Rapid Modeling Method for The Digital Twin of Five-hundred-meter Aperture Spherical Radio Telescope

Jinjie Wen, Zhiguo Liu, Yufei Song*, Xi Meng, Jingfa Yao

***Abstract*—The Five-hundred-meter Aperture Spherical Radio Telescope (FAST) is the largest radio telescope ever built by far. No electromagnetic signal is allowed within 5 km of FAST to avoid radio interference. Therefore, the FAST faces the urgent problems currently that how to carry out health monitoring, component maintenance, scientific popularization, information inheritance and protection. Aiming at the above problems, this paper analyzes and designs a structural monitoring scheme of FAST based on digital twin. In addition, this paper proposed a rapid modeling method for the digital twin of FAST. In the final part of this paper, a digital twin prototype system of FAST has been developed to verify the effectiveness and practicability of this rapid modeling method.**

***Index Terms*—Five-hundred-meter Aperture Spherical Radio Telescope; Digital Twin; Rapid Modeling**

I. INTRODUCTION

AS an important tool of frontier science, a large-scale scientific facility plays a vital role in promoting scientific progress and social development. For example, the Arecibo telescope in the United States made major contributions to astronomy and won the Nobel Prize in Physics in 1993. Unfortunately, due to aging equipments, natural erosion and soaring maintenance costs, the Arecibo telescope is now rusting like a giant garbage dump. It's very possible that Arecibo will be abandoned in recent years. In 2016, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) in China replaced Arecibo as the largest single dish radio telescope in the world[1]. No electromagnetic signal is allowed within 5 km of FAST to avoid radio interference. Therefore, how to avoid Arecibo's dilemma is a key problem that the FAST project faces.

Manuscript received August 12, 2021; revised March 11,2022.

This work was supported in part by the National Key Research and Development Program of China (2016YFD0200403). Scientific Science and Technology Research Projects of Universities in Hebei (QN2021409). Foundation for doctoral research of Shijiazhuang University (21BS017).

Jinjie Wen is a lecturer of Hebei Key Laboratory of Optoelectronic Information and Geo-detection Technology, Hebei GEO University, China., Shijiazhuang 050043, China. (E-mail: 474600137@qq.com).

Zhiguo Liu is an associate Professor of Shijiazhuang University, Shijiazhuang, 050035, China (E-mail: 66344844@qq.com).

*Corresponding author: Yufei Song is a lecturer of Shijiazhuang University, Shijiazhuang, 050035, China (E-mail: songyufei0311@163.com, Tel:+86-0311-66617195).

Xi Meng is a lecturer of Shijiazhuang University, Shijiazhuang, 050035, China (E-mail: mengxi19930511@163.com).

Jingfa Yao is a lecturer of Hebei Agricultural University, Baoding, 071000, China (E-mail: 77126855@qq.com).

In recent years, information technology represented by artificial intelligence, cloud computing, Internet of things and virtual / augmented reality has developed rapidly. In this context, digital twin technology, as a key technology to integrate the physical world and the information world, has attracted extensive research. Digital twin technology creates digital entities of physical entities in a virtual space, which uses data collected by sensors to simulate the behavior of physical entities in a real environment. It builds a bridge between the physical world and the virtual world with the help of virtual reality (VR), Big Data (Big Data), high performance computing (HPC), artificial intelligence (AI)[2,3] and other technologies. Therefore, the technology of digital twin consists of three components, which are physical entities in physical space, digital entities in virtual space and the data and information between physical space and virtual space. Its main role is to ensure the long-term operation of physical entities in physical space by simulating, monitoring, diagnosing, predicting and controlling the behavior of physical entities based on the digital entities in virtual space.

Based on the comprehensive analysis of the issues facing FAST and the advantages of digital twin technology, this paper proposes a structure monitoring scheme, which realizes real-time health monitoring, component maintenance, science popularization, and information inheritance and protection of FAST in the whole life cycle by using digital twin technology. A modeling method is proposed in the process of establishing digital twin in FAST project. Finally, the digital twin prototype system of FAST is designed and developed.

II. RELATED WORKS AND PROBLEM DEFINITION

A. The Structure Analysis of FAST and Problems It Faces

FAST is a massive Chinese scientific project that aims to build the world's largest single-dish radio telescope. FAST first went online on September 25, 2016. The main observables of FAST are pulsars, the 21cm atomic hydrogen hyperfine transition, molecular transitions including masers, and radio continuum. Its unmatched sensitivity and superior speed of measurement will allow astronomers to greatly expand the amount of knowledge they have about compact objects, gaseous galaxies and the interstellar medium. The potential discoveries of FAST include thousands of new pulsars, the first pulsar in a spiral galaxy beyond Milky Way, dark galaxies that make up part of the so-called missing baryons, new component of the molecular universe, and many more. Compared to Arecibo, the world's leading single-dish telescope, FAST has three innovations:

--An active reflector with 4450 adjustable panels to realize pointing and tracking as the world's largest steerable antenna under 3 GHz;

--A light-weight feed cabin driven by six cables and servo-motors under closed-loop control up to a precision range of 5 decades;

--A site of deep Karst depression situated in mountains, which helps shield radio frequency interference.

As shown in Fig.1, the FAST structure is mainly composed of Supporting Cables (SC), Supporting Towers (ST), Feed Cabin (FC), Reflector Units (RU), Circle Beam Units (CBU), Lattice Columns (LC) and Actuator (AC).

Detailed information is provided in TABLE I.

TABLE I
DETAILED INFORMATION OF FAST STRUCTURE

Component	SC	ST	FC	RU	CBU	LC	AC
Number	6670	6	1	4450	50	50	2225

However, the FAST project mainly has the following four problems currently.

FAST is situated in Pingtang County, Guizhou Province, China. The site is very remote, about 200 kilometers from the city. Moreover, the one hundred kilometers area around FAST is off-limits to the public in order to avoid electromagnetic pollution. As a result, the outside world can only understand the tip of the iceberg of FAST through news reports. Therefore, how to promote popular science education is a problem that FAST needs to solve.

Due to the erosion of environment and harmful substances, the effects of vehicles, wind, earthquake, fatigue and human factors, and the deterioration of material properties, all components of the FAST would probably be damaged and deteriorated before they reach the design life. If these damages cannot be detected and repaired in time, the service life of FAST will be reduced seriously. Therefore, real-time health monitoring, component maintenance and life prediction without affecting normal work are the basis of long-term operation of FAST.

FAST is the largest spherical radio telescope in the world that can detect signals from pulsars 13.7 billion light-years away. If only words or pictures are used to illustrate the detection results of FAST, it is very vague and difficult to understand for non-specialists. Therefore, how to illustrate the detection results of FAST popularly, visually and scientifically is the problem that FAST needs to face.

As a mega scientific facility, it takes nearly a month to complete the overhaul of FAST. During the overhaul period, FAST have to suspend its work, which causes a serious waste of scientific facility resources. So how to maintain each component of FAST and predict its replacement time is the guarantee that FAST works efficiently.

B. The Current Situation and Capability of Digital Twin

The concept of digital twin was firstly presented by Grieves in the course of Product Life Cycle Management in 2003. With the introduction of the concept of American Industrial Internet, German Industrial 4.0, Made in China 2025, Cyber Physics System (CPS) and so on, digital twin has attracted wide attention[4,5]. Gartner, the most authoritative IT research and consulting company in the world, has listed digital twin as one of the top ten strategic technological trends in the past four years. Lockheed Martin Space Systems Company, the largest weapons manufacturer in the world, is ranked number one in six technologies for the future defense and aerospace industry. At the World Intelligent Manufacturing Summit, the Intelligent Manufacturing Academic Alliance of the China Association for Science and Technology listed digital twinning as one of the top ten scientific and technological advances in intelligent manufacturing. In addition, many distinguished international enterprises or institutions, such as Dassault, Siemens, General Motors, NASA, Parametric Technology Corporation have begun the application research of digital twin.

Based on real-time data collection, big data analysis, HPC, VR, AI and other technologies, Digital Twin has core capabilities such as simulation, monitoring, prediction, and control.

Simulation: The digital entities can be utilized to simulate the operation process of the physical entities in the virtual simulation environment before putting physical entities into operation. The state, behavior, failure probability, operation parameters and potential problems of physical entities in the real physical environment would be grasped as far as possible, which provides basis for the formulation of practical tasks, the setting of operation parameters and the analysis of anomalies.

Monitoring: Users can dynamically monitor the health of an entity through digital twin depending on data collected in real time by sensors in the entity's service life. Besides, faults of physical entities can be diagnosed, located and discovered through analysis of the real-time monitoring data and historical data.

Prediction: The real-time operation data and external environment data collected by sensors are mapped to digital entities. Besides, the health status, residual life and fault information of physical entities can be predicted accurately based on the physical property model, material evolution model, product simulation and analysis model.

Control: The control instructions of component action and working process can be generated by analyzing the real-time operating data. Then, the digital entities in the virtual control environment are driven according to the motion instructions to get the verification results. If there is no problem, the control instructions are transmitted to the execution units to control the motion of physical entities.

III. OVERALL ARCHITECTURE AND RAPID MODELING METHOD

A. Overall Architecture

The overall architecture of digital twin of FAST is shown in Fig.2, which includes data transmission module, digital entity module, technical support module and main function module.

Data transmission module: It is the link between physical space and virtual space. The operating state parameters of the components collected by sensors are transmitted to the digital entities in the virtual space in real time through the data transmission module. At the same time, the control instructions can be fed back to physical entities through the data transmission module[6].

Digital entity module: Digital entities are the real reflection of physical entities in the virtual space. The fidelity of digital entities determines the success of digital twin. Physical entities have different physical property models such as fluid dynamics model, structural dynamics model, thermodynamic model, stress analysis model, and material evolution models (including material stiffness model, strength model and fatigue strength model). Combining the physical property model and material evolution model into the Three Dimensional (3D) model is the key to establish accurate and scientific digital entities and give full play to the role of simulation, monitoring, prediction and control[7].

Technical support module: The application of big data, Internet of Things, HPC, VR and AI makes it possible to collect, store and analyze real-time dynamic and historical data of entities. It is an important support of real-time association and interaction between physical space and virtual space[8].

Main function module: The main function module corresponds to the core capabilities described in Section Ⅱ part B. So it will not repeats here.

B. Rapid Modeling Method

The first step to construct the digital twin of FAST is to build the 3D model of FAST. The core component information of FAST is shown in TABLE II. For such a complex and huge structure model, the traditional modeling method cannot be applied efficiently. Therefore, it is necessary to adopt appropriate modeling methods and tools. In the actual modeling process of FAST project, this paper explores and forms a modeling method based on node coordinate data, namely "point to line, line to panel, panel to model". It can be divided into the following steps:

1) Data preprocessing.

Data preprocessing is divided into determining node coordinates and determining the connections between nodes.

Determining node coordinates: Through on-the-spot investigation, FAST consists of circle beam and active reflector. The top view and side view of FAST are presented in Fig.3. Considering the engineering data of FAST is inconvenient to be shared with the general public, this paper uses the ideal approximation data. The circle beam (see Fig.3) has two layers and three circles in each layer, with a total of 2400 nodes. The reflector has twenty-seven layers, with a total of 1957 nodes. The rule to define the node numbering is: from top to bottom, from inside to outside, and counterclockwise numbering. Taking the circle beam as an example, the node number and node coordinates are shown in TABLE II. The numbering rule of reflector nodes is the same as the rule of the circle beam. So it will not be described here.

Determining the connections between nodes: The presence of connections between nodes indicates that there is a steel column between the nodes. In this paper, the node adjacency matrix $A=(a_{ij})_{2400*2400}$ is used to represent the connection relationship between nodes. If $a_{ij} = 1$, it indicates that there is an edge between node i and node j. Thanks to the circle beam and reflector of FAST have strong regularity, it only needs to determine the node connection relationship of one circle beam unit. The connection relationship of other nodes can be derived according to the first circle beam unit. Taking the nodes numbered 1-10 in the circle beam as an example, the row number and column number of the element which value is 1 in the node adjacency matrix A are given in TABLE III.

TABLE II
THE CORE COMPONENT INFORMATION OF FAST

Layer Number	Circle Number	Number of nodes	Starting&ending Number	Cylindrical coordinates	Cartesian coordinates
1	1	600	1,600	r1,θ,z1	r1×cosθ,r1×sinθ,z1
	2	300	601,900	r2,θ,z1	r2×cosθ,r2×sinθ,z1
	3	600	901,1500	r3,θ,z1	r3×cosθ,r3×sinθ,z1
2	1	300	1501,1800	r1,θ,z2	r1×cosθ,r1×sinθ,z2
	2	300	1801,2100	r2,θ,z2	r2×cosθ,r2×sinθ,z2
	3	300	2101,2400	r3,θ,z2	r3×cosθ,r3×sinθ,z2

Where θ=360*(x-y)/n， n is the number of nodes x is the node number y is the starting number，r1, r2 and r3 are the radius of the node in cylindrical coordinates，z1 and z2 are the height of the node.

TABLE III
THE ROW NUMBER AND COLUMN NUMBER OF THE ELEMENT WHICH VALUE IS 1 IN THE NODE ADJACENCY MATRIX A

i	1	2	3	4	5	6	7	8	9	10
j	2	1	2	3	6	5	6	7	10	9
	600	3	4	5	4	7	8	9	8	11
	601	601	602	602	603	603	604	604	605	605
	1501	602	1502	603	1503	604	1504	605	1505	606
		1501		1502		1503		1504		1505
		1502		1503		1504		1505		1506

The node coordinates data and the connections data between nodes are stored in Excel.

2) Data verification.

This paper processes the data stored in Excel and generates the 3D structure diagram of FAST using MATLAB to verify the correctness of data. It consists of the following three main steps:

Step1: Read the node coordinates stored in Excel and draw a 3D scatter plot.

Step2: Read the data of connections in Excel to construct node adjacency matrix ***A***.

Step3: Connect the 3D scatter plot according to the node adjacency matrix ***A***.

The top view and local enlarged drawing of the 3D structure diagram of FAST generated in Matlab are shown in Fig.4. It is confirmed that the data is correct.

3) Generating model

It consists of the following three main steps.

Step1: The command of "3D PLOY x, y, z" is run to generate a closed circle in AutoCAD, which converts the node coordinates in Excel into 3D line segments in AutoCAD. Each layer generates a closed curve separately. Besides, each two-layer node is considered as a group.

Step2: Export the generated file to DWG-formatted file. There will be 27 DWG-formatted files.

Step3: Import the 27 DWG-formatted files generated in step 1 into 3D Max one by one.

Step4: Select the point level and perform the welding operation.

Step5: Right click on the model and convert the model to editable polygon.

Step6: Select all components and link them each other.

The 3D reflector model of FAST generated according to the above steps is shown in Fig.5.

4) Generating maps

The reflector of FAST is composed of 4450 adjustable reflector units. Each reflector unit is a triangular panel in the 3D model and each panel can be operated separately. This paper adopts a batch mapping method to avoid inefficiencies caused by separate mapping. The main steps are as follows:

Step1: Select all triangle panels in the 3D model.

Step2: Click the Collapse command. Then the 4450 reflector units are integrated into one object.

Step3: Weld the joints with fusion threshold is 0.01.

Step4: Select the UVW expansion in the modifier list and render the UVW template.

Step5: Save the UVW template as PNG-formatted file.

Part of the maps generated according to the above steps is shown in Fig.6.

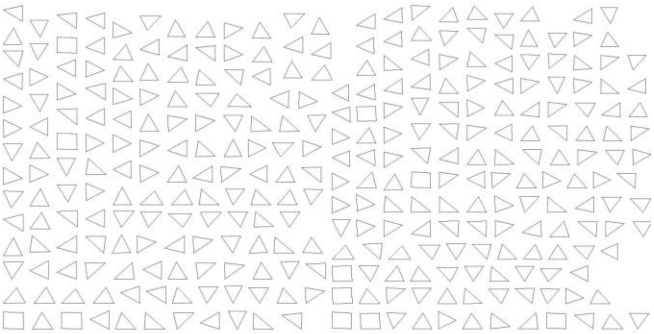

Fig.6. Part of the maps for FAST.

5) Manual Modeling

Some components of FAST cannot be generated by the rapid modeling method. Manual modeling method draws a complex 3D model in 3D Max software using basic geometric elements such as spheres, cylinders, cones or cubes. The 3D model of the Actuator, Lattice Column, Supporting Towers, Feed Cabin and the Supporting Platform for Feed Cabin are shown in Fig.7.

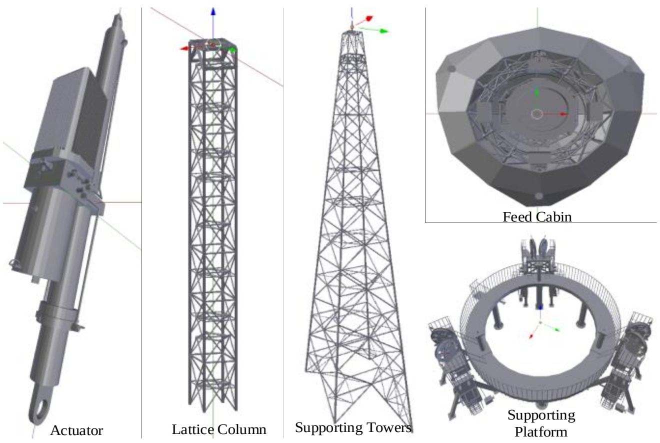

Fig. 7. The 3D model of the Actuator, Lattice Column, Supporting Towers, Feed Cabin and the Supporting Platform for Feed Cabin.

IV. DATA ACQUISITION AND HEALTH DIAGNOSIS

A. Data Acquisition

Data acquisition is the key to realize "virtual" and "real" mapping by using sensors to quickly collect actual physical data and map these data into digital twin table in real time. Twin data includes state process data and operation data.

1) State process data is mainly divided into environmental data, operation data and observation data. The environmental data include temperature, humidity, air pressure, wind speed, wind direction, rainfall (snow), light intensity, cloud amount, visibility, etc. Environmental data can help staff prevent disastrous weather. These data are combined with FAST operation data for data mining to help employees operate in different weather conditions.

2) The operation data is generated when the telescope performs observation tasks. These data mainly include the angle, position, pulsar signal frequency, signal strength, observation time, direction, attitude, speed, operation track, reflector change process, driver control operation data and operation instructions executed by the administrator. The observation data is mainly the pulse signal received by the receiving device of the feed cabin. These data are read by single chip microcomputer, embedded and other equipment, and then transmitted to the digital twin unit of FAST for processing and storage by the OPC Unified Architecture (OPC UA).

B. Health Diagnosis

Health diagnosis is mainly used to monitor the status of component level equipment of each system of the physical entity of FAST. Then analyze its performance, structure and other conditions through the monitoring data to judge its health state. The emergency early warning function refers to the prediction and early warning of FAST emergencies through mathematical models. Unlike emergency warning, health diagnostic is a long-term monitoring to judge their status, performance or predict its functional integrity and assess their health status. By summarizing the historical data and analyzing the abnormality, signal deviation and signal loss degree of sensor signal, the fatigue and damage degree of equipment such as light steel cable mechanism, feed cabin, actuator device and cable net can be predicted. These prediction results can help users maintain FAST[9]. For example, the vibration sensor is used to monitor the feed cabin. When the vibration signal is abnormal, on the one hand, the system will send an abnormal signal for on-site staff to check and deal with. On the other hand, the system will save, compare and further analyze and mine the signal records, judge the health status of the equipment. Then it will give the causes of signal abnormalities and maintenance strategies, so as to provide an effective basis for the design and transformation of subsequent radio telescopes.

V. PROTOTYPE SYSTEM IMPLEMENTATION

The 3D rendering engine can manage and organize all elements of the 3D scene effectively. At present, mainstream 3D rendering engines include OpenSceneGraph (OSG), Virtual Reality Platform (VRP), Delta3D, Open-source Graphics Engine (OGRE), Unity3d and so on. Compared with other 3D rendering engines, OSG has the characteristics of open source, cross-platform and high efficiency. In this paper, we adopt OSG as the 3D rendering engine to control the digital twin of FAST in real-time. The digital twin prototype system of FAST is shown in the Fig.8.

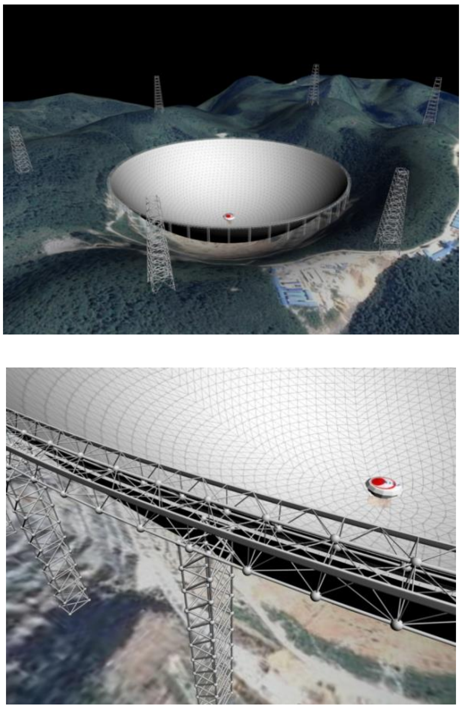

Fig.8. The digital twin prototype system of FAST.

VI. Conclusion and Outlook

As the world's largest radio telescope, FAST will make significant contributions to the development of human science and technology. In order to ensure the long-term operation and maintenance of FAST, this paper presents a technical scheme of health monitoring, component maintenance, science popularization, and information inheritance and protection for FAST based on digital twin. Besides, this paper proposed a rapid modeling method formed during the construction process of digital twin of FAST[10,11].

Digital twin is the real reflection of physical entities in virtual space, while it is impossible that they are identical. Digital twin is a multi-disciplinary collaborative design modeling technology, which involves product digital twin, attribute digital twin, performance digital twin and operation digital twin[12]. It is one of the research difficulties to integrate structural mechanics model, material evolution model and environmental evolution model into digital entities in virtual space scientifically and accurately.

With the development of new information and communication technologies such as Internet of Things, big data analysis, HPC and VR, fine control and prediction of product manufacturing process based on real-time field operation data and historical data collected by sensors will be the next research focus.

References

[1] Nan R D, Zhang H Y, Zhang Y, et al. Construction Progress of the FAST Project [J]. Chinese Astronomy & Astrophysics, 2017, 41(3):293-301.
[2] Kai Liang Lew, Kok Swee Sim, Shing Chiang Tan, and Fazly Salleh Abas, "Virtual Reality Post Stroke Upper Limb Assessment using Unreal Engine 4," Engineering Letters, vol. 29, no.4, pp1511-1523, 2021
[3] Alam K M , El Saddik A . C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems[J]. IEEE Access, 2017, 5:2050-2062.
[4] Qi Q, Tao F. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison[J]. IEEE Access, 2018:1-1.
[5] Oleg V. Chernoyarov, Vladimir A. Ivanov, Tatiana I. Demina, Serguei Dachian, and Alexandra V. Salnikova, "Spatial-Time Relationships When Measuring the Range and the Velocity of Spacecrafts," Engineering Letters, vol. 29, no.3, pp1044-1059, 2021
[6] Tao F , Cheng J , Qi Q , et al. Digital twin-driven product design, manufacturing and service with big data[J]. The International Journal of Advanced Manufacturing Technology, 2017.
[7] Schleich B , Anwer N , Mathieu L , et al. Shaping the digital twin for design and production engineering[J]. CIRP Annals - Manufacturing Technology, 2017:S0007850617300409.
[8] Zhuang C B, Liu J H, Xiong H,etc. Connotation, architecture and trends of product digital twin[J]. Computer Integrated Manufacturing Systems, 2017, 23(4):753-768.
[9] Moises Jimenez-Martinez, and Mariel Alfaro-Ponce, "Fatigue Life Prediction of Aluminum Using Artificial Neural Network," Engineering Letters, vol. 29, no.2, pp704-709, 2021
[10] Li D, Dickey J M, Liu S. Preface: Planning the scientific applications of the Five-hundred-meter Aperture Spherical radio Telescope [J]. Research in Astronomy and Astrophysics, 2019, 19(2): 3-4.
[11] Kan Z, Wang X L. The Design of Remote Monitoring and Warning System for Dangerous Chemicals Based on CPS. Journal of Information Processing Systems, 2019, 15(3): 632-644.
[12] Gartner.https://www.gartner.com/en/search?keywords=Top%2010%20Strategic%20Technology.

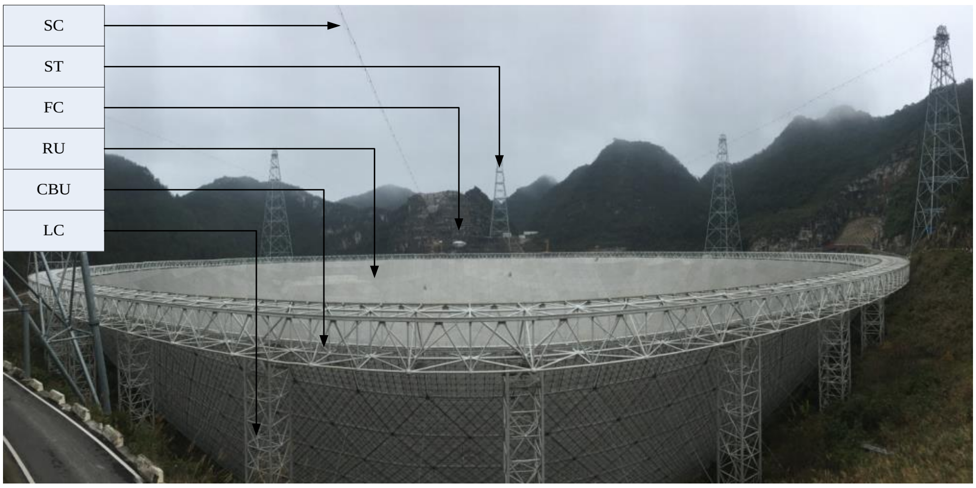

Fig.1. The structure diagram of FAST.

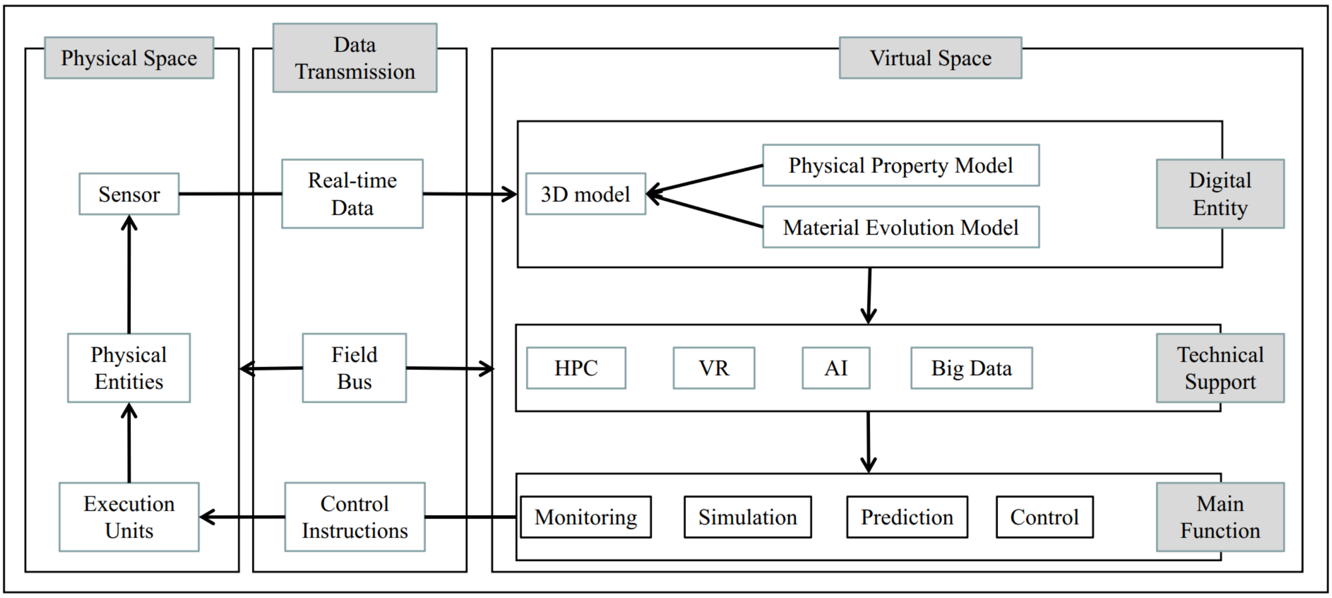

Fig.2. The overall architecture of digital twin of FAST

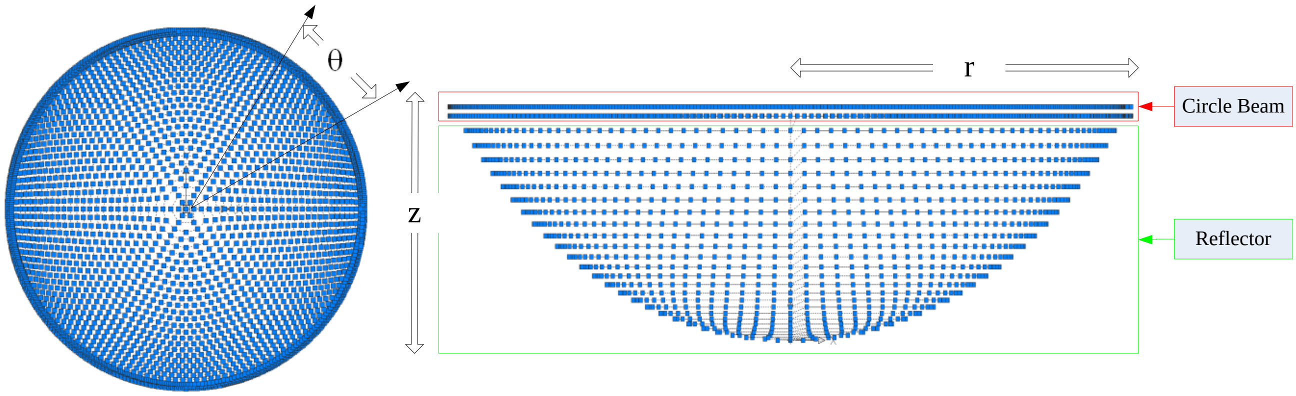

Fig.3. The top view and side view of FAST.

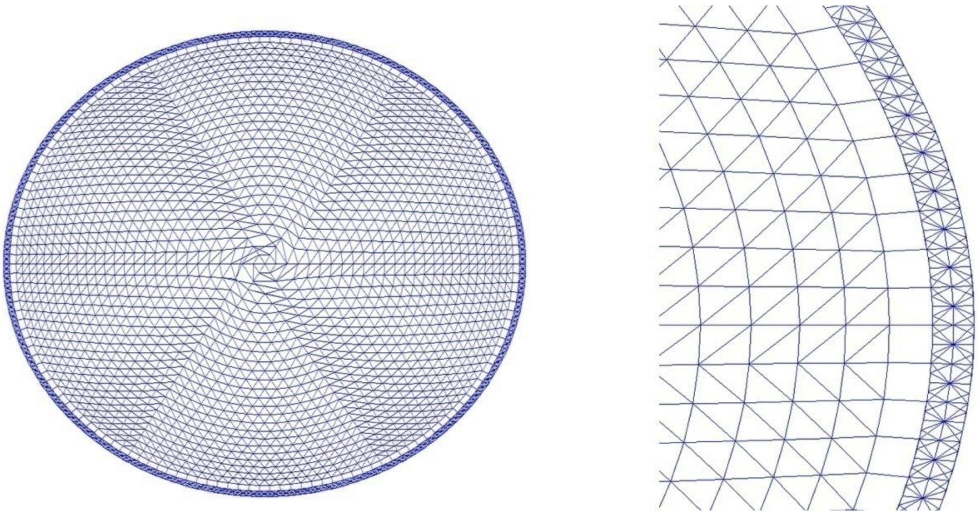

Fig. 4. The top view and local enlarged drawing of the 3D structure diagram of FAST generated in Matlab.

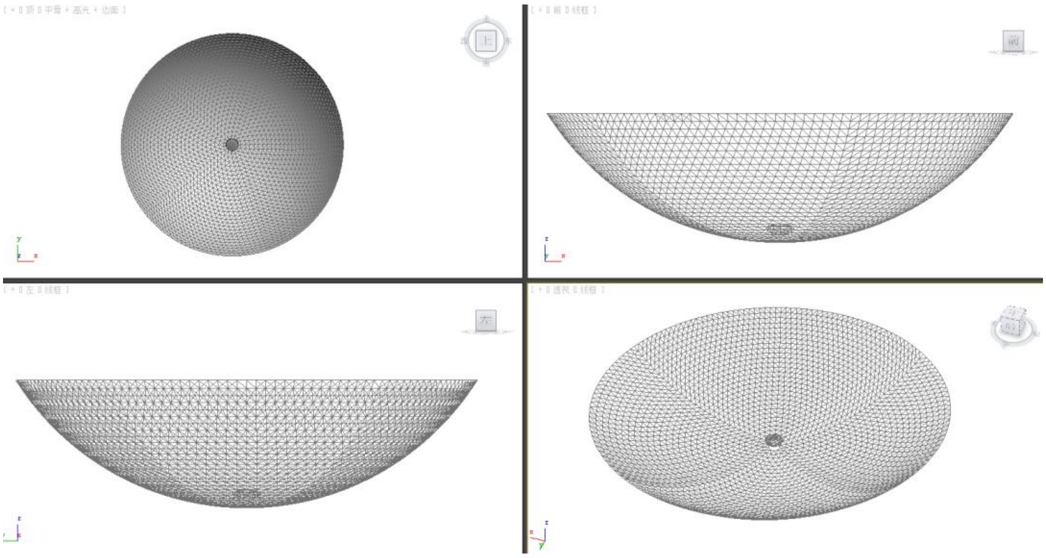

Fig.5. The 3D reflector model of FAST.