better than that of 48mm, and the space position error of the antenna phase center of the receiver is 4.36mm better than that of the 10mm.Meet the requirements[8].

6. CONCLUSION

FAST has entered the commissioning phase, and all aspects of the measurement and control system have met the requirements of the first stage.

At present, the main problems are the influence of atmospheric disturbance on measurement data, and the non-uniformity of measurement data delay and sampling period.

The distance intersection is used instead of triangulation to reduce the influence of atmospheric disturbance on angle measurement. The prediction algorithm reduces the delay effect of measurement data, installs gyro and accelerometer equipment, and increases the sampling rate of measurement data.

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