Construction and Application of Digital Twins of Large Radio Telescopes

Shilei Lu*, Zhengxu Zhao, Yao Xiao

Abstract—**To mitigate radio interference, electromagnetic signals are prohibited within a 5-kilometer radius of the 500-meter Aperture Spherical Radio Telescope (FAST). Consequently, ensuring effective state monitoring, information transmission, and protection has become a critical challenge for FAST. Current research, however, suffers from low automation levels and an inability to provide real-time feedback on Tianyan's overall operational status, leaving a gap in comprehensive and feasible solutions for its information preservation and state monitoring.To address these issues, this study analyzes the structural characteristics of FAST and proposes a rapid modeling approach to construct its digital twin. A state monitoring framework based on this digital twin is then developed. Leveraging FAST's actual construction data, a 1:100 scale physical model is fabricated, and experiments are conducted using the OPC UA industrial communication protocol for data acquisition, state monitoring, and decision control.The experimental results demonstrate that the deformation of FAST's active reflector is accurately reflected in real time within the virtual model. The system operates smoothly, enabling seamless command issuance via the control system and precise execution in the physical entity.**

Index Terms—**FAST; State Monitoring; Information Preservation; Rapid Modeling; OPC UA**

I. INTRODUCTION

THE national large-scale scientific research infrastructure, exemplified by the 500-meter Aperture Spherical Radio Telescope (FAST), plays a crucial role in supporting higher education institutions and research institutes in their scientific endeavors, societal service provision, and cultural innovation endeavors. It stands as the technological cornerstone and a vital instrument for probing the uncharted realms of knowledge and surmounting frontier scientific challenges [1]. Consequently, bolstering the information legacy, safeguarding, and condition monitoring of such colossal scientific facilities has emerged as a pressing issue that demands immediate attention [2]. However, the sheer magnitude and stringent precision requirements of FAST render manual maintenance both time-consuming and arduous. Furthermore, situated in Pingtang Country, Guizhou Province, approximately 200 kilometers distant from the nearest urban center, FAST is encircled by a 100-kilometer exclusion zone to mitigate electromagnetic interference, thus precluding public access. This distinctive geographical setting not only furnishes FAST with an environment virtually devoid of human-generated radio interference but also introduces complexities in its day-to-day management and operational utilization [3].

To address the aforementioned challenges, numerous scholars have proposed diverse information inheritance and status monitoring strategies, each exhibiting distinct advantages and limitations. For instance, Zhao Zhengxu et al. [4] investigated digital technologies for information preservation and developed a 3D model of the FAST telescope. They classified and encoded the model, employing VR technology for visualization. However, this approach was primarily designed for display purposes and did not incorporate state monitoring capabilities. Lei Zhen et al. [5] introduced a method for constructing the thermal temperature field of radio telescopes by integrating measured and simulated data. They developed a digital twin system to dynamically compensate for thermal deformation in radio telescope structures. While this system effectively addresses the challenge of measuring and compensating structural deformation under solar thermal loads, its applicability is limited to small radio telescopes and focuses solely on thermal deformation compensation. Zhang Tao [6] utilized 3D modeling techniques to create digital twins for FAST's active reflector system and feed support system, offering innovative insights for the digital twin development of large-scale scientific facilities and information preservation. Nevertheless, the system suffers from weak interactivity and low automation levels.

Despite significant advancements, existing research on FAST suffers from critical limitations, including inadequate automation and the lack of real-time operational feedback. Consequently, no proposed solution provides a comprehensive and practical framework for addressing FAST's information inheritance, protection, and status monitoring challenges.

Digital twin technology offers a promising solution by enabling bidirectional mapping between physical entities and their virtual counterparts. This approach leverages perception, computation, and modeling techniques to drive digital twin models with real-time data, facilitating seamless bidirectional synchronization and virtual-physical interaction. As a cutting-edge information technology, digital twins have been successfully applied across diverse industries, including aerospace [8], smart manufacturing and factories [9–10], smart cities, and healthcare [11]. Their integration into FAST systems could address the aforementioned limitations by providing robust information management and real-time monitoring capabilities.

This article proposes an intelligent state monitoring and control method based on the digital twin of a large radio

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telescope. A rapid construction method for the digital twin of a large radio telescope is introduced. Then, the effectiveness of data acquisition and status monitoring of the digital twin system is verified through a miniature physical model. This provides a theoretical basis and method for utilizing digital twin technology to inherit and protect information and check real-time status of FAST[12].

II. Construction of 3D Model for FAST Facilities

A. Construction Process of Active Reflector System Active Reflection Surface Construction

Active Reflection Surface Construction

As the core component of the FAST (Five-hundred-meter Aperture Spherical Telescope) facility, the active reflector surface constitutes a spherical structure with a diameter of 500 meters and a radius of 300 meters. It comprises 4,450 individual reflector panels, a back frame, 6,670 main cables, 2,250 actuators, and 2,250 lower cables. The entire system is supported by 50 lattice columns and a ring beam with an outer diameter of 522 meters and an inner diameter of 500 meters, forming a highly precise active reflective spherical mechanism.Each reflector panel is 1.2 millimeters thick, with a 65-millimeter gap between adjacent units [13]. The active reflector is divided into five identical sectors, enabling modular construction—only one sector needs to be fabricated and assembled before being replicated and rotated into position, as illustrated in Figure 1.

The reflective surface unit is categorized into four structural types:

1)Basic Type: A triangular structure comprising 341 variations and 4,273 individual units.

Theoretical side lengths range from 10.38 m to 12.40 m.

2)Special Type: Divided into three distinct forms, totaling 54 variations and 177 units.

Measurement Base Pier Units: 23 variations (23 units) feature a central hole to accommodate the measurement base pier.

Cable Net Center Units: 1 variation (5 units) is positioned at the center of the cable net.

Cable Net Edge Units: 30 variations (149 units) are located at the cable net's edges, connecting to the lower chord of the ring beam and forming a quadrilateral structure.

In accordance with the specifications for the FAST project, the apex of each reflective surface panel is situated on a spherical surface with a 300-meter diameter, while the reflective surface itself has a curvature radius of 315 meters. The reflective surface panels are created using the following procedure:

1)Starting with the triangular mesh data (which represents discrete triangles centered at point O1 with coordinates (0,0,0) and a radius of 300 meters), identify the details of each triangle, labeled as type A.

2)Within the plane of triangle A, move each side inward by 32.5 millimeters, which is half the distance between adjacent reflective surface panels, to create a new triangle, A1.

3)Utilizing the fact that the three vertices of triangle A lie on both a sphere with a radius of 300 meters (with center O1 at (0,0,0)) and another sphere with a radius of 315 meters, determine the center O2 of the latter sphere.

4) By applying the spherical equation (1) and the spherical parametric equation (2), adjust the positions of the three vertices of triangle A1 to fit a surface with a radius of 315 meters centered at point O2, resulting in triangle A2. This adjusted triangle A2 corresponds directly to a single reflective surface panel and serves as a unique identifier for distinguishing between different panels. Specifically, if two reflective surface panels have corresponding A2 triangles that are congruent, then those two panels are identical.

$$x^2+y^2+z^2=R^2 \tag{1}$$

$$\begin{cases} x = R\sin\varphi\cos\theta \\ y = R\sin\varphi\sin\theta \quad (0 \le \theta \le 2\pi, 0 \le \varphi \le \pi) \\ z = R\cos\varphi \end{cases} \tag{2}$$

φ is the elevation angle, and θ is the azimuth angle.

5) Store the acquired triangular vertex coordinate data and establish corresponding composition rule files for lines and faces, along with connection rules for reflective surface units, including vertices, edges, and faces. For instance, the notation 'faces[0] = [0,1,2]' indicates that face number 0 is composed of three vertices numbered 0, 1, and 2. This structure can be easily implemented and accessed using Python code.

Back-frame Construction

As illustrated in Fig. 1, each reflective surface unit is paired with a corresponding back frame, which serves to fix and support the panel. Consequently, the classification of the back frame aligns with that of the reflective surface unit [15–16]. All reflective surface units must be positioned on a spherical surface with a curvature radius of 315 m. The vertical distance from the upper surface of the reflective surface to the center of the upper chord of the back frame is h = 177.7 mm, while the thickness of the back frame is H = 1000 mm. The theoretical side length of the back frame ranges from 10.344 m to 12.366 m, and the gap between adjacent back frames is 120 mm. The radial positional relationship between the reflective surface unit and the back frame is depicted in Fig. 2.

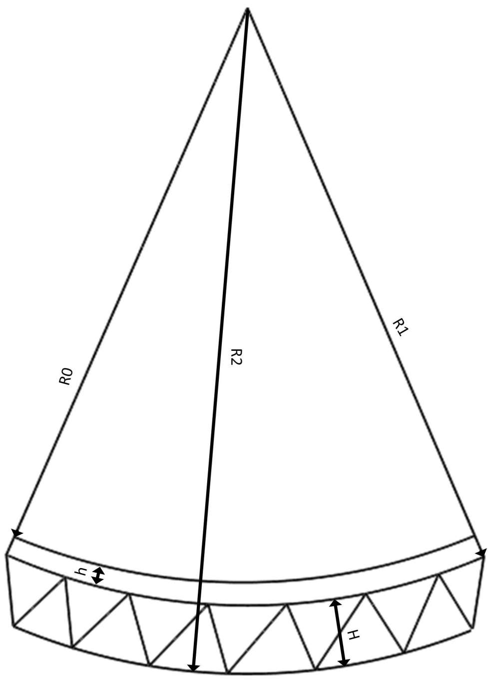

Fig.2. The radial positional relationship between the reflective surface unit and the back-frame.

R0=315000mm, the radius of curvature for the panel; h=177.7mm, the distance from the panel's surface to the center of the upper chord of the back frame; H=1000mm, the thickness of the back frame structure; R1=R0+h=315177.7mm, R1 represents the radius of the sphere centered at the upper chord of the back frame; R2=R1+H=316177.7mm, R2 is the radius of the sphere centered at the lower string of the back frame.

The back frame unit features a double-layered grid structure composed of upper chord members, lower chord members, web members, and bolt balls, arranged in a triangular pyramid configuration with bolt-ball joints. Connecting rods are installed at the vertices of the back frame unit and linked to the node disks of the cable network. Additionally, an adjustment device is mounted above the bolt ball of the upper chord, connecting to the reflective surface tray to provide support and ensure precise alignment of the reflective surface.

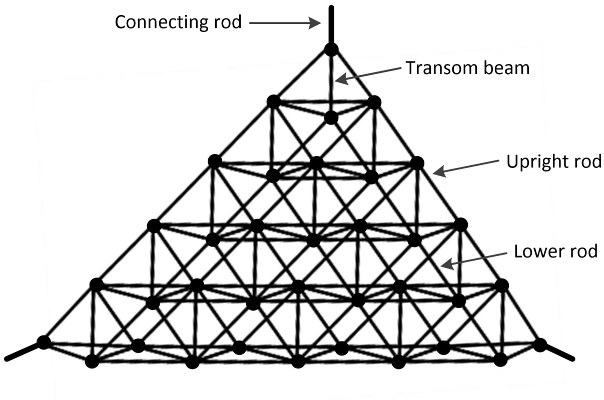

Fig. 3. Back-frame unit structure.

As shown in Fig. 3, the triangular vertex of the back-frame unit lies on a sphere centered at (0, 0, 0) with a radius of 300.1777 m. Based on this geometric constraint, the modeling approach for the reference reflector element of the back-frame unit is derived through the following steps:

1) Initial Triangle Selection O1=(0,0,0) with an initial radius of 300 m, each triangle is identified by a unique code A.

2) Spherical Correction to Radius (300+h) m:

Using the spherical equation (1) and its parametric form (2), the three vertices of triangle A are adjusted to lie on a sphere of radius (300+h) m centered at O1=(0,0,0), resulting in triangle B.

3) Edge Inward Offset to Form Triangle B1:

In the plane of triangle B, each edge is translated inward perpendicularly by 60 mm (half the inter B1).

4) Determination of Sphere Center O2:

Since the vertices of triangle B lie on both a sphere of radius (300+h) m (centered at) and a sphere of radius (315+h) m, the center O2 of the latter sphere can be geometrically derived.

5) Final Correction to Sphere (315+h) m:

The vertices of triangle B1 are projected onto the sphere of radius (315+h) m centered at O2 , yielding triangle B2.

This triangle B2 serves as a unique geometric signature for the back B2, they are considered the same. Thus, the classification of back B2 triangles.

The triangle B2, generated using the aforementioned method, represents only the upper chord frame triangle of the back frame element. The structural framework of the back frame element consists of a double-layered aluminum alloy grid with bolt-ball joints, arranged in a triangular pyramidal configuration. To complete the structure, the following steps are required to generate the lower chord nodes and associated structural elements:

1) Numbering the Upper Chords and Triangular Units:

Assign a numerical identifier to each upper chord of the back frame unit.

Label the triangular units formed by these upper chords accordingly.

2) Determining the Lower Chord Node (Point D):

For each triangular unit with an odd-numbered identifier, draw center-lines along its three sides.

At the intersection point of these center-lines (the centroid of the triangle), construct a perpendicular line.

This perpendicular line intersects a sphere centered at O2 with a radius of (315 + h + H) meters at point D, which serves as the lower chord node of the back frame unit.

3) Constructing the Lower Chord and Belly Members:

Connect the lower chord nodes (points D) to form the lower chord of the back frame structure.

Link each lower chord node to its three nearest upper chord nodes to create the belly members (web members).

4) Generating Bolt Balls:

Define the radius of the bolt balls.

Place bolt balls at all upper and lower chord nodes, thereby completing the assembly of the back frame structure.

The detailed construction process is illustrated in Fig.4.

The modeling approach for the back frame of specialized reflective surface elements mirrors that of the standard types. The distinction lies in the back frame's contour at the cable network's edge, which forms a quadrilateral, while its components remain triangular. At the base pier, the reflective surface unit's back frame is hollow, allowing the pier to pass through centrally. This model can be created using the standard back frame generation method and subsequently adjusted according to the base pier's hollow dimensions.

Construction of Cable Net and Supporting Structure

The cable net comprises a primary cable net and a secondary cable structure. The primary cable net serves as the support for the reflective surface units, mirroring their spherical shape. Each main cable network node, excluding those at the boundaries and center, connects to six main cables, six sets of panels and back frames, and one secondary cable. This configuration transmits the operational dynamics of the secondary cable to the back frame and reflective surface, enabling active control over the surface's shape.

The positional relationship between the mesh nodes and the triangular vertices of the reflective surface elements is consistent, allowing the mesh nodes to be generated directly from the coordinates of these triangular vertices. The process is as follows:

1) Mesh Generation:

Utilize the triangular mesh data (discrete triangular elements centered at point O1=(0,0,0) with a radius of 300 m as the primary reference for the main cable mesh nodes.

Incorporate the corresponding anchor point locations and the cross-sectional area of each cable segment to construct the mesh structure.

Systematically connect each main cable mesh node to form a cohesive network.

2) Lower Cable Model Construction:

Link each main cable mesh node to its respective anchor point.

Assign the appropriate cross-sectional area to each cable segment to complete the lower cable model.

The ring beam and lattice column collectively serve as the support structure for the active reflector surface, ensuring stable and efficient support for the spherical main cable network. Although the supporting structure is large and complex, it follows a systematic design pattern: small structural units are repeated to form a three-dimensional truss framework.

By drawing inspiration from the construction principles of reflective surface units, back frame units, and cable networks, programmatic modeling techniques can be employed for efficient design [17–19].

Finally, the cable network and supporting structure are integrated as illustrated in Fig. 5.

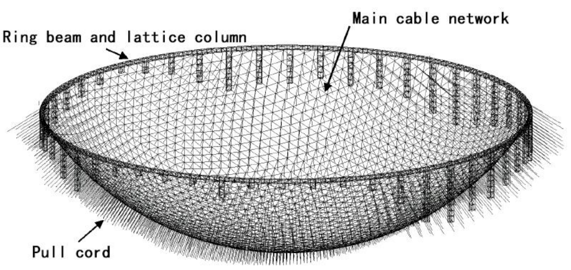

Fig. 5. Cable Net and Supporting Structure.

B. Construction of Feed Source Support System

The feed support system is a large-span rigid-flexible coupling mechanism comprising the feed cabin, cabin docking platform, feed support tower, and cable drive components [20]. The FAST feed source support system enables precise positioning of the approximately 30-ton feed source receiver by controlling its movement along a spherical crown surface with a diameter of ~200 meters. This is achieved through cable-driven traction anchored to six feed source support towers, facilitating centralized signal reception.

The structural models of each component are summarized in Table I.

III. Physical Entity Construction

This study presents the construction of a 5-meter-scale miniature FAST (Five-hundred-meter Aperture Spherical Telescope) active reflection spherical experimental platform, as illustrated in Fig. 6, to validate the data communication capabilities between a digital twin system and physical entities. The platform is built at a 100:1 scale, featuring a spherical diameter of 5 m, a spherical radius of 3.15 m, a crown angle of 113°, and an upward-facing aperture.

The reflective surface is partitioned into triangular facets using a subdivision scheme. It is divided vertically into 10 layers from bottom to top and longitudinally into 5 meridional zones. Each zone contains 100 reflective surface units, resulting in a total of 500 units. To accommodate feed cabin docking, the bottom unit in each zone may be omitted, reducing the total count to 495 units if excluded.

The reflective sphere employs a flexible cable as the primary structural element, interconnecting all reflective panels into a cohesive assembly. Actuation mechanisms are installed at each connection point to enable deformation of the spherical structure, adjusting the position of circular connecting components to modify the sphere's shape. Displacement sensors are integrated into the driving devices to monitor the movement of individual reflective surface units.

Each reflective surface unit is connected to the main cable via circular connecting pieces—one on each side of the unit. These connectors have a diameter of 60 mm and feature 12 peripheral screw holes for securing the reflective surface unit to the main cable, ensuring a cross-connection configuration. An additional central screw hole accommodates the attachment of the driving device. The FAST experimental platform is depicted in Fig.6.

IV. FAST Device Data Acquisition

A seamless connection is established between the FAST digital twin and the experimental platform, leveraging the OPC UA industrial Internet communication protocol for efficient data exchange. This integration enables real-time status data collection from the FAST experimental device and facilitates command issuance from the digital twin control system, thereby forming a comprehensive digital twin framework. The system architecture comprises five key layers:

1) Perception and control layer

This layer governs the dynamic adjustment of the main reflector's shape by actuating the main cable net, ensuring precise motion control. It integrates sensing and control devices—including the main reflector, actuators, feed cabin, and cable net—to enable coordinated operation of FAST's physical components [21–22].

2) Data processing layer

This layer processes raw data from perception devices, filtering and extracting actionable insights [23–24] while converting it into a format compatible with information models. It supports real-time life-cycle monitoring of FAST, generating service-driven decisions. Key functions include data cleaning, classification, compression, and transmission, with stringent requirements for real-time performance, data integrity, and security throughout [25].

3) Model layer

The digital twin's core resides in its multidimensional models, which include:

Behavioral models: Capturing component responses to external commands.

Data-driven models: Leveraging cloud computing and big data to analyze historical data for FAST characterization.

Information models: Managing life-cycle data to support intelligent decision-making.

Geometric models: Visually representing FAST's physical structure as the twin's intuitive interface [26].

4) Functional layer

Built upon the model and data processing layers, this layer visualizes and monitors FAST's operational status. It includes:

Status display: A virtual representation of FAST's digital twin, derived from the model layer.

State monitoring: Real-time data acquisition from perception devices to track and describe system behavior [27–28].

5) Application layer

This layer translates operational status data into actionable commands, enabling life-cycle management of FAST through the control system[29-30].

The FAST digital twin service architecture is shown in Fig.7.

By synchronizing virtual models with physical entities in real time, the system achieves bidirectional information flow:

Physical status is reflected in the virtual model.

Control commands are executed on physical components.

This dual capability ensures continuous monitoring and decision-making. As shown in Fig. 8, the virtual model dynamically displays the active reflector's deformation, confirming the system's feasibility for state monitoring and data acquisition. The smooth operation of the FAST digital twin validates its effectiveness in both surveillance and control.

V. DISCUSSION

This article investigates the structural characteristics of China's FAST telescope, proposes an efficient modeling approach, and conducts experiments on data acquisition, status monitoring, and decision control using a physical model of the FAST telescope. The study provides a comprehensive and practical framework for the information preservation, protection, and operational monitoring of FAST. However, the current work focuses solely on data acquisition from the active reflector surface and has not yet achieved full integration of the entire FAST system or implemented fault prediction capabilities. The completeness of the digital twin system remains to be further enhanced.

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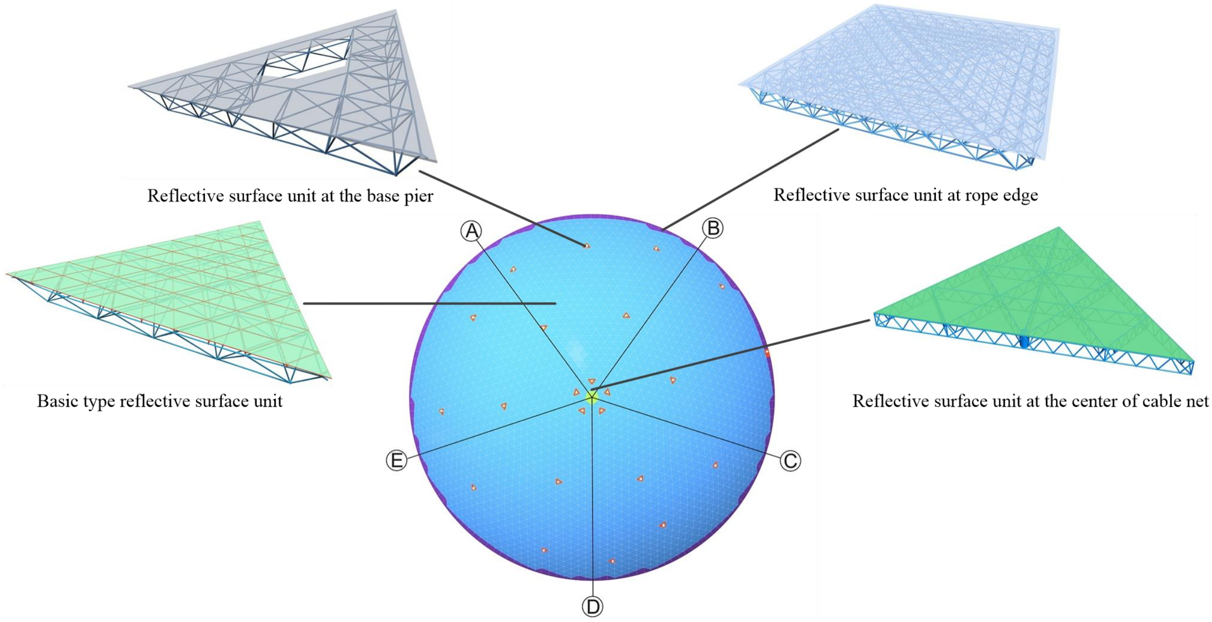


Fig.1. Structural Diagram of Active Reflective Surface.

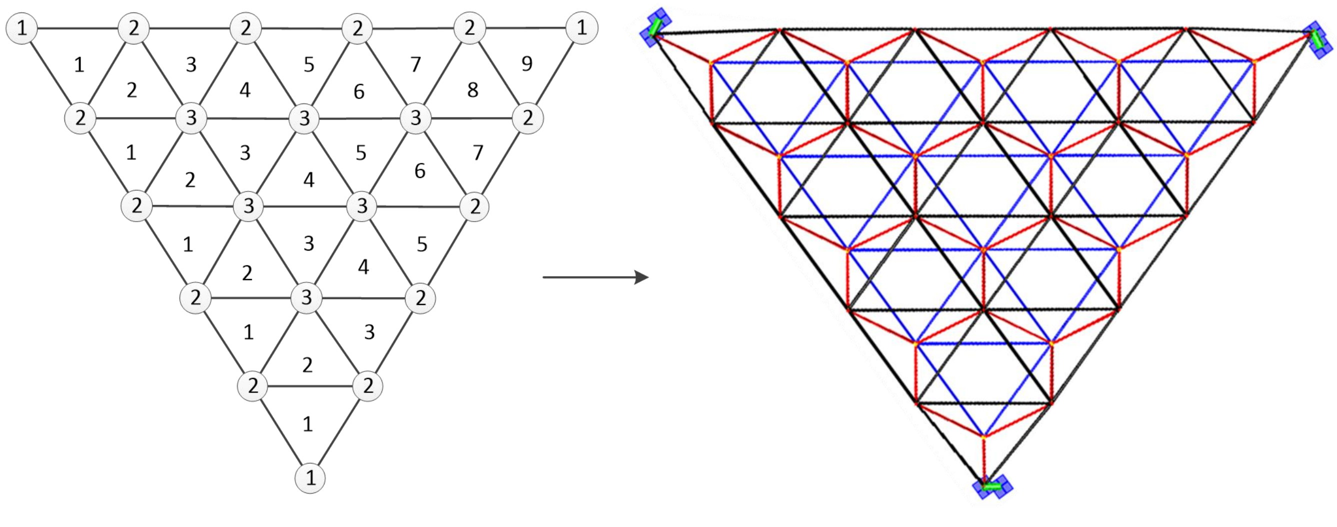


Fig.4. Basic Type Back-frame Construction Process.

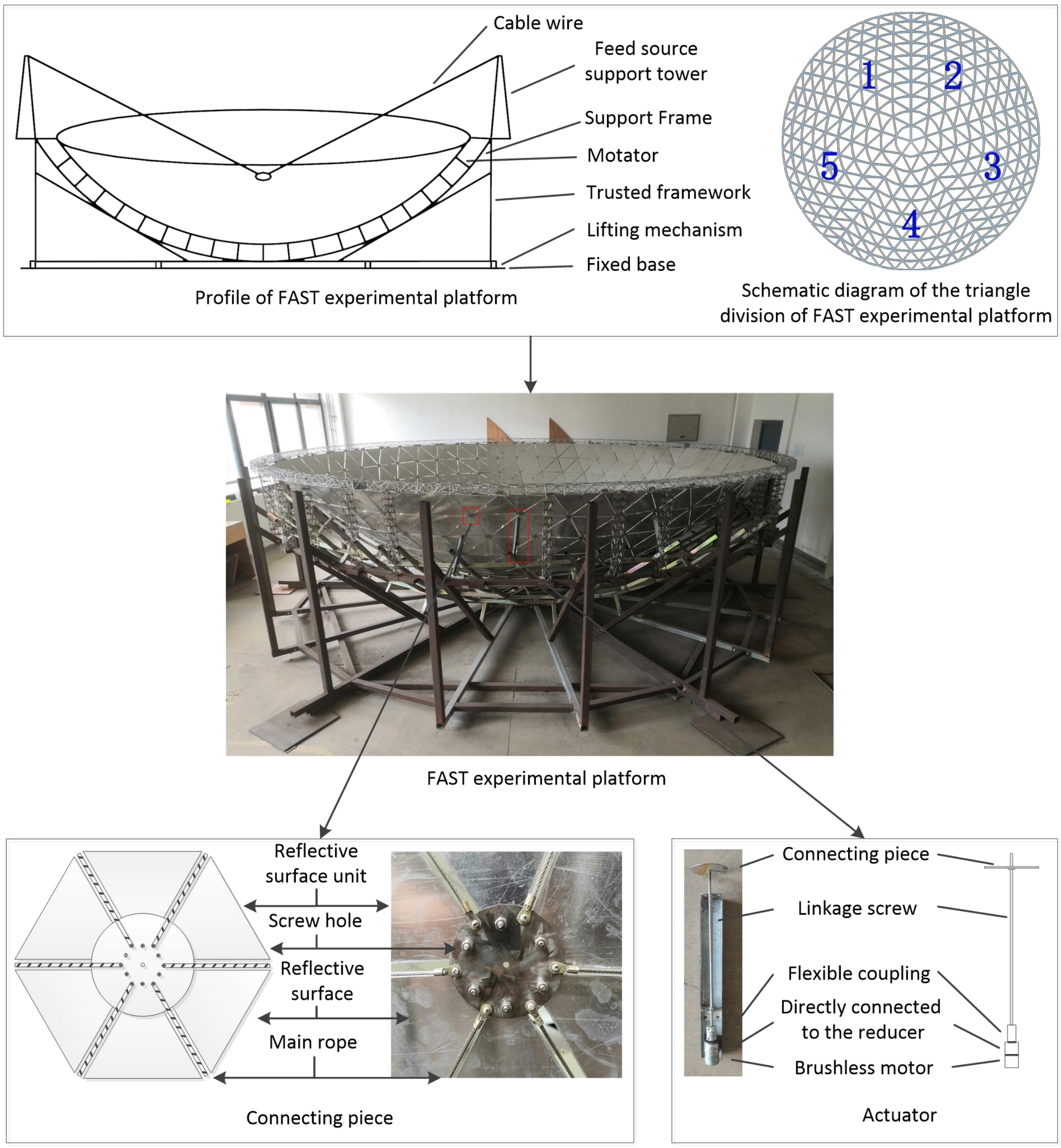


Fig.6. 5-meter Caliber Miniature Variant of the FAST Experimental Platform.

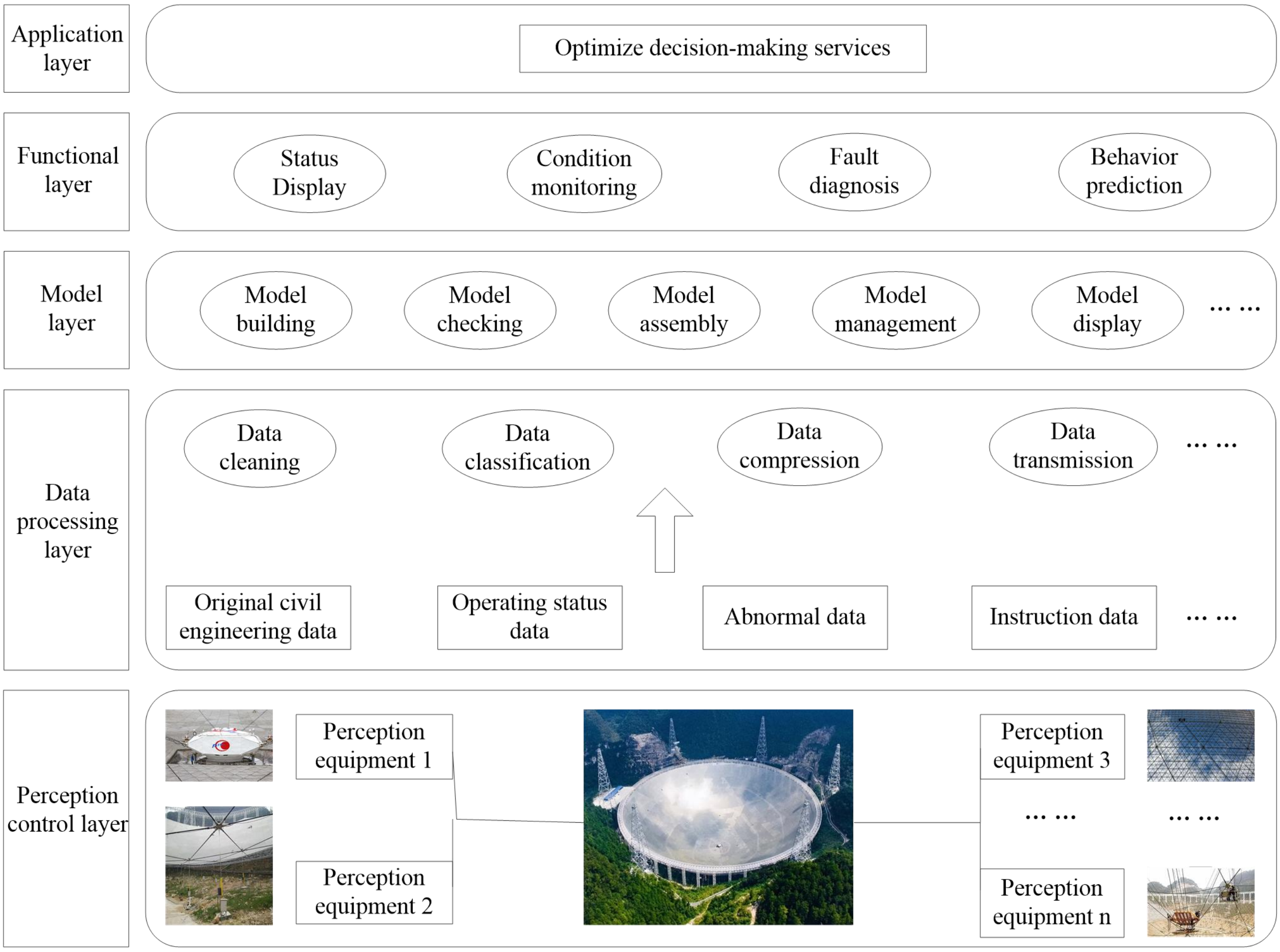
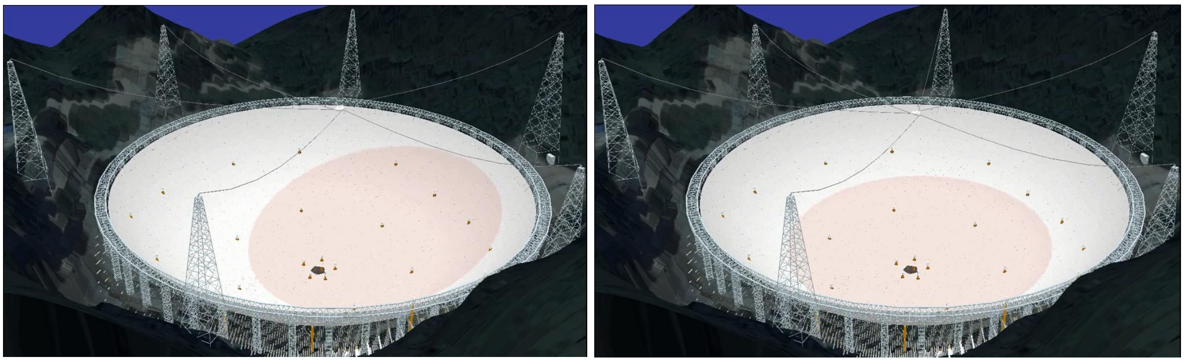


Fig.7. FAST Digital Twin Service Architecture.

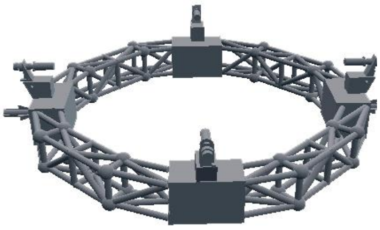
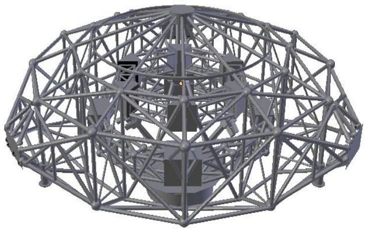
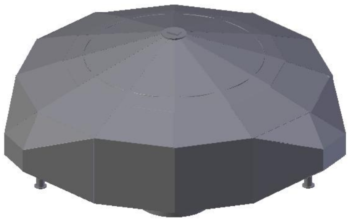
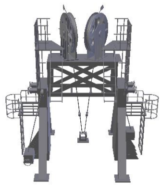
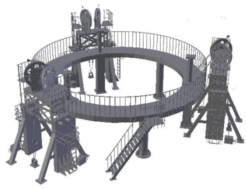
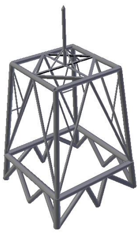
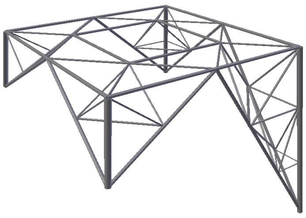
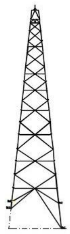
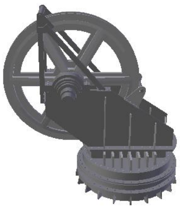
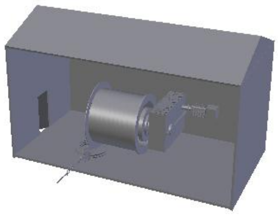


a) The active reflective surface is not deformed

b) Active reflective surface completes deformation

Fig.8. The Transmission of Data Communication Utilizing Multiple Protocols.

TABLE I
MODEL LIST OF FEED CABIN SUPPORT SYSTEM

Name	Models		
Cabin	 Feed cabin AB axis	 Star shaped structure of feed source cabin	 Cabin
Docking Platform	 Feed source cabin support device	 Pulley support device	 Cabin docking platform
Support Tower	 Tower top	 Tower bottom	 Support tower
Cable driven	 Tower top guide pulley	 Tower bottom guide pulley	 Ground winch