Analysis of Industrial Ethernet used in Active Surface System of QTT

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Abstract. Industrial Ethernet is widely used in automation and control system because of its high reliability and good communication performance. There are several protocols for Industry Ethernet. In different applications, it is necessary to select a appropriate protocol standard according to different needs. In order to apply industrial Ethernet in the active surface system of QTT, the control network requirements of active surface system were summarized. The period and jitter of three protocol standards, Ethernet/IP, Profinet RT and EtherCAT, were tested by evaluation hardware. The differences between network configuration and ring redundancy settings are analyzed. The results show that EtherCAT is more suitable for the network application requirements of active surface system of QTT.

1. Introduction
At present, there are many industrial Ethernet protocol standards in the market. Although they all use the same OSI physical layer, they have made different modifications to data processing. There are some differences in performance and function. Although multiple communication stacks can be run through proxy devices, there is still a considerable degree of incompatibility between devices and protocols on industrial ethernet [1]. In order to apply industrial Ethernet in engineering, we need to consider many different factors, such as real-time performance, installation cost and maintenance cost, to determine the appropriate protocol standard. Therefore, it is important to select the appropriate standard of industrial Ethernet protocol.

Industrial Ethernet has been applied in the construction and upgrading of several astronomical telescopes recently. Different telescopes choose different protocol standards. GBT adopts EtherCAT communication in the antenna azimuth and elevation drive system [2]. LMT applies EtherCAT to active surface system of telescope [3]. Profinet protocol is adopted in FAST.

The QTT telescope, which will be built at Qitai in Xinjiang, also plans to apply industrial Ethernet in its active surface system to realize the task of multi-node control. In this paper, according to the requirement of redundancy and topology of the active surface system, we will select the appropriate protocol from Profinet RT, Ethernet/IP and EtherCAT. The period and jitter of three protocols is tested by an evaluation board.
2. Active Surface System and its Control Network of QTT

Xinjiang Qitai Radio Telescope (QTT) with 110-meter aperture covers the working band from 150 MHz to 115 GHz [4]. The active surface system of telescope is composed of intelligent actuator, control module, fieldbus and power supply module. The control module communicates with the actuator through the fieldbus. The control network is a multi-node control system with about 2000 network nodes. It is a large spherical network in structure. Functionally, it can form a specific paraboloid by controlling the position adjustment of the actuators on the main reflector to improve the surface accuracy.

In order to improve the reliability of the system and the efficiency of data distribution, the control network of active surface system will adopt a hierarchical structure design. The top master station is the antenna active surface control computer. It receives the commands of the antenna control computer. According to the pre-stored actuator displacement matrix or real-time correction, it sends the displacement instruction packages to the middle controllers. Then, the middle controllers distributes the control commands to the nodes in the network segment. In addition, the middle layer is also responsible for the actuator state feedback and fault alarm upload. The actuator is equipped with displacement sensor to complete its position closed-loop control. The actuator feeds back the fault diagnosis, equipment status and operation information to the upper layer in real time. The overall structure is shown in Figure 1.

![Figure 1. Network structure of QTT](image)

As a multi-node control network, active surface control system needs the requirements of stability, electromagnetic compatibility, reliability and maintainability [5]:

- In order to complete the basic functions of command receiving and sending, condition monitoring and support the requirements of closed-loop quasi-real-time control, it is necessary to adopt a high transmission rate protocol.
- In order to meet the requirements of RFI, optical fiber will be used.
- In order to ensure the reliability and reduce the complexity of routing, bus topology is adopted.
- In order to improve the reliability of the system, the form of ring redundancy will be adopted.
- In addition, other requirements for selected communication protocol standards include: High reliability of communication; Flexible topology and good expansibility; Perfect detection and diagnosis functions; Widely support for equipment and technical; Long technical life cycle.

There are more than ten Fieldbus in IEC61158 international standard [6]. However, most of these buses are low-speed buses, with the maximum transmission rate not exceeding 16Mbps. It limits the data communication capability and access scale of the system. After screening, this paper will select one from three protocol standards: Ethernet/IP, Profinet RT and EtherCAT.
3. Three Industrial Ethernet Protocols

3.1. Ethernet/IP

Ethernet/IP is a protocol developed by Rockwell Automation in 2001. It is currently maintained by ODVA. It communicates through standard Ethernet hardware and TCP/IP and UDP/IP stacks. Ethernet/IP uses CIP (Common Industrial Protocol) in its application layer, session layer and presentation layer, and TCP/IP or UDP/IP in its network and transport layer.

Under CIP, Implicit message (UDP/IP) is used to transmit cyclic process data, which is prioritized by Ethernet priority tags. Explicit message (TCP/IP) is used to transmit configuration, diagnosis and other data. The producer-consumer model is used for communication between nodes. Here, messages for specific nodes are transmitted to all nodes. However, once a node receives a message, it filters it, so it only reaches the expected node [7,8,10]. As shown in Figure 2. It needs to broadcast and filter in each node. Because the data link layer still contains CSMA/CD, star topology and switch are usually used to avoid network conliction.

![Figure 2. The producer and consumer model](image)

3.2. Profinet RT

Profinet is a family of protocols developed by Siemens. It can be divided into three categories: standard communication, RT and IRT. They realize transmission in the network by sharing bandwidth. Bandwidth is divided into IRT channel and standard communication channel. The standard channel is shared by RT and standard communication. PROFINET RT is designed for process data transmission between a controller and multiple devices. RT and standard Ethernet devices can be used in the same physical network because they both use standard Ethernet media access mechanisms.

Profinet RT uses OSI layers 1, 2, 7, and no IP for data routing. In this case, the address of the packet is not realized by IP address, but by the MAC address of the receiving device. Some protocol layers are removed to reduce message length. Data is controlled according to priority. Communication uses the producer-consumer model. Cyclic process data is transmitted from the transmitter to the receiver at a fixed time interval. The data is unprotected and unacknowledged during transmission [9,10].

3.3. EtherCAT

Beckhoff released Ethercat in 2003. At present, it is supported by ETG. The host of EtherCAT can be implemented with standard Ethernet hardware, but the slave needs a dedicated EtherCAT controller. The basic principle of EtherCAT is based on logical ring topology.

EtherCAT adopts master-slave communication mode. The master station sends an Ethernet frame to the ring containing all the input process data of the slave station. Then, the frame is "dynamically" processed by each slave station: it extracts input data, inserts output data, and forwards the frame to the next slave station. This process is performed on hardware, resulting in low and fixed delays. At the end of the loop, the fully processed frame is sent back to the master station. On the Ethernet layer, all EtherCAT slave devices use the same MAC address and do not provide IP connection, but the transmission of Ethernet standard communication in the EtherCAT network is transparent [8-10].

4. Experimental Setup for Communication Network

Ethernet/IP and Profinet RT adopt producer-consumer communication mode. EtherCAT adopt master-slave communication mode. In order to facilitate comparison, we choose the time interval TcM and TcS of master and slave communication, shown in figure 4 and 5, as the evaluation criteria. NetSHIELD of Hilscher and STM32 Nucleo-F767ZI of STMicro are used as slave communication
module and application layer. Hischer's cifX 50E is the master communication module. Using the same hardware, different protocol stack firmware is loaded to realize different protocol communication. The communication rate is 100Mbps and the communication period is set to 1ms. As shown in figure 3, the topology is bus type, and the length of each cable is 1m. The number of slave stations is 1 to 10 and the input and output data are 10 Bytes to 50 Bytes.

![Figure 3. Hardware configuration for testing](image)

5. Test Result

Figure 4 is the data exchange sequence of Ethernet/IP and Profinet RT. The master station acts as a producer to send data to a slave consumer. The slave station consumes the data. The slave station acts as the producer to send data to the master station consumer. The master station consumes the data. Because of the point-to-point transmission, there is a time loss of media contention in the data transmission process.

![Figure 4. Data exchange sequence of Ethernet/IP and Profinet RT.](image)

![Figure 5. Data exchange sequence of EtherCAT.](image)

Although the communication period is set to 1 ms, in practice, the transmission interval TCm of the master station, shown in figure 4, and the transmission interval TcS of the slave station, shown in figure 5, are more than 1 ms in most cases, but the deviation is not large. This is mainly due to the processing time of protocol stack in the case of pure software implementation. Moreover, the interval time tends to increase with the number of slave stations in the network, which is related to CSMA/CD mechanism. However, there is no obvious trend in the number of different bytes, which indicates that the amount of data has little effect on the cycle at 100Mbps communication rate.
Because Profinet RT has a minimum communication byte limit (40Bytes), this test adds a set of 64Bytes test data. Figure 8 and figure 9 show that Profinet RT and Ethernet/IP test results are similar. TcM and TcS also have some deviations from 1ms. Because it is also a form of software communication protocol. Moreover, the deviation increases with the increase of the number of slave stations.
Figure 5 is the data exchange sequence of EtherCAT. Data frames are always sent from the main station and eventually back to the master station. When only EtherCAT communication exists, there is no media contention problem. But the data transmission time will increase with the number of slave stations in the network.

![Figure 10. TcM of EtherCAT](image1)

![Figure 11. TcS of EtherCAT](image2)

Because the communication process of EtherCAT is handled by hardware, its TcM and TcS are stable in 10 to 50 bytes of communication data and different numbers of slave stations, as shown in Figure 10 and Figure 11. It is slightly less than 1 ms, although the communication period is set to 1 ms.

![Figure 12. Time cost of EtherCAT master station](image3)

Figure 12 is the communication time cost Ttr of the EtherCAT master station, shown in figure 5, from sending to receiving. The amount of communication data has little effect on time cost. It should be noted that the actual amount of data sent by the master station of EtherCAT increases from 20Bytes to 1000Bytes because the data sent by the master contains all the input and output data of all the slave stations. It can be seen that at 100Mbps communication rate, the influence of 1000Bytes data per frame on periodic jitter is still very small.
The number of slave stations has a certain linear relationship with time-consuming. Because the length of the cable is only 1 m, the increase of transmission time on the cable due to the increase of slave station can be neglected. The main time cost increase occurs in the process of the receiving and sending of the newly added slave station.

6. Discussion
According to the test results, it can be estimated that the $T_{cM}$ and $T_{cS}$ of Ethernet/IP and Profinet RT in 100 slave stations with 50 bytes of data are less than 1015us. But this kind of calculation is a linear one. According to the conclusion of literature [11] the collision probability does not increase linearly with the increase of slave stations. Therefore, the actual $T_{cM}$ and $T_{cS}$ will be significantly larger than 1015us. For Profinet RT, the time offset of different slave stations can be set in the communication cycle to reduce the probability of collision. But this increases the workload of configuration. Ethernet/IP has no corresponding functions. Therefore, when the number of slave stations is large, star topology is recommended for both protocols. To achieve better real-time performance, Ethernet needs to use hardware-supported CIPSync protocol, and Profinet also needs Profinet IRT.

When extended to 100 slave stations, the communication time of EtherCAT shows a linear trend. The number of bytes in all slave stations will exceed the maximum frame length of 1514 bytes. Data will be sent in multiple data frames. It is expected that EtherCAT can still ensure the stability of $T_{cM}$ and $T_{cS}$, and is less than 1 ms.

There are some differences in the network configuration and ring redundancy of these three protocol standards when they are applied in the active system of QTT.

Ethernet/IP can use DHCP to configure slave IP. But in the application of this paper, the displacement commands sent by the controller need to correspond to the actual position of each actuator on the main reflector of the antenna. Therefore, it is necessary to set a static IP for the actuator to ensure that the IP address corresponds to the actuator one by one. This increases the workload of network configuration. Profinet RT has the same problem. Although IP address is not necessary, the DCP mechanism of Profinet protocol requires the slave station to have its station name. Therefore, the station name must correspond to the actuator one by one. EtherCAT has a variety of addressing methods. The address obtained by location addressing corresponds to the actual physical location of the slave station in the network. Compared with the previous two protocols, it saves a lot of work. After all actuators are installed, the actuator network information consistent with the actuator physical connection can be obtained through network scanning. On this basis, the network configuration can be easily completed.

Both slave and master stations of EtherCAT can achieve circular redundancy without additional hardware, which improves the reliability of the network. Ethernet/IP needs splitter. Profinet RT requires additional redundancy managers. The implementation of ring redundancy in Ethernet/IP and Profinet RT will be more complex than that in EtherCAT.

7. Conclusion
According to the system requirements described in chapter 2, we expect the QTT active surface system control network to be a hierarchical structure. Each network segment contains 80 to 120 slave stations. The slave stations are connected to each other in a Daisy chain and form a ring redundancy. The communication data of each slave station is about 50 bytes of input and output.

Under these conditions, EtherCAT has better real-time performance than Ethernet/IP and Profinet RT. Moreover, it is simple to realize circular redundancy. It is also more flexible and convenient in network configuration. Although its hardware cost is higher than the other two. Unless Ethernet/IP and Profinet adopt hardware-supported protocols as well as EtherCAT, performance similar to EtherCAT can be achieved. But the configuration and topology constraints they are subject to will also increase. Therefore, this paper considers that EtherCAT is a better industrial Ethernet protocol standard which is suitable for the requirements of the active surface system of QTT.

8. Acknowledgments
This work was supported by the National Natural Science Foundation of China(Grant NO. 11803078).
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