Reflector adjustment for a large radio telescope based on active optics

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ABSTRACT

The reflector deformation caused by gravity, temperature, humidity, wind loading and so on can reduce the global performance of a large radio telescope. In this paper, considering the characteristics of the primary reflector of a 13.7 m millimeter-wave telescope a novel reflector adjustment method based on active optics has therefore been proposed to control the active surface of the reflector through the communication between the active surface computer and embedded intelligent controller with a large quantity of displacement actuators, in which the active surface computer estimates and controls the real time active surface figure at any elevation angle, reduces or eliminates the adverse effects of the reflector deformation to increase the resolution and sensitivity of the radio telescope due to the more radio signals collected. A Controller Area Network /Ethernet protocol converter is designed for the communication between the active surface control computer as a host computer in Ethernet and the displacement actuator controller in Controller Area Network. The displacement actuator is driven by a stepper motor and controlled by an intelligent controller with the data from the active surface computer. The closed-loop control of the stepper motor improves the control accuracy greatly through the feedback link based on the optical encoder.

Keywords: 13.7 m millimeter-wave telescope, Active surface, Displacement actuator, Intelligent controller, Controller Area Network /Ethernet protocol converter

1. INTRODUCTION

Active optics is a technology used with reflecting telescopes developed in the 1980s, which actively shapes a telescope's mirrors to prevent deformation due to external influences such as wind, temperature, humidity, mechanical stress and so on. Active optics could be divided into two types: the thin-mirror active optics and the segmented-mirror active optics. The active optics makes the image quality is better, cost is less, and to build a very large telescope becomes possible.

To collect more radio signal and increase resolution and sensitivity, researchers have expended tremendous efforts in recent years to increase the size of radio antenna together with building a radio antenna array. The active optics applied in radio telescope makes things much easier for getting larger single aperture and shorter observing wave length. Radio telescope usually has a very large diameter with its antenna consisting of a great number of small regular panels. Traditional radio telescope usually adopts passive antenna. Before or between the operations, the antenna is tested and adjusted at an intermediate elevation of its operation sky area and will not be actively aligned during running.

The below is the preliminary configuration for the primary reflector. As shown in fig. 1, the segmentation layout for the telescope primary reflector of Delingha 13.7 m millimeter-wave telescope from Purple Mountain Observation China has 2 rings of keystone panels. The inner ring is made up by 24 identical panels while the outer ring 48, totally 72 panels fixed on back structure through 216 mount points. The relative position of mount points is changed by the deformation of back structure due to gravity, temperature, etc., resulting in the deformation of each panel besides its own.

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As we know, the radio telescope will suffer the influence of gravitational deformation, wind load, etc. and its parabolic global antenna figure should be maintained within the tolerance range as frequently as it can. Large (more than 10 m in diameter or length) radio telescopes always bend during operation, due to their enormous weight, environment temperature, etc. and the fact that even the strongest materials are not perfectly stiff. This bending, typically in the range of a few millimeters, does not affect low frequency operation much, but dramatically reduces the efficiency of the telescope such as the millimeter/sub-millimeter telescope at higher frequencies where the wavelengths are comparable to the distortion. (Typically, the efficiency of a telescope drops appreciably when the deviation from the desired shape is more than 1/10 of the considered wavelength).

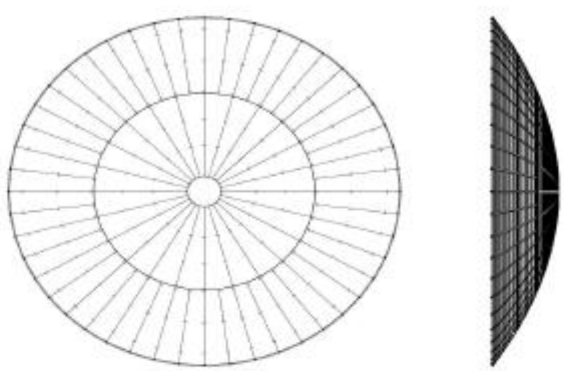

Figure 1: Layout of primary reflector.

An active surface is a surface of a radio telescope that is under the active computer control of its shape. For a radio telescope's antenna with panels, these panels are installed and adjusted to be a continuous surface at the corners, where there is a conjunct displacement actuator supporting the several neighbor panels. Besides the design of improved and enough stiff antenna mechanical support, an active surface, as key techniques for construct a large radio telescope, is now developed to solve the above problem, which uses numerous small actuators to move the surface panels with respect to the underlying frame, and thus maintains the correct shape, like the segmented mirror active optics widely applied in optical/infrared segmented primary reflecting telescopes.

An active surface can try to compensate for many different types of errors. The first is gravity - this is simplest since previous measurements, or even a mathematical model, can be used to predict (and correct) any bending. The more difficult is the correction for wind and thermal errors, since these errors require measuring and correcting in real time. Therefore, a real time system should be developed to implement the active surface control and estimate the real time figure at any elevation angle, which would real time test all the surface deflection of all panels of the whole antenna, thus real time aligning them through actuators' adjustment.

The key techniques of active optics in radio telescope are similar as those of the optical telescope, including the wave front measuring and co-phase sensing, active correction and maintenance for all panels. The Shack-Hartmann (S-H) wave front measuring method and displacement sensor have been already used in several large optical telescopes with segmented mirrors, such as Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) for its two segmented mirrors.

LAMOST project's having been completed successfully indicates that the key techniques of active optics have been mastered by the Chinese astronomical community. LAMOST project developed active optics for both of segmented mirror and deformable mirror. The techniques developed in large optical telescope like LAMOST for segmented primary mirror can be applied in the active surface of the millimeter/sub-millimeter-wave telescope, but with much lower requirement in accuracy comparing with the extremely large optical telescope of the same aperture. Compared with different optical waveband, the requirement of radio telescope antenna is several hundred times looser. According to diffraction condition, the figure requirement of millimeter/sub-millimeter-wave telescope with the shortest radio wavelength is about several microns root mean square.

Experts of Nanjing Institute of Astronomical Optics and Technology (NIAOT), builders of LAMOST, started to consider how to use the above techniques developed in large optical telescope such as LAMOST to improve the performance of millimeter wave/sub-millimeter-wave telescope. In order to do more research work about active optics of millimeter/sub-millimeter band and improve the global performance of the above 13.7 m millimeter-wave telescope, researchers of NIAOT intend to upgrade the reflector accuracy of this telescope with active surface techniques. Of course, our aim is also to find the techniques that can be applied universally in almost every occasion for active surface of a radio telescope.

In this paper the preliminary work of the accuracy-upgrading task is introduced for the above 13.7 m millimeter-wave telescope. A Shack-Hartmann device is proposed to measure and maintain the curvature of the active surface and co-focus, together with a set of displacement sensors at the edge of each panel to maintain co-phase of the active surface. Comparing with the optical telescope, there is something still different for Shack-Hartmann wave front measuring, because the working wavelength is much longer than that of visible light, and it should be used in daytime without stellar sources for wave front sensing. For displacement sensor, since it only needs accuracy in micron meters, which is about a hundred times lower than that of optical telescope, a kind of displacement sensor with micron meters accuracy such as LVDT should be good enough and inexpensive. The following is the scheme of reflector adjustment system for the above 13.7 m millimeter telescope.

2. SCHEME OF REFLECTOR ADJUSTMENT SYSTEM

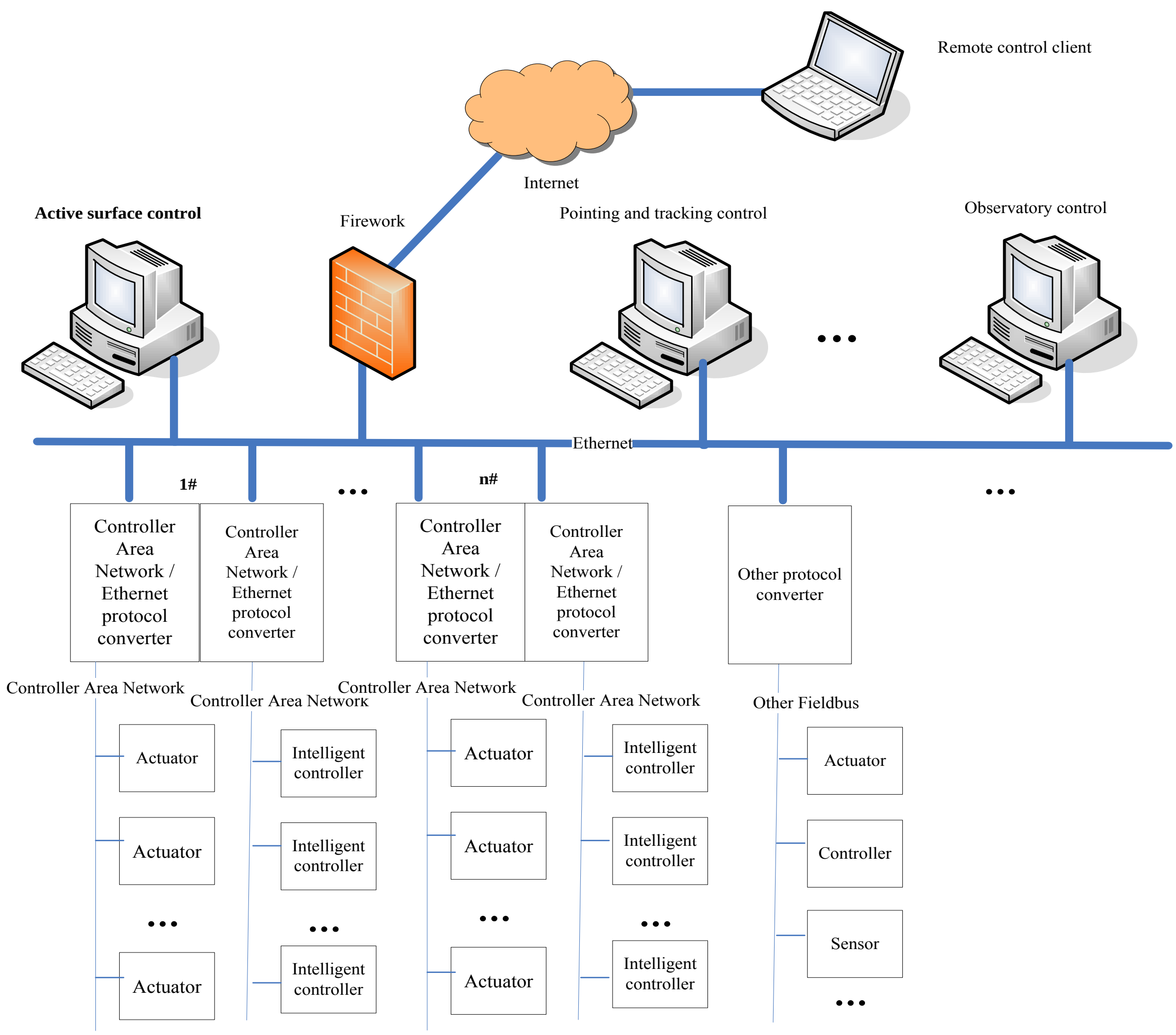

Figure 2: The scheme of **a** reflector adjustment system for the above 13.7 m millimeter telescope

Due to gravity, temperature, wind, etc., there are errors between the actual surface and the ideal surface of the antenna consisting of panels when a large radio telescope is at work. To compensate for these errors, the reflector adjustment system shown as fig. 2 is introduced to improve the observation efficiency of the antenna at high frequencies according to the changes of the antenna situation in the observation process through the communication between the active surface control computer and intelligent controllers based on Controller Area Network. The active surface control computer estimates the real time active surface figure at any elevation angle and sends the compensations to the intelligent controllers to reduce or eliminate the adverse effects of the reflector deformation. The intelligent controller issues action orders to the displacement actuators to adjust the real-time position of the antenna panels for the required antenna reflector accuracy. At the same time, the intelligent controllers report the current situation of the actuators to the active surface control computer to monitor the real-time status of each control node. The real time active surface figure is estimated and controlled through the actuator displacement calculation of the active surface control computer as follows.

3. CALCULATION OF DISPLACEMENT

A displacement actuator is placed at the common point of per four panels. There are N sets of displacement actuator. x_i is the displacement of the i actuator, s_{i0} is the acquisition value of coplanar calibration, s_{ij} is the feedback value of real-time control at j moment, $S_0 = \begin{bmatrix} s_{10} \\ s_{20} \\ \cdots \\ s_{n0} \end{bmatrix}$, $S_j = \begin{bmatrix} s_{1j} \\ s_{2j} \\ \cdots \\ s_{nj} \end{bmatrix}$, $Y = S_0 - S_j$ *and* $a_{ij} = \dfrac{\partial s_{ij}}{\partial x_i}$.

Then the control equation:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1i}x_i + \cdots + a_{1n}x_n = y_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2i}x_i + \cdots + a_{2n}x_n = y_2 \\ \cdots \\ a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{ni}x_i + \cdots + a_{nn}x_n = y_n \end{cases} \quad (1)$$

Written in matrix form:

$$A\vec{X} = -\vec{Y} \quad (2)$$

$$A = \begin{bmatrix} a_{11}, a_{12}, a_{13}, \cdots a_{1m} \\ a_{21}, a_{22}, a_{23}, \cdots a_{2m} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ a_{n1}, a_{n2}, a_{n3}, \cdots a_{nm} \end{bmatrix}$$

is the actuator influence function, N=486.

Using the least squares method, there is the equation:

$$A^T A\vec{X} = -A^T \vec{Y} \quad (3)$$

According to the above equation, write a program run in the active surface control computer to solve the actuator displacement X with Gaussian elimination method, and then convert it into the steps of the stepper motor to achieve automatic control of the displacement actuator. A Controller Area Network /Ethernet protocol converter is designed below for the communication between the active surface control computer as a host computer in Ethernet and the displacement actuator controller in Controller Area Network.

4. CONTROLLER AREA NETWORK/ETHERNET PROTOCOL CONVERTER DESIGN

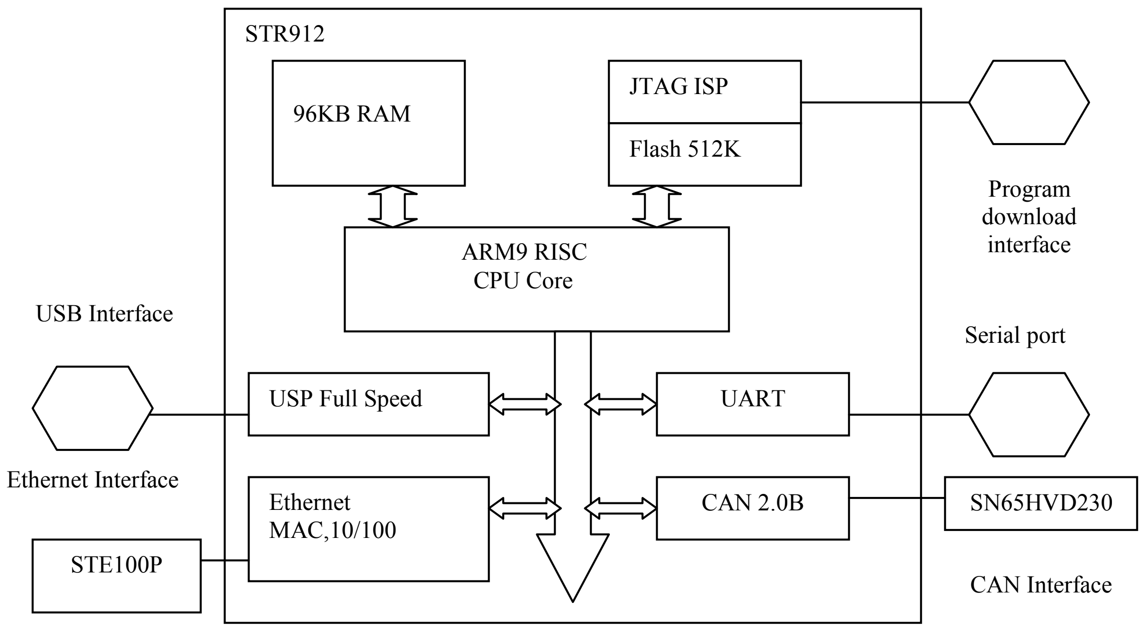

Figure 3 Hardware structure of protocols converter

The protocol conversion hardware and software structure is shown in fig. 3 and fig. 4 respectively. TCP/IP protocol stack is implemented by TcpIp_Task. Data receiving of CAN is triggered by interrupt. In the interrupt service program, Messages are sent to Can_Task and Can_Recv() is called to judge the data type. Messages are sent to drive Udp-Task if it is query message and to drive Can_Udp_Task if it is alarming message.

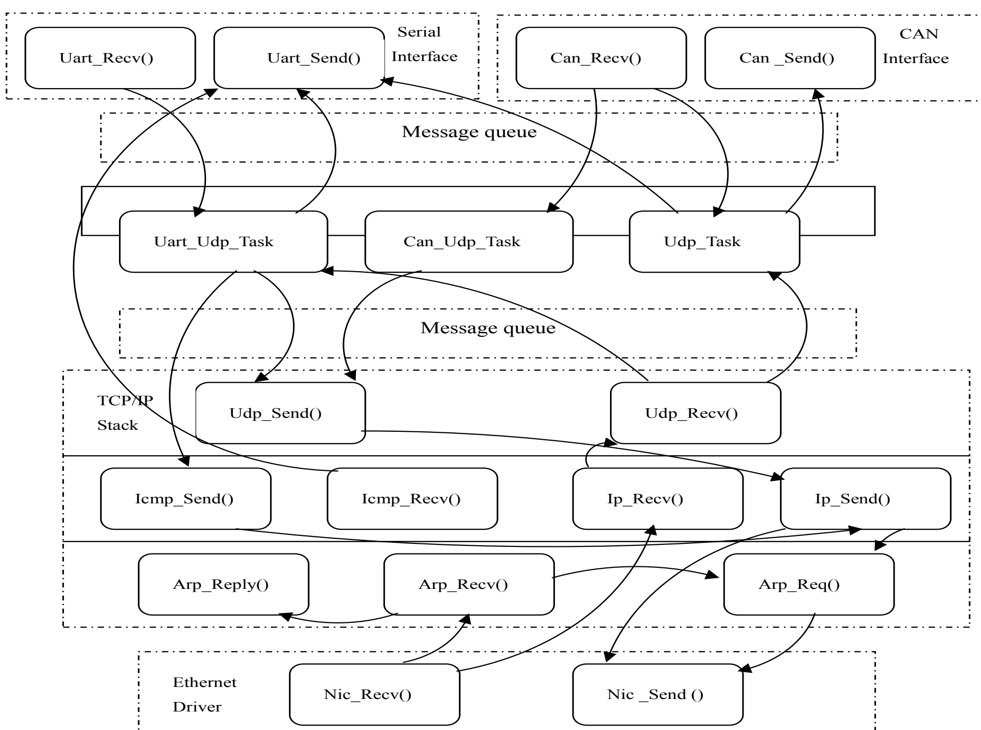

Figure 4 Software structure of protocols conversion

5. ACTUATOR AND ITS INTELLIGENT CONTROLER

The displacement actuator controller as follows in Controller Area Network receives the displacement estimation from the active surface control computer in Ethernet through the above protocols converter. As shown in fig. 5, the entire close-up control system of displacement actuator includes driver, intelligent controller and feedback link based on the optical encoder. Integrating the controller and driver achieves the closed-loop control of the stepper motor and improves the control accuracy greatly.

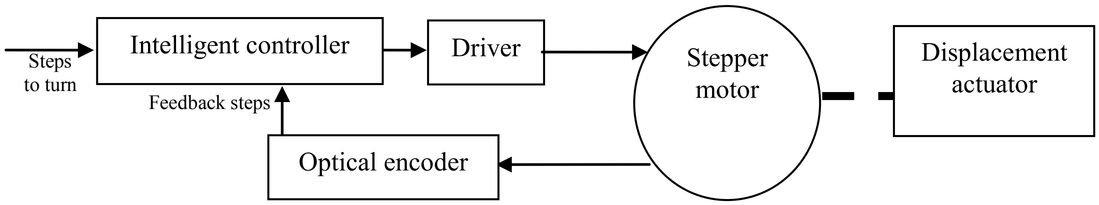

Figure.5 Close-loop control of displacement actuator

The optical encoder built in a stepper motor detects the rotation angle of the stepper motor to make the driver with out-of-step detection and stall protection function.The intelligent controller receives instructions from the active surface computer and judges and regulate step losses.

6. CONCLUSIONS

To collect more radio signals and increase resolution and sensitivity of a radio telescope, researchers have expended tremendous efforts in recent years to increase the size of radio antenna together with building a radio antenna array. A radio telescope usually has a very large diameter with its antenna consisting of a great number of small regular panels. A traditional radio telescope usually adopts a passive antenna. Before or between the operations, the antenna is tested and adjusted at an intermediate elevation of its operation sky area and will not be actively aligned during running. However, due to gravity, temperature, humidity, wind loading and so on, there are errors between the actual surface and the ideal surface of the antenna when a large radio telescope is at work. In this paper, the outline of active surface technique of a large radio telescope is analyzed to increase its resolution and sensitivity. Then considering the characteristics of the primary reflector of a 13.7 m millimeter-wave telescope, a novel active surface control method is proposed to compensate for the above errors and improve the observation efficiency of the antenna at high frequencies according to the changes of the antenna situation in the observation process through the communication between the active surface control computer and intelligent controllers based on Controller Area Network. A Controller Area Network /Ethernet protocol converter is designed for the communication between the active surface control computer as a host computer in Ethernet and the displacement actuator controller in Controller Area Network. The displacement actuator is driven by a stepper motor and controlled by an intelligent controller with the data from the active surface computer. The closed-loop control of the stepper motor improves the control accuracy greatly through the feedback link based on the optical encoder.

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