Research of Maintenance Manipulator in Remote Handling System for Small Openings

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Abstract. Remote handling maintenance system, especially in the cavity with small openings and complex inner geometry, has been regarded as the key issue on the maintenance for the Magnetic Confinement Fusion (MCF). The maintenance system presented here is specially researched for Tokamak of ITER that need to be monitored to guarantee working well and safely. Due to neutron activation, the repair, inspection or maintenance of in-vessel components of Tokamak has to be carried out remotely. With the increasing demand of communication bandwidth, response speed and real-time of open control system for multi-DOFs manipulator and considering the current system's shortage in real-time and stability, this paper presents the control system of 12-DOFs maintenance manipulator in remote handling system. The system based on the EtherCAT network performances well in real time with sufficient stability.

Keywords: ITER · Real-time Ethernet · EtherCAT · Remote handling

1 Introduction

ITER machine, the full superconducting tokamak with doughnut-shape chamber and no-circle cross-section, which will be built at Cadarache in the South of France, aims to verifying that the whole system function works properly and is ready for the operation. Remote Handling maintenance system, especially in the Tokamak with small openings and complex inner geometry, has been regarded as the key issue to the maintenance for the Magnetic Confinement Fusion (MCF) [1] and are engaged in the maintenance process (viewing, dust deposition, fault detection, fault diagnosis, maintenance) of MCF [2, 3]. The maintenance system of the Magnetic Confinement Fusion (MCF) need to be monitored to guarantee working well and safely. Meanwhile the repair, inspection and maintenance of it has to be carried out remotely due to neutron activation [4]. In order to complete the maintenance task, such as fixing a loose screw mounted on the inner cavity surface, the mechanical system design of multi-DOFs manipulator, control system design, remote handling, motion control and other technology should be taken into account. Many remote handling researches have been done in the past regarding inspection and maintenance tasks of tokamak vacuum vessel, such as the vehicle-manipulator system for blanket maintenance [5], the dexterous water hydraulic manipulator [6], the flexible in-vessel inspection

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system for the plasma facing components (PFCs) [7] and an 8-m long multilink articulated inspection arm robot [8], etc. Although lots of researches on the remote handling system, such as blanket handling system, diverter handling system, close inspection of PFCs system, have been carried out, there is no one system focusing on sophisticated tasks, such as mounting an screw on the inner wall of cavity. Without any doubts such complex system may bring into some disastrous defects because of its complexity and the lacking experience of researchers and the system itself should have a better performance of communication bandwidth, response speed and real-time because of the high-precision in motion controlling. In recent years, more and more fieldbus apply to the open control system of multi-DOFs manipulators, especially for the sophisticated system. However, the control system transmitted by conventional bus will be faced with severer problems of real-time and coordination especially while controlling more axes and joints and cannot meet the demands gradually.

Real-time EtherCAT can achieve high performance of anti-interference and robustness in process, especially for high-speed, high-reliability and high real-time data transfer applications. It overcomes the bottleneck of high performance of data transmission in complex remote handling system. In this paper, we present the complex remote handling system including the mechanical design of manipulator and the control system architecture. In detail, the paper is organized as follows. In Sect. 2, a brief description of EtherCAT is presented and the remote handling system and the mechanical design of manipulator is proposed in Sect. 3. The details of control system architecture and some insights on system behavior and performance based on EtherCAT networks are presented in Sect. 4. Finally, Sect. 5 draws the corresponding conclusion.

2 EtherCAT

EtherCAT (Ethernet for Control Automation Technology) is real-time Ethernet network that achieves high communication efficiency that reaches cycle times well below 1 ms. EtherCAT protocol is a kind of industrial communication protocol that makes full usage of Ethernet full-duplex features. EtherCAT overcomes the traditional field-bus and industrial Ethernet bottlenecks, making real-time performance higher. Therefore, EtherCAT has obvious advantages of precious position control of serial robots.

EtherCAT relies on a master/slave medium access control policy where a single master sends commands to the slave devices to read and write values [9]. The master has to process, send and receive Ethernet frames for slave nodes during each network cycle. Usually all nodes communication are completed within one or two frames each cycle. EtherCAT does not require a dedicated master card: any standard Ethernet Controller is suitable, since the master protocol is implemented in software on the host CPU that runs the application program as well [10]. EtherCAT slave device must have EtherCAT slave controller while no need of a microcontroller at all. Simple devices that get by with an I/O interface can be implemented only with the ESC and the underlying PHY, magnetics and the RJ45 connector.

3 Remote Handling System and Mechanical Design

At the beginning of the system design study, it is necessary to make an analysis of the requirements and constraints for the remote handling system. Firstly the geometrical requirements are the ITER Tokamak parameters ($R = 6.25$ m, $a = 4.5$ m), the remote handling equatorial port ($W \times H$, 2 m × 2.5 m) and the limited small openings in the Tokamak. Here, the design and system verification in details should be done according to the model proportion of 1:10. Secondly the workspace should be able to reach the overall volume of the Tokamak and the accuracy is within 1 mm. Thirdly, the system should ensure not damage or collide the normal operation area of MFC during fault diagnosis and maintenance. The last one is that the operation should be controlled remotely.

Considering the actual geometric requirements and the intensity of the Tokamak equatorial port distribution, it seems that the system with multi-DOFs manipulator (macro-micro structure) is a good choice for executing detecting and maintaining tasks. The task can be naturally divided into three subtasks: transfer the manipulator folded in cassette mover to reach the vessel and lock with the maintenance port of the vessel, push the 12-DOFs manipulator to slide into the vessel and execute the detecting and maintenance task in the vessel. A long distance multi-DOFs manipulator is distinguished by its larger doughnut-shape workspace, narrow cross-section corresponding to the small openings and lightweight design. Unfortunately, increasing the joints' numbers and decreasing its mass enhance obviously structure compliance [11, 12]. Usually, two sets of remote handling maintenance systems are typically used to achieve some collaborative maintenance. The 3D model view of the remote handling maintenance with Tokamak and its non-circular cross-section is shown in Fig. 1.

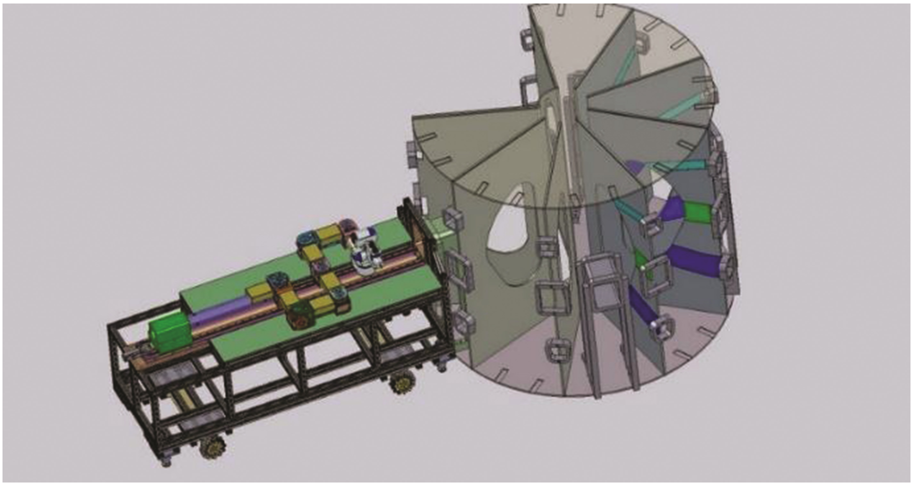

Fig. 1. 3D model of the ITER Tokamak

The architecture of the remote handling system is a modular subsystem design that consists of a long distance multi-DOFs manipulator with 12 degrees of freedom (DOF) including a 6-DOFs macro arm and another 6-DOFs teleoperation manipulator also known as micro arm. Furthermore, a designated multipurpose transport cask (MTC) provides one DOF for pushing the 12-DOFs manipulator to slide into the Tokamak vessel. The function of the MTC, which has four omnidirectional mobile wheels and a high-precision translational guide rail, is to store the 12-DOFs manipulator and transmitting the manipulator into the vessel. The macro arm, which has six modular rotary axes, is used to carry and transmit the micro arm into the Tokamak in the range of 180° along the horizontal direction as shown in Fig. 2. All the joints of the manipulator are driven by the actuator with harmonic gear and have a planet or spur gear mechanism for all revolute joints.

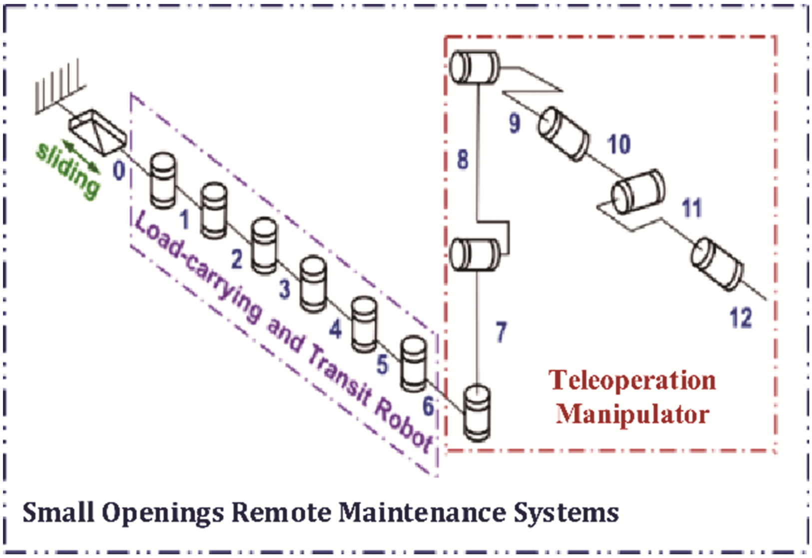

Fig. 2. The configuration of the 12-DOFs manipulator

4 Remote Handling System Architecture

The remote handling system is one of the numerous ITER Plant systems that are closely based on the hierarchical structure of the ITER CODAC system [13, 14]. The control system presented in this paper is especially suitable for remote handling system that is designed for performing maintenance tasks in the Tokamak. The remote handling system mechanical structure is shown in Fig. 3. Taking into account the complexity of inner geometry features of Tokamak, working randomness and uncertainty, we should ensure high response speed of motion control, multi-axis synchronous operation and higher motion accuracy of the system.

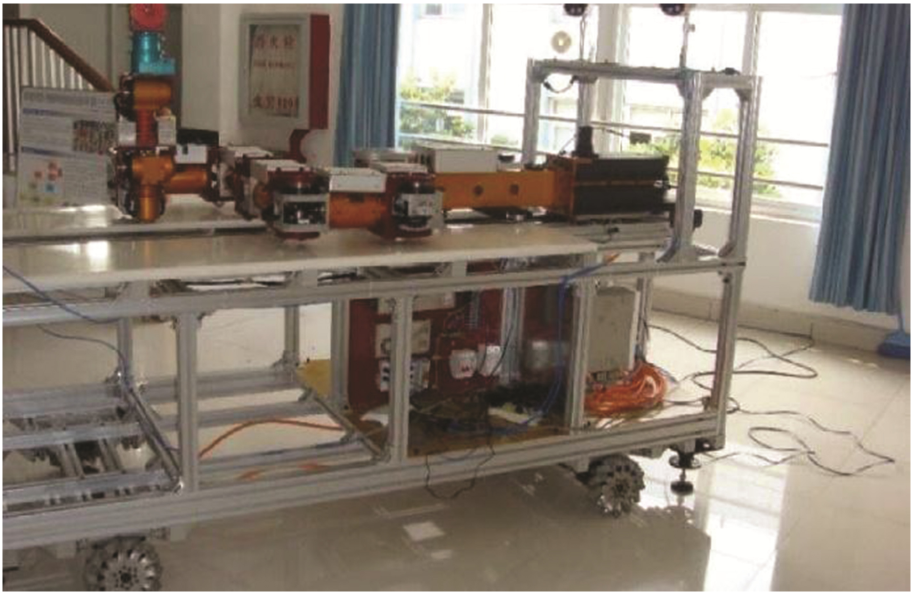

Fig. 3. The real photo of the remote handling system

The remote handling system based on EtherCAT network takes a master/slave control approach. The master is industrial computer while slave devices are servo drivers in favor of EtherCAT protocol, sensors, EK1100 and EL6752 terminal boxes developed by Beckhoff, etc. We adopt the simple line structure as shown in Fig. 4 considering that the wiring length of mechanism has a great impact on the robot movement and that the performance of bus coupler influences the network cycle.

In order to ensure the maintenance tasks successfully completed in the cavity, some sensors have access to the network such as force sensors, laser sensors and cameras. The force sensor based on DeviceNet is accessed to the network by EL6752 DeviceNet master terminal from Beckhoff for force feedback of the manipulator end. The laser based on RS232 interface is used for the location of manipulator end in the cavity and has direct access to the master. The camera is applied to the real-time feedback of working condition through wireless transmission. Servo drivers connected to the EtherCAT networking are available in a variety of feedback selections such as incremental encoder and digital hall and I/O configuration possibilities.

As to the software, we adopt the TwinCAT (The Windows Control and Automation Technology) as communication application. The Ethernet card integrated on PC motherboard is used as communication module instead of dedicated PCI card, which simplifies the complexity of system but increases the stability. It turns almost any compatible PC into a real-time controller with a multi-PLC system and replaces conventional PLC controllers. Therefore, the PC acts as the EtherCAT master. TwinCAT software architecture can be divided into three layers: user interface layer, intermediate layer and motion control layer. The user interface layer is to realize human-robot interaction via HMI (Human Machine Interface). Intermediate layer mainly made up of run-time system

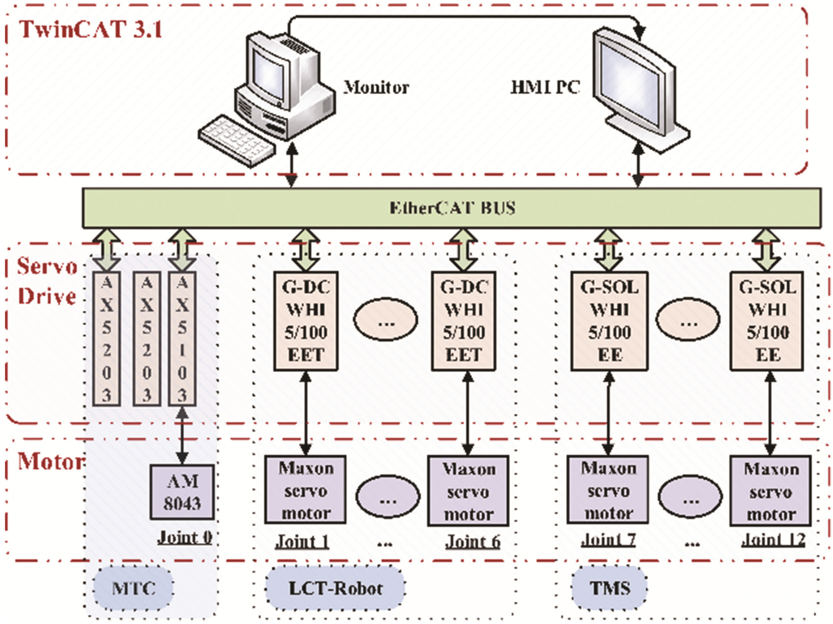

Fig. 4. System hardware components

is applied to realize the interaction between user interface layer and motion control layer via configuring different task information, I/O information and NC axis variables information. Motion control layer includes PLC control unit and servo control unit.

This paper takes the 12-DOFs manipulator as test platform and do some basic analysis of real-time parameters of EtherCAT network such as communication cycle time and propagation delay time. The propagation delay consists of a time component for forwarding a frame and the medium delay [15]. The cycle time is basically stable at 1 ms when we set the cycle time to 1 ms. In addition, there is nearly no change between the different slave nodes when the nodes are no more than 30. To a conclusion the system based on EtherCAT network achieves a good performance of real-time and stability. Although the presence of jitter in the communication process, the rate is small and the jitter substantially has no effect on the cycle. Additionally, propagation delay will increase as slave nodes increase. Nevertheless, sub-microsecond rise time almost has no influence on the real-time.

5 Conclusion

The remote handling system is under design and manufacture for the purpose of remote flexible inspection and maintenance of the surface of ITER Tokamak, helping to understand what would happen in the Tokamak and how to handle some special breakdown during operation. We present the detailed design of remote handling system that has the benefit of easy passing each equatorial port and the potential to be developed into a components replacement remote handling system. Some elementary analysis work, such as mechanical design and the control system architecture, was fulfilled.

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