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Abstract

The in-vessel components of fusion reactor, such as the divertor and blanket that face the hot plasma during plasma operation, need regular maintenance due to the damage caused by the heavy heat load, the thermal stress and the complex electromagnetic force during the reactor operation. All the maintenance work of the key components in fusion power plant cannot be carried out by human directly without the remote handling (RH) technology due to the Deuterium-Tritium (D-T) reaction in the tokamak machine. The RH system has a significant effect to the fusion reactor' components design, the maintenance efficiency and cost as well. The RH maintenance technology is one of the most interesting fields for the fusion technology research. It has been identified as one of the most critical issues on the road to the commercial fusion power plant.

The RH maintenance system includes many complex subsystems, such as the mechanical, electrical, hydraulic, and control systems. The failure of the RH system can cause great damage to the tokamak machine due to its complex structure and functions. Therefore, it is important to improve the reliability of the RH system of the future fusion reactor in the field of nuclear fusion technology. The purposes of this dissertation is to carry out the fusion reactor maintenance research work based on the functional requirements and the maintenance feasibility of the fusion reactor. The necessity and importance of the remote handling and maintenance of fusion reactor and its basic principles were expounded. The key technical problems and the future development of remote handling and maintenance were discussed. Different maintenance schemes were evaluated based on the availability, reliability, efficiency and cost of different systems. The integrated upper maintenance scheme with the comparison advantages disadvantages of these proposals was adopted. Different RH systems, aiming for the in-vessel components maintenance in the fusion reactor, were designed based on the optimum design methods of the reliability theory. The organization of this dissertation was briefly described below:

Firstly, the structure design and kinematics analysis of the divertor RH were performed according to the functional requirements of the maintenance system. And its simulation model was built to verify the kinematics model. The actuator system and transmission mechanism scheme were designed and determined.

Secondly, the reliability based optimization analysis of the 3-DOF lifting platform for the divertor RH maintenance was studied. The mathematical model of the 3-DOF lifting platform was built based on the reliability optimization and design. The optimized parameters of the 3-DOF platform were obtained by using the intelligent optimization algorithm to meet the requirements on reliability, structural stiffness and strength.

Then, the overall control strategy and the architecture design of the control system were studied. The hydraulic driving system of the robot was designed, and the simulation model of the hydraulic driving system was built. The experiment platform was set up to verify the hydraulic servo driving system's dynamic simulation and optimization control with the differential evolution (DE) algorithm. Based on the reliability design and analysis of the RH maintenance 3-DOF platform, the water hydraulic servo control experiment was built to verify the influence on accuracy with different control strategies. The accurate position control of the hydraulic servo was realized by performing the comparative analysis between the DE optimization control and the fuzzy adaptive PID control. The experiment results showed that the DE optimization control algorithm has the advantages of small overshoot, fast response. Therefore, the DE based optimization control algorithm was applied to the water hydraulic servo control system.

Finally, further work was addressed at the end of thesis. In the design phase, several critical issues were addressed and required to be solved by both qualitative and quantitative approaches. Dynamic modelling of RH system and advanced robust control algorithms need to be developed in near future.

Keywords: fusion reactor, tokamak, remote handling maintenance, Reliability based design and analysis, differential evolution, water hydraulic servo control

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Wenlong Zhao

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Lappeenranta, Finland

Dedicated

To the memory of my grandparents and father.

Contents

Nomenclature

Abbreviations

ASIPP   Institute of Plasma Physics, Chinese Academy of Sciences

ACDE   Adaptive Centre Differential Evolution

AIA   Articulated Inspection Arm

AMM   Assumed Modes Method

ANN   Artificial Neural Network

ATS   Air Transport System

CAD   Computer Aided Design

CAE   Computer Aided Engineering

CAM   Computer Aided Manufacturing

CAS   Chinese Academy of Sciences

CCD   Charge-Coupled Device

CCFE   Culham Centre for Fusion Energy

CEA   Commissariat a I'energie atomique et aux energies

CMM   Cassette Multifunctional Mover

CODAC   Control and Data Acquisition

CTM   Cassettes Toroidal Mover

DE   Differential Evolution

DEMO   Demonstration reactor (of Europe)

D-H   Denavit-Hartenberg

DHT   Digital Human Models

DIV   Divertor

DMU	Digital Mock-Up
DOF	Degress of Freedom
DRHS	Divertor Remote Handling System
DSC	Differential Scanning Calorimetric
D-T	Deuterium-Tritium
DTP2	Divertor Test Platform 2
EA	Empresarios Agrupados
EAMA	EAST Articulated Maintenance Arm
EAST	Experimental Advanced Superconducting Tokamak
ECTS	Equatorial Cask Transport System
EFDA	European Fusion Development Agreement
ELM	Edge Localized Modes
EM	Electromagnetic
EMAT	Electromagnetic-Acoustic Transducer
ENEA	Ente per le nuove tecnologie, l'energia e l'ambiei
ESM	Element Stiffness Matrix
EU	European Union
F4E	Fusion for Energy
FEA	Finite Element Analysis
FEM	Finite Element Method
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects & Criticality Analysis
FOSM	first order and second moment
FPP	Fusion Power Plant
FRDB	Failure Rate Database

FW	First Wall
GA	genetic algorithm
GUI	Graphical User Interface
H&CD	Heating and Current Drive
HC	Hot Cell
HCCB	Helium Cooled Ceramic Breeder
HCCR	Helium Cooled Ceramic Reflector
HCF	Hot Cell Facility
HCLL	Helium Cooled Lithium Lead
HCPB	Helium Cooled Pebble Bed
HCS	Helium Cooling System
HEX	Heat Exchanger
HLCS	High Level Control System
HMI	Human Machine Interface
HP	High Pressure
HRS	Heat Rejection System
HTR	High Temperature Recuperator
HTS	High Temperature Superconductor
HVAC	Heating, Ventilating and Air Conditioning
IAEA	International Atomic Energy Agency
IB	Inboard
ICRH	Ion Cyclotron Resonance Heating
IDM	ITER Document Management System
IDEFØ	Integration Definition Function modelling-0
IEC	International Electrotechnical Commission

IFMIF	International Fusion Materials Irradiation Facility
IMMS	ITER Maintenance Management System
IO	ITER Organization
IRFM	Institute for Magnetic Fusion Research
ITER	International Thermonuclear Experimental Reactor
IVVS	In Vessel Viewing System
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus
MDT	Mean Down Time
MDTNS	Mean Down Time Non-Scheduled
MDTS	Mean Down Time Scheduled
MPD	Multi-Purpose Deployer
MTBF	Mean Time Between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time To Repair
MUT	Mean Unavailability Time
NBI	Neutral Beam Injector
NDT	Non-Destructive Testing
PFCs	Plasma Facing Components
PID	Proportional Integral Derivative
PSO	Particle Swarm Optimization
RAMI	Reliability, Availability, Maintainability and Inspectability
RBD	Reliability Block Diagram
RH	Remote Handling

RMS   Remote Maintenance System

SOSM   Second Order and Second Moment

SS   Stainless Steel

TBR   Tritium Breeding Ration

TCS   Transfer Cask System

TUT   Tampere University of Technology

VR   Virtual Reality

VTT   Technical Research Centre of Finland

VV   Vacuum Vessel

1 Introduction

1.1 Background

Currently, we use the fossil fuels such as coal, petroleum and natural gas along with nuclear power to suffice the energy requirements of our highly technology-oriented society. Fossil fuels are limited resources, which should be primarily used as raw materials (Zhu, 1992). Many problems remain to be solved regarding the use of nuclear fission reactions to generate electrical power (Qiu, 2001). While the world population continues to increase, our consumption of energy continues to increase. In this situation, it is universally acknowledged that the development of a new, sustainable energy source is the most important task that we face (Hiwatari, et al. 2005; Wan, et al. 2004). Humankind has used sunlight, an energy source derived from nuclear fusion, in daily life from the beginning of time. If the nuclear fusion that occurs in the sun can be replicated on earth, it will be possible to turn the heavy hydrogen that is available in abundance in seawater into a permanent source of energy. Research on nuclear fusion is already being actively conducted in many countries of the world, and remarkable results have been achieved in the effort to the produce and control high-temperature plasma. Although we are now at the phase where we can see the clear prospect of realizing a nuclear fusion reactor from a scientific veiw, there are still many problems to be solved before a commercial reactor can be constructed (Li, 2007; Wu, 2005).

The international thermonuclear experimental reactor (ITER) is a experimental nuclear fusion device will provide an integrated scientific and technical foundation for the demonstration reactor and the fusion energy power plant. The ITER is now in the construction phase (Holtkamp, 2007; Feng, 2009).

The strategic goal of the Chinese fusion research is to promote the realization of nuclear fusion power plant in China as early as possible (Zhao, 2004). Due to the design and construction of a fusion reactor is a long-term project, we must carry out the research on integration design and the key technology of fusion reactor from now (Li, 2008).

The China Fusion Engineering Test Reactor (CFETR) will be built to bridge the gap between the ITER and the DEMOnstration fusion power reactor (DEMO) of European to realize the fusion energy in China (Wan, 2012; Wan, 2014). According to the design requirements, the CFETR should be a good complement to the ITER (Song, et al. 2014). It will provide the fusion energy with a fusion power of 50-200MW, the long pulse or steady-state operation with run-time duty cycle 30-50%, and a full cycle of tritium self-sufficiency with TBR $\geq$ 1.2. From the current experience, the remote handling (RH) for

blanket and divertor in both the ITER and the DEMO can be changed to a more easy way (Loving, et al. 2014). Based on the investigated and evaluated results, the maintenance scheme for the blanket, which is in the form of multi-module segment, accessed via vertical ports and the maintenance scheme for the divertor cassette accessed via the lower ports are developed as the most promising configurations, as shown in figure 1.1 (Song, et al. 2014; Sibois, et al. 2014).
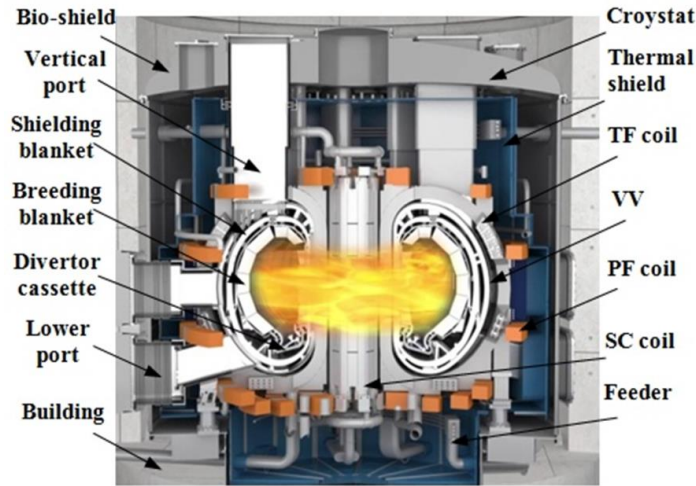
Fig. 1.1: Section view of the CFETR layout.

In order to fulfil the design of the vacuum vessel and the magnet system of the three kinds of divertor configuration, the CFETR's main design parameters are shown in the table 1.1:

Table 1.1: Main design parameters of the CFETR.

Plasma radius	R = 5. 7 m
Small radius of plasma	r = 1.6 m
Center field strong	Bt = 5. 0 T
Machine power	50 ~ 200 MW
Burning time	~ (30 ~ 50%)
Blanket thickness	0. 8 ~ 1. 0 m
Plasma boundary region waviness	<0. 5%

The CFETR consists of tokamak (vacuum vessel and its internal components, blanket and divertor, superconducting magnet system and related components), the low temperature equipment and the cryogenic circuit, the power system, the outer cryostat and its thermal shielding, the feeder system and the ash discharge system (including the ash handling system), the water cooling system, plasma diagnostic system, the heating and current driving systems and their power system, a laboratory plus its subsidiary system, and a remote maintenance system as the major components of the fusion tokamak system, as shown in the figure 1.1.

1.2   **Research background of remote maintenance technology**

In the CFETR tokamak machine, the nuclear fusion produces high-energy neutrons of power more than 14MeV, which are the main carrier of the nuclear fusion energy, accounting for 80% of nuclear fusion energy, while the energy will be absorbed by water and then converted into thermal energy to generate power. However, highly energized neutrons have strong penetration power and can react with most of the material elements, consequently resulting in induced radioactivity, deterioration of the physical and mechanical properties of materials, and loss of proper function of some materials (Buckingham, R., & Loving, A. 2016). Therefore, the first wall and the shielding components need to be regularly replaced and cleaned in the life cycle of the reactor. These activated materials, even after decades of decay, human still cannot directly touch. In addition, some hazardous materials are involved in the fusion reactor, such as beryllium and tritium. The assembly and maintenance of these hazardous materials will be carried out in accordance with the existing work safety regulations: i) to ensure the safety of the staff when contacting with toxic substances; ii) to guarantee the radiation dose (by tritium or activated material) within the safety range. For example, in the vacuum vessel of the machine, some components are made of material that contains beryllium, which itself is a highly toxic substance, even the air with 1 milligram beryllium dust per cubic meter will make people infected with acute pneumonia, so-called the beryllium lung disease, and its compounds are more toxic. Other components in the vicinity may also carry the dusts of beryllium and its compounds, therefore such components should be tele-operated even from the beginning stage, i.e., the assembly phase. During the D-T process, the components inside the vacuum vessel are contaminated by tritium; operators are not allowed to touch it directly. The maintenance of these components will be conducted in the hot cell. During the transportation of the components from the tokamak machine to the hot cell, the spread of toxic substances into the hall and the external environment is strictly prohibited. The interior of the fusion reactor is an extreme and very complex environment: high temperature, high vacuum, strong radiation and strong magnetic field.

In addition, inside the reactor, there are the various different kinds of components, the intricate pipes network, and the small workspace, besides some components contaminated by radioactive and toxic substances, and the maintenance personnel cannot or should not directly operate the related parts even during the maintenance period. Therefore, we need the RH technology to complete the assembly work and the maintenance operations of these components such as the monitoring, assembly, disassembly, welding, transportation, decontamination, storage and the corresponding components are completed through the remote control system. The remote maintenance system is a key critical subsystem of the CFETR (Wan, et al. 2016).

The remote handling is the collaborative integration of technology and engineering management systems, and enables operators to perform operations safely, reliably and repeatedly on activated components (Haist, et al. 2009).

At present, the CFETR is under the conceptual design stage. One thing should be addressed is the compatibility between the RH system and components which need RH maintenance. The RH system greatly influences the design of the related key components, such as blanket modules, divertor cassette, port plug and pipe layouts. Therefore, in the initial phase of the core system design, the RH principle should be considered (Rolfe, 2012): i) Modularize and simplify the design of components need to be maintained, simplify the component replacement procedure and standardize the procedure into steps and develop simple, feasible and efficiency RH equipment and tools. ii) Keep in mind the safety and economy of the reactor, reasonably allocate the RH maintenance time and design the task completion procedure in order to realize the task of effective maintenance of the fusion reactor. iii) The maintenance equipment must have high survivability and the maintenance tasks must be put into effect safely and reliably in pre-defined time.

The RH will have an important role in the CFETR tokamak. When an operation begins, it will be impossible to make changes, conduct inspections, or repair any of the tokamak components in the activated areas other than using the RH system. Very reliable and robust RH techniques will be necessary to manipulate and exchange components, which weigh up to 50 tons. The reliability of these techniques will also impact the duration of the machine's shutdown phase.

The main purposes of using the RH system are: 1) To provide the personal safety for the maintenance personnel; and 2) to expand the human ability in completing the task that cannot be directly operated.
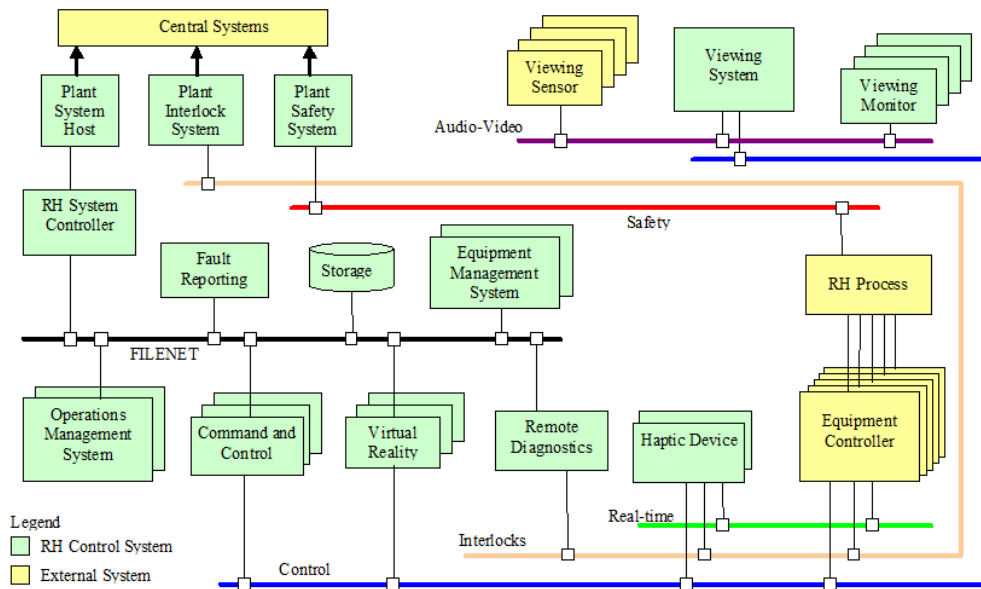
Figure 1.2: Typical architecture of remote handling maintenance system.

A typical RH maintenance system architecture includes (Murcutt, et al. 2011): the RH manipulator, the main controller operating system and the RH maintenance control system, as shown in figure 1.2. With the continuous development of the nuclear fusion research, the RH technology encounters higher requirements, e.g., i) the RH maintenance of fusion has extreme environmental conditions over other industries: high temperature, strong radiation, strong magnetic field, nuclear pollution and high vacuum; ii) the operation objects are large and heavy parts with high tolerance (the maximum weight of blanket module is 100 tons and divertor is about 20 tons), the limited operation space and poor visibility in tokamak machine. The design of the RH maintenance system will provide a technical basis for the smooth progress of the fusion reactor project.

1.3 RH maintenance development status

1.3.1 International research status

The remote handling technology is an important topic in the field of robotics developed since the 1960's, and it has been gained great economic benefits in the fields of industry, space development, biomedical engineering and other fields (Ribeiro, I, et al. 2011). RH enables the operators to do manual handling work without being physically present at that work site. Unlike conventional robotics, RH always involves a human being within the

process. The main handling device is a man-in-loop manipulator, not a robot, because the majority of RH tasks need the intuition and intelligence of a human being. The RH system used for maintenance at the nuclear fusion experiment includes robotic devices, advanced computers, virtual reality, television and a wide range of specialist tools. The technological expertise required of the personnel to design and operate these systems, which cover mechanical, electrical and electronic engineering, software, real time control, ergonomics, hydraulics, welding and cutting (David, O et al. 2005).

The development of the RH technology promoted the design of tokamak nuclear fusion to some extent and the tokamak RH maintenance technology has become one of the important research areas. Until now, several RH maintenance systems are successfully developed or under construction in the JET, the Tore-Supra, and the international cooperation project ITER (Mindham, et al. 2011).

Europe has conducted the nuclear fusion machine of the Joint European Tokamak (JET), located in the UK and master-slave control manipulator arm that can be remotely controlled through a vacuum vessel port was developed. In the world, the JET is the only tokamak machine, which can successfully conduct the maintenance operation of the internal components of reactor through the remote handling operation. The machine uses the master-slave remote handling to complete the equipment maintenance and other operational tasks, as shown in figure 1.3 (Rolfe, 2013).

Figure 1.3: JET remote handling with double arm.

The JET's RH research and development from the beginning of JET machine construction in 1990 and test were carried out in 1998. The entire set of the RH maintenance tasks of the JET internal components were completed, and it was regarded as an important

milestone in the development of the RH maintenance technique of tokomak (Rolfe, & Team, 1998).

As the world's largest experimental reactor of fusion research machine, the ITER needs extremely sophisticated RH system in order to conduct operations, such as diagnosis, disassembly, maintenance on the damaged components by remote handling systems, for example, the blanket RH system and the divertor RH system. The blanket RH lays a toroidal track at the central position in the equatorial port of the vacuum vessel through a complex track-laying system, and the operating arm and the end effector of the blanket RH system can travel on the track, thus performing the maintenance operations. As the divertor RH system, divertors are mounted on a toroidal track in the vacuum vessel, and conduct the maintenance operations through the Cassette Toroidal Mover (CTM) and the Cassette Multifunctional Mover (CMM).
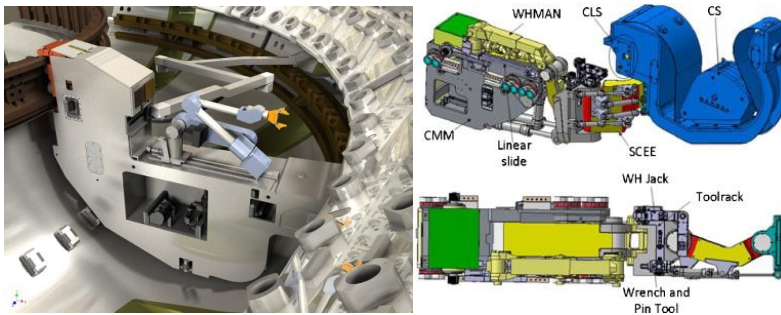
Figure 1.4: ITER remote handling and maintenance system.

The ITER has invested a lot of money in the development of the critical technology for the RH systems, and has also made some prototypes in the remote control operation, such as the Japan's Crawler Robot, the divertor multifunction mobile platform and the Divertor Ring Drive (Damiani, et al. 2014). The Technical Research Centre of Finland (VTT) and the Tampere University of Technology (TUT) have built a test platform for the ITER divertor remote maintenance of Divertor Test Platform 2 (DTP2), which is used for the development and testing of the remote maintenance system for the divertor components. The DTP2 system is showed in figure 1.5:

Figure 1.5: ITER divertor remote handling maintenance test platform (Lyytikäinen, et al. 2013). At the research base at Tokai, a test platform for the blanket replacement system has been cooperatively developed, as shown in the figure 1.6. The test platform provides the sensor-based control system tests and track-laying system test for blanket replacement operations. Through the 3-D virtual modelling of the test robot, the virtual environment simulation test is realized; and during this test, the blanket replacement work is finished under the virtual environment.
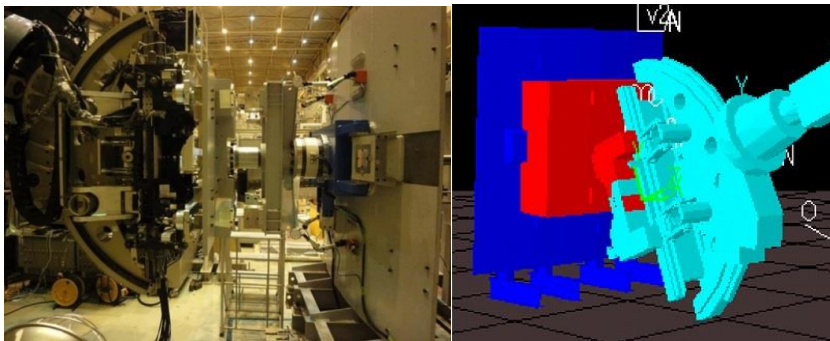
Figure 1. 6 Blanket replacement robots and virtual test environment

The Institute for Magnetic Fusion Research (IRFM), CEA, France, developed the Articulated Inspection Arm (AIA) (Cordier, et al. 2005) based on the Tore-Supra. The joint arm consists of five parts: front-end camera, about 8 m long, 8 degrees of freedom, weight 150 Kg, and load capability about 10 Kg, the articulated arm of high strength titanium alloy material, solid lubrication, the single joint angle range of equatorial plane being ± 90 ° and vertical plane being± 45°, built-in -module electronic components and drives (motor) with sealing treatment and very good environmental adaptability (Arhur, et al. 2005). The purpose of the IRFM's work is to verify the feasibility of observing and monitoring the internal components by visualizing the manipulator under the premise of vacuum, high temperature and other operating environments in the vacuum vessel. The

development and successful operation of AIA play a favourable role not only for a better understanding of the superconducting tokamak during the operation of the vacuum vessel, but also in laying a certain technical foundation in observation operations in fusion reactor maintenance for the ITER and the future reactor (Perrot, et al. 2005).

Figure 1.7 Articulated robot arm and Tore-Supra tokamak machine

1.3.2 Research status in China

In the field of remote control robot technology for fusion machine, some pre-research work was also carried out in China (Qin, 2014). The research group of the plasma research team of the Chinese Academy of Sciences (CAS) participated in the design work of the transfer CASK of the ITER RH. The CAS have carried out the research, and clarified the functional requirements of the automatic transporter system in the nuclear environment, and innovatively solved the key technologies under heavy-loaded and extreme conditions, completed the concept design of manipulator and its feasibility was demonstrated, as shown in figure 1.8 (Tao, 2008).

Figure 1. 8 ITER transfer CASK system

Although in recent years, a lot of systematic research work has carried out worldwide in the remote control robot operating system of tokamak, the key issues of remote handling system under the extreme environment, such as high temperature, vacuum and strong radiation are still unresolved, such as the reliability of the system architecture design, the protection of the electronic components under nuclear radiation environment, the remote sensing and the intelligent control technology.
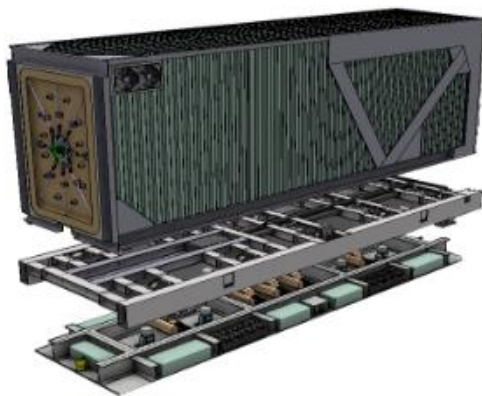
1.4   Development and application of reliability design analysis

1.4.1   The importance of reliability design analysis

Reliability design can be defined as: the ability, with which a product completes the required function under specified conditions within the prescribed time (Faravelli, 1989, Agency, 2007). The analysis and design of reliability exists throughout the entire process, starting from the system design, manufacturing process, installing and running, and the necessary reliability test is needed. The key of the system reliability assessment is to obtain adequate reliability data in order to establish the reliability database and to provide suggestions or improvements for design, manufacture, installation and maintenance. Through the scientific and rational analysis of reliability, recommendations for system design, manufacture, and installation session are proposed, special attention is given to weakness of system, thereby the reliability of design, manufacturing processes and installation conditions are improved. Reliability engineering theory has been widely applied in the fields of aerospace, electronic products and nuclear power stations. It has attracted lots of attentions in the field of nuclear fusion experimental machines.

The remote maintenance system of nuclear fusion machine is a complex system, which involves the field of mechanics, electronics, hydraulics and other fields. It is a demanding challenge to ensure the reliability and safety of the system during design, manufacture, installation and maintenance.

1.4.2   The development of reliability design and analytical methods

There are a lot of reliability models, e.g., the normal distribution, the exponential distribution, and the Weibull distribution model. The commonly used standard reliability values include the reliability, the probability of failure (failure rate) and the average life (mean life). The reliability of complicated system is related not only the reliability of the system systems (mechanical elements, electrical parts or hybrid systems), but also the

combination and matching of the various systems. Usually, the reliability design of complex products includes the following aspects (Engelund, & Rackwitz, 1993):

(1) Identification of the design and manufacturing requirements for mechanical components and electrical components in complex products.

(2) System reliability modelling. The commonly used reliability modelling methods are: series system modelling, parallel system modelling, hybrid system modelling, k/n system modelling and reserve system modelling. Through these mathematical models plus the appropriate algorithms, the reliability of complex systems can be calculated.

(3) Reliability prediction. To predict the reliability of a system (mechanical system, electrical system or hybrid system) we must first determine this system's basic failure rate, which is obtained under certain environmental conditions, and can be found in the relevant manuals in design phase. Then we determine the applied failure rate of each system according to the formula 1.1:

$$\lambda = k\lambda_b \tag{1.1}$$

where, λ failure rate of the system; k the correction coefficient and can be found through specialized information; λ_b the basic failure rate of the system. For different complex systems, the reliability is predicted with different methods, and the commonly used ones are the element statistics, the mathematical modelling, and the fault tree analysis.

(4) Reliability distribution. For a complex product, it is decided according to the conditions of each system, such as the technical level, complexity, importance and the related cost; overall, it is to obtain the highest reliability of the system. The commonly used distribution methods are equi-distribution, re-distribution, agreed allocation, relative failure and relative probabilities.

The application and research of reliability started in the World War II. In 1947, Freudenthal proposed the "the Safety of Structures" (Faravelli, 1989). In the 1950s, the US military began to systematically carry out the reliability research. In addition, some countries, like the former Soviet Union, Japan, Britain, France, and Italy, have also systematically carried out the research work on reliability from the late 1950s or early 1960s. In 1956, for the first time, the concept of structural failure probability and reliability index was explicitly put forward. In the 1970s, the reliability theory based on probability theory became matured; the design method of load and resistance factor came out based on the component reliability design; this phase was mainly aimed at electrical products, and the specification, the leading principles and the standards of reliability work

were determined. In 1969, Cornell for the first time in history explicitly gave the formula for calculating reliability index; in 1974, Cornell and Ang A. H.-S established the basic theory of the FOSM (first order second moment), and applied to the structure design. Shinozuka as the pioneer first expressed the determination the design point as a constrained optimization problem, and proved that the design point is the "most available failure point"(Shinozuka, & Itagaki, 1966). At the same time, he firstly introduced the "important sampling method" into numerical simulation analysis of structural reliability. Hohenbichler and Rackwitz first proposed the FORM approximation of structural reliability (Hohenbichler, & Rackwitz, 1982). Faravelli first proposed the response surface method of structural reliability analysis (Faravelli, 1992).

In China, the reliability engineering started in the 1960s, mainly in fields of the aviation, aerospace, electronics, mechanics, etc. The late 1950s and early 1960s, the internal journals of former Ministry of Electronics Industry reported about the reliability work carried out in foreign countries. By the late 1980s, the reliability theory of structural systems has become a research hotspot in structural engineering, and many articles were published, and the reliability analysis and advanced computational methods for complex structural systems were well developed. A number of works on reliability were published, and the government has promoted a lot of standards on reliability. Many industrial sectors involved in the reliability research. As the former Ministry of Aviation Industry clearly specifies that for new design or an improved product, the reliability assessment and analysis must be carried out before the phase of acceptance and identification (Zhang, 2010).

1.4.3   Application and significance of reliability analysis

Reliability analysis of design and engineering systems has become an essential part for any technology product design process (including the performance design and reliability design). Reliability is so important that must be considered in the design of the remote handling maintenance system. In order to maintain the higher reliability and robustness and availability of the system design, the effects of uncertainties on the reliability and robustness of the remote maintenance operation system must be fully considered. The significance of studies on reliability design and analysis are: 1) in the product design process, if a structural parameter has a greater impact on the reliability, then the parameter will be strictly controlled in the design and manufacturing process to ensure that its structure has sufficient safety and reliability; while if the variability of a parameter has no significant effect on the structural reliability, then it can be treated as a constant value in the structural reliability analysis to reduce the number of random variables. This is valuable for improving the efficiency of structural reliability analysis. 2) If the reliability

or failure probability of the structure does not meet the predetermined design criteria, the input variables that have important influence on the reliability must first be adjusted and optimized. If the dispersion of output variables is small then the reliability or failure probability of structural design conditions is accepted.

Reliability research plays an important role in the nuclear fusion science and engineering. Through the reliability design and analysis, the possible weakness and main failure modes of the integrated system and subsystems were obtained. The reliability modelling of the remote maintenance system was established and the average time between failures was obtained by the analysed of the system parameters.

1.5   Outline of the dissertation

The remote maintenance system is one of the key subsystems for reliable operation of tokamak fusion machines. The intelligent remote maintenance technology has been recognized as one of the difficult problems that must be solved before the fusion reactor applications become commercial. This dissertation focuses on the scheme of RH maintenance system of fusion reactor, the design of large-scale heavy-duty divertor maintenance system platform and its reliability analysis, control of hydraulic servo system. The main purposes of this dissertation were: established the system RH maintenance schemes and compared their advantages and disadvantages from the aspects of reliability, safety and availability; simulated and verified the proposed maintenance scheme mechanical structure, drivers and transmission mechanism; established the servo driven platform to validate the servo control of the water hydraulic system with different control algorithms.

This doctoral dissertation consists of six chapters, the structure and contents of which are organized as follows:

Chapter1 present the necessity and importance and basic principles on fusion reactor remote handling and maintenance, and introduce the speciality and current international research progress on the fusion related remote handling and maintenance technology. Discuss in detail the classification of fusion reactor maintenance and the features of each subsystem. Systemically discuss the existing key technical issues in the field of remote handling and maintenance and the direction of future development.

Chapter2 carry out the design of the RH and maintenance system, i.e., the structural design of divertor RH and maintenance system, kinematics and dynamics modelling, analysis, and simulation, transmission mechanism design and selection.

Chapter3 present the RAMI based reliability analysis for the RH maintenance system design through theoretical calculations. RAMI Functional and reliability block diagrams, of availability and reliability analysis; risk matrix diagram showed the risk levels under different failure models; the occurrence probability of failures, the impact of failures, and recommendations to reduce risks. The curve of failure rate over time of the system provides the theoretical foundation for reliable system operation and prompt maintenance were illustrated.

Chapter4 present the reliability analysis and the optimization for the RH hydraulic lifting platforms. For fulfilling the requirements, such as the minimum weight, the economic efficiency, etc., build the reliability-based model, conduct the prediction and distribution of reliability, the malfunction or failure mechanism analysis, and perform the reliability optimization design and finally obtain the optimal solution.

Chapter5 carry out the simulation and optimization analysis for hydraulic servo driven system, and verification by using experimental platform. Both the differential evolution optimization control algorithm and the adaptive fuzzy control algorithm were employed and the results were compared, the water hydraulic servo control experimental platform was built up for verifying the simulation results. By the comparison between the experimental data and the simulation data on the RH and maintenance system, theoretical references for safe, stable, and reliable operation are provided.

Chapter6 systematic summarized the research work of this dissertation, and provided some suggestions for future work on several key problems to be solved in the RH maintenance system.

1.6   Scientific contributions and publications

The main scientific contributions of this thesis are the following:

- Systematically illustrated the necessity and importance of RH maintenance of the reactor including the basic principles and classified RH maintenance systems and the characteristics the key technologies of future RH maintenance development.
- Based on the current design stage of fusion reactor CFETR, the main maintenance components and maintenance operations have been summarized and classified. The advantages and disadvantages of different reactor designs and maintenance schemes have been compared and the selection proposal of maintenance strategy for the reactor has been given.
- Overall control strategy of the RH maintenance system was studied for the control system architectural design. The large-scale heavy-duty hydraulic driven system

and the simulation model of the hydraulic drive system were established. The simulation and optimization analyses of the hydraulic servo driven system were carried out, and an experimental platform was built to verify the system reliability and safety.

- The fuzzy adaptive PID and the differential evolution optimization algorithm were used to realize the high precision control of the hydraulic cylinder system. The water hydraulic servo control experiments demonstrated the DE optimization algorithm with smaller overshoot, higher robustness, quicker response and stronger anti-interference ability of the hydraulic servo control optimization.

The results described in the thesis have been published in the following papers and patents. The rights have been granted by publishers to include the material in dissertation.

I.   Zhao, W., Song, Y., Wu, H., Cheng, Y., Peng, X., & Li, Y., et al. (2015). Concept design of the CFETR divertor remote handling system. Fusion Engineering & Design, s 98–99, pp. 1706-1709.
II. Han, M., Zhao, W., Cheng, Y., Ji, X., & Xu, Y. (2015). Concept design of water hydraulic circuit for manipulator of CFETR blanket maintenance. Journal of Fusion Energy, 34(4), pp. 765-768.
III. Han, M., Song, Y., Zhao, W., Cheng, Y., & Xiang, J. (2015). Simulation and Optimization of Synchronization Control System for CFETR Water Hydraulic Manipulator Based on AMEsim. Journal of Fusion Energy, 34(3), pp. 566-570.
IV. Song, Y., Wu, S., Wan, Y., Li, J., Ye, M., Zheng, J., & Zhao, W., et al. (2014). Concept design on RH maintenance of CFETR tokamak reactor. Fusion Engineering & Design, 89(9–10), 2331-2335.
V.   W.L.Zhao, Y.T.Song, H.P.Wu, et al. (n.d.). Maintenance strategy assessment of CFETR divertor remote handling system. Fusion Engineering and Design. To be submitted for journal publication 2017.
VI. W.L.Zhao, Y.T.Song, H.P.Wu, et al. (n.d.). Development of 3-DOF Platform for High Reliability of CFETR Divertor Remote Maintenance. Fusion Science and Technology. To be submitted for journal publication 2017.

Patents:

I.   Zhao Wenlong, Song Yuntao, Cheng Yong. A removable rail connector for a fusion machine. CN103824602A [P]. 2014.
II. Zhao Wenlong, Song yuntao, Cheng Yong, Li Yang. Remote handling of a fusion machine components transport programme. CN105261400A [P]. 2016.

III.   Li Yang, Song Yuntao, Cheng Yong, Zhao Wenlong, A heavy lifting bodies for a fusion machine components . CN105110244A [P]. 2016.

IV.   SongYuntao, Wei Jianghua, Pei Kun, Zhao Wenlong. A nuclear fusion machine vacuum line tele-operated institutions for cutting and welding CN104400276A [P].2015.

2 Structure design and analysis of RH system for fusion reactor

2.1 Introduction

The design of the remote handling maintenance of a fusion reactor has an important impact on the tokamak machine. To meet requirements for the reliable operation of the machine and maintenance efficiency, the corresponding maintenance plan should be considered at the beginning of the machine structural design. The in-vessel components, such as the divertor, the shielding blanket and the breeding blanket, require regular maintenance and replacement due to intensive nuclear radiation (Reich, et al. 2011). The plug-in heating system, the plug-in limiters and some diagnostic plug-ins are installed in the vacuum vessel port area and are very close to the plasma. Since they play an indispensable role in the operation of the machine, they require regular maintenance. Components, such as the cryogenic pump in the vacuum vessel, cryostat, port bellows, magnet coils, etc., do not need any maintenance in the lifecycle of the tokamak, since they are quite far away from the plasma region. However, failure of one such components will result in a long maintenance. Hence, it is necessary to rank the maintenance of the environment and components which need maintenance to insure that their maintenance equipment and maintenance cycles meet the design requirements (Noguchi, et al. 2016).

2.2 Requirements of fusion reactor maintenance system design

2.2.1 Maintenance system operating environment for CFETR

After an operation, the inside environment of the vacuum vessel of the fusion reactor will change drastically because of nuclear radiation, radioactive dust, the electromagnetic field and so on. The working environment for a remote maintenance system in the fusion reactor is very poor (Coleman, et al. 2014). Since the internal part of the vacuum vessel should be kept clean and pollution-free, the structure and materials of the maintenance system should withstand the high temperature, radiation or not cause any damage to the vacuum vessel (Yu, et al. 2015). The operating environmental of the RH maintenance system is shown in Table 2. 1.

Table 2.1 Operation environment of the RH maintenance system

Working environment	Environmental parameters
Radiation dose rate	Maximum 10000Gy / hr (after discharge)
Contaminants	Tritium, activated dust (C, Be, W)
Magnetic field	<1mT
Operating temperature	<50°C
External environment	Air
Working pressure	0. 90 bar to 1. 05 bar

2.2.2   Functional requirements of maintenance system

2.2.2.1 Requirements of the RH maintenance level

The RH maintenance level indicates the maintenance frequency at which an object receives RH maintenance. It ranges from one to four, where the highest level of maintenance is 1 and the lowest level is 4. Since the components inside the chamber are subject to different amounts of radiation and each has different radiation resistance capability. In vessel components need to be maintained at different frequencies. Table 2.2 shows the RH maintenance-required components of the reactor and the maintenance levels (Maisonnier, et al. 2006).

Table 2.2: The RH maintenance-required components of the reactor and the maintenance levels.

RH Maintenance Level	Maintenance requirements	Fusion reactor components
1	Regular maintenance or replacement	Divertor, shield blanket breeding blanket NBI ion source
2	From time to time maintenance or replacement, Less maintenance	Limiter plug-in, partial diagnostic plug-in Low temperature valve Electron cyclotron / ion cyclotron heating antenna plug

		Part of the diagnostic plug-in
		NBI source cleaning apparatus
		The cryogenic pump body installed on the vacuum vessel or Cryostat
3	Generally, maintenance is not required during the life of the reactor, but if the part fails, it will cause the reactor to be interrupted and the maintenance work will take longer	Part of a diagnostic machine, NBI rear module
		Port bellows assembly
		Magnet terminal and module side connector
		Magnet coil, vacuum vessel ring, cold screen, other components of the Cryostat container.
4	No need for remote maintenance or repair	Failure to affect the reactor does not affect the operation of the components
		Basic components that will not fail

2.2.2.2 Requirements of the RH operation and maintenance

According to the different types of trigger events, RH maintenance of the machine is divided into the following different maintenance phases, and different trigger events require different maintenance operations, as shown in Table 2.3 (Bonnemason, et al. 2009).

Table 2.3: The RH maintenance phases of a fusion reactor.

Trigger event	Response operation	Maintenance category	For example
The machine cannot continue to run	Immediately perform maintenance and replacement	Unplanned downtime maintenance	Vacuum system has a large leak; The first wall structure is damaged in large area
The machine can continue to run, but there is a small range of damage	To be repaired and replaced as planned	Scheduled downtime maintenance	Local diagnosis or heating system failure; The first wall part is partially damaged
The operating performance of the machine is gradually	Perform downtime to prevent possible component failure	Scheduled downtime maintenance	Replace blanket components; Replace the divertor

| reduced at a known rate and requires regular maintenance | | | |
| Machine to achieve some kind of experimental purposes for the upgrade | Perform a component replacement upgrade | Scheduled downtime maintenance | Replace some test modules |

To ensure good compatibility between the RH equipment and the reactor, standardization and modularization of the RH design criteria need to be considered in the RH design and manufacturing phases. The following are the specific measures:

I) Design phase

(1) Use relatively unified dimension series, such as the same-sized water pipes;

(2) Use standard parts with unified specifications, such as electrical connectors, flanges, fittings, fasteners, etc.

(3) Easy to assemble, such as chamfer alignment, easy-to-grab feature surfaces, visual positioning points;

(4) Use unified treatment approaches, such as welding and cutting methods;

(5) Reserve maintenance space for RH maintenance;

(6) Use components that are easy to be replaced or handled, such as removable screw sets;

(7) Specify gap values that are suitable for observation and measurement in order to facilitate the RH equipment to sense maintained objects;

(8) Predefine the appropriate material of the objects to facilitate the RH equipment to sense during sensing and treatment;

(9) Specify protection methods for components, which can be easily damaged during RH maintenance.

II) Processing and construction phases

(1) Apply the guidelines of the prescribed quality control, such as the standards of dimensional tolerances of threads, the standards of the surface quality and dimensional tolerances of the mating faces;

(2) Test and verify RH maintenance performance on the objects;

(3) Practicality: the design of the various components should be as simple as possible to facilitate installation and maintenance;

(4) Inspectability: at the beginning of the design, the inspectability of each component to be detected and treated should be considered.

2.3 Comparison of various maintenance schemes of fusion reactors

The fusion reactor conducts maintenance in two ways: inside the machine and in the Hot Cell (HC) where the maintained-components are transported. A schematic diagram of the maintenance area is illustrated in figure 2.1 (Heemskerk, et al. (2009). To minimize the maintenance time for replacing components, the internal components of the chamber should be modularized assembly. In the concept design of the vacuum vessels of the existing fusion reactors in the world, the structural assemblies of the internal components (blanket, divertor) of the vacuum vessel are different. The proposed maintenance schemes for future fusion reactors are as follows: a large port scheme (Tobita, K., et al. 2006), an equatorial port scheme, an ITER-like scheme, and an integrated port scheme (Federici, G., et al. 2016).
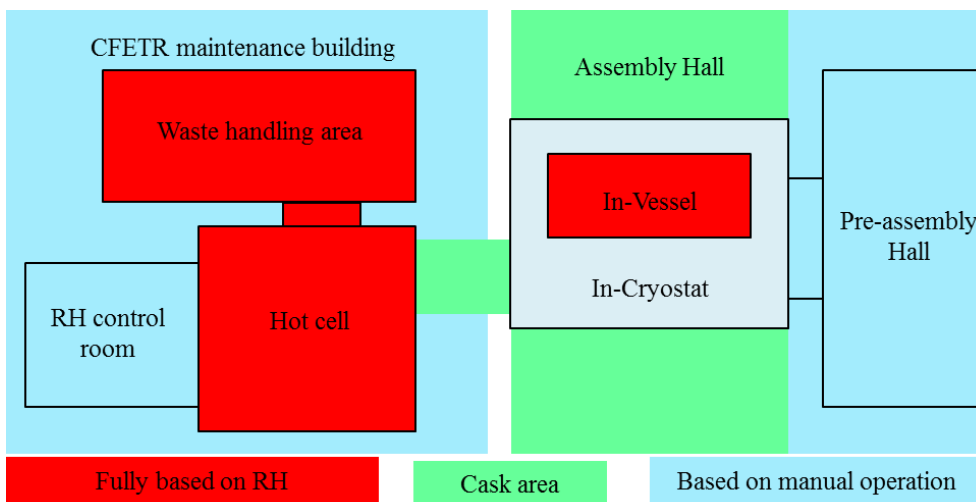

Figure 2.1: Schematic diagram of the maintenance area of a fusion reactor

2.3.1   **Maintenance scheme of the large port**

The large port maintenance scheme (figure 2.2) is to minimize maintenance time in replacing blankets. This proposal uses 16 large full-size ports and the design of the divertor and blanket systems are modularized. The integrated assembly of sector facilitates the maintenance and replacement of the internal failure components. In addition, the precision manipulators for assembly and disassembly are not involved during the maintenance operation of the internal components, and the blankets do not require disassembly inside the vacuum vessel individually (Palmer, et al. 2007).
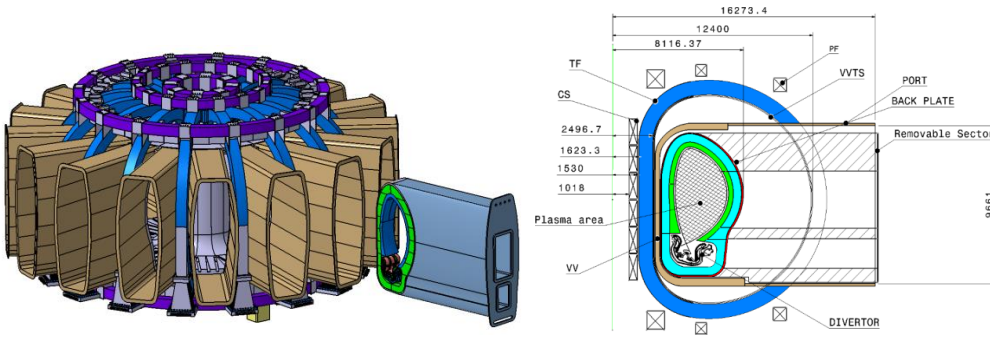

Figure 2.2: Structural diagram of machine for the large port maintenance scheme (Najmabadi, & Abdou, 2006).

In this scheme, the blanket, divertor and the connection backplane are designed with the overall modularization concept. The whole circle is divided into 16 identical sectors; each sector has a wedge angle of 22.5°. The overall assembly of sectors scheme facilitates maintenance and replacement of the internal components during the experiment, reduces maintenance time, and greatly promotes the economy of the machine. In addition, the modular design simplifies the connection of the blanket, divertor and backplane. The maintenance of the internal components does not need the precision manipulator, nor is it necessary to carry out the disassembly of blankets inside the vacuum vessel. Therefore, the large port design can greatly reduce difficulty in the design of the remote handling assembly tool, significantly improve reliability, and implement ability of the tokamak machine.

In order to keep the sectors intact and simplify the assembly process, non-interference installation and disassembly of sectors are key points for the large port scheme design. A junction area between every two neighbouring sectors should be avoided (the length of the straight line segment, *L*, is zero, in figure 2.3). The seamless area of the wedge-shaped sector has a large measurement D, and a 50 mm minimum safety gap should be considered for the moving sector throughout the port. Therefore, this large port scheme requires a

wider port, which means that the TF coil structure need to be designed large enough so that the integrated module can be pulled out from the vacuum vessel.

The advantage of this solution can effectively reduce maintenance time to satisfy the duty-time requirements of the reactor. The disadvantage is that the TF size has to be larger than the small port and the weight of the integrated sector is about 340 tons, which needs a higher load capability tool and will have more challenges during maintenance period.
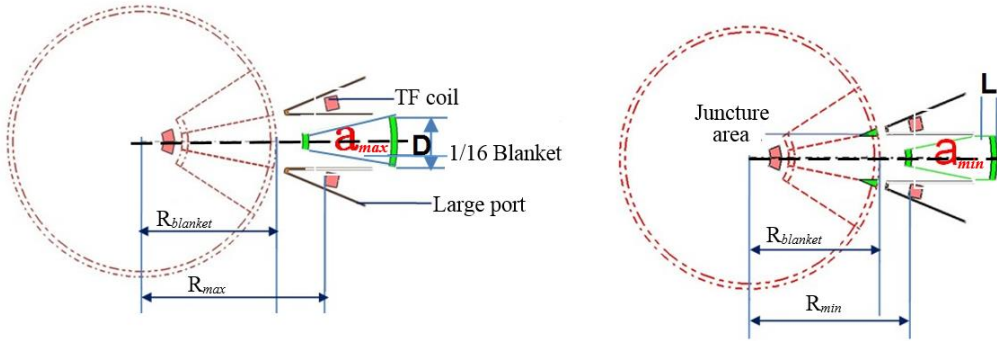
Figure 2.3: Diagram of the seam area in the large port scheme sector.

This proposal has the following characteristics:

1) It takes a short time which helps to improve the in-operation prepare time. It also reduces on-site maintenance time; during the operation, a large number of tests and maintenance work can be carried out in advance for the upcoming replacement and maintenance of internal components.

2) The test and maintenance system of the Hot Cell is huge and takes up a large space. It contains, for example, the test and maintenance platforms for the overall modules, divertors, shielding blankets and breeding blankets.

3) It does not require the large and complex robot arm system in tokamak. The removal and installation of the blankets and the divertor modules are carried out in the Hot Cell and the geometric environment of maintenance is greatly improved.

4) The high requirement of the CASK loads capability. The RH maintenance scheme requires a high load capability CASK to transfer the whole sector of 340 tons from each port to the hot cell.

The large port maintenance scheme requires the remote handling CASK system to pull every single sector out of the vacuum vessel through the large port. Inside the CASK, there are two multi-functional manipulators, the upper transportation system and the bottom rail system. To maintain clean environment in the vacuum vessel during assembly and disassembly, a double sealing door is designed at the front of the CASK. The basic structural of the maintenance components is shown in figure 2.4.
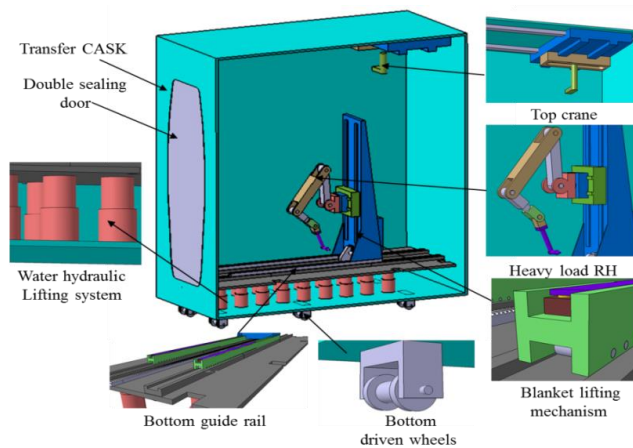
Figure 2.4: Structural of the RH maintenance system in a large port scheme (Utoh., et al. 2015).

In summary, the large port maintenance scheme reveals that 1/16 of the internal components of the vacuum vessel will be transferred to the Hot Cell by the CASK, which avoids cutting internal pipes and improves maintenance efficiency. The maintenance process of the internal components is shown below (figure 2.5):

Step 1   Step 2   Step 3   Step 4   Step 5
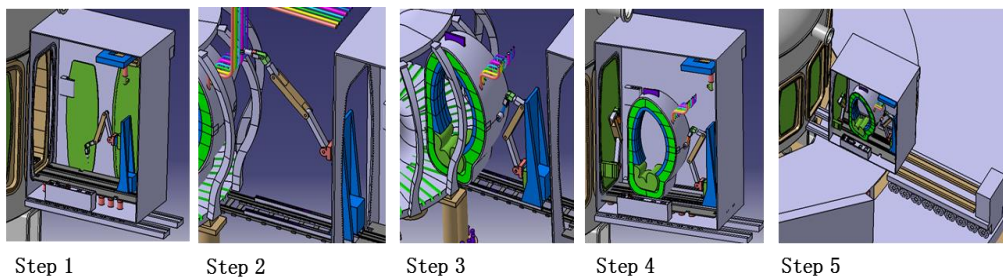
Figure 2.5: Maintenance processes of components in a large port scheme.

2.3.2   Maintenance scheme of the equatorial port
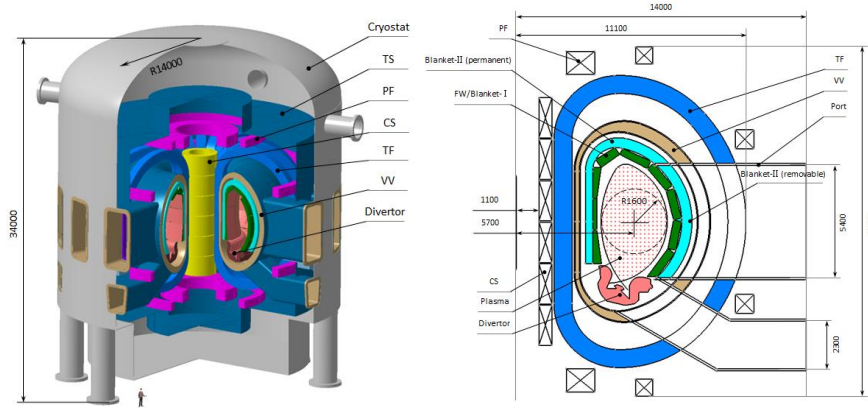
Figure 2.6 Structural of equatorial port maintenance scheme (Song, et al., 2014).

In the equatorial port maintenance scheme, as shown in figure 2.6, a total of 16 equatorial ports are distributed uniformly along the track. Each port has the corresponding passages for sector maintenance, water-cooling and tritium extraction. There are eight lower ports, distributed evenly along the track, which are mainly used as the water-cooling passage, the deuterium-tritium recycling port, and the maintenance passage for the CASK.

The equatorial port maintenance scheme utilizes the idea of moving out the blanket in blocks, and it overcomes the shortcoming of large load capacity for transporting the large size and heavy-weighted sectors. In addition, dividing the blanket into blocks lowers the requirements on the port for the blanket assembly. The main structure of the shield blanket is permanently connected to the inner wall of the vacuum vessel (Loving, et al. 2014).
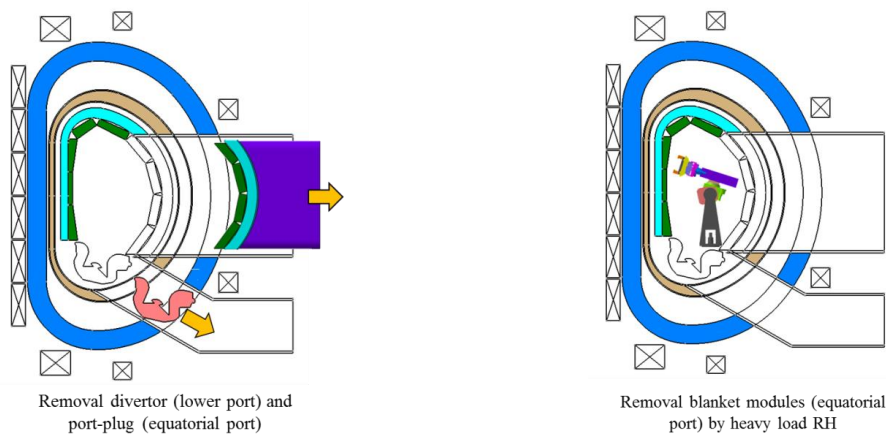
Figure 2.7: Maintenance strategy in equatorial port maintenance scheme.

During the maintenance process, the transfer CASK, to give space to maintain the breeding blanket and then move it remotely by a manipulator to the Hot Cell, first removes the shield blanket close to the port area. The maintenance strategy of the internal components is shown in figure 2.7, which shows that the breeding blanket and shielding blanket close at the port and are regarded as a whole plug-in structure during assembly and disassembly. The rest of the breeding blanket will be disassembled by the RH system with modules of 1.5m×1.5m× (0.2-0.4) m, and the divertor is removed from the lower port.

2.3.3   **Maintenance scheme of the ITER-like port**
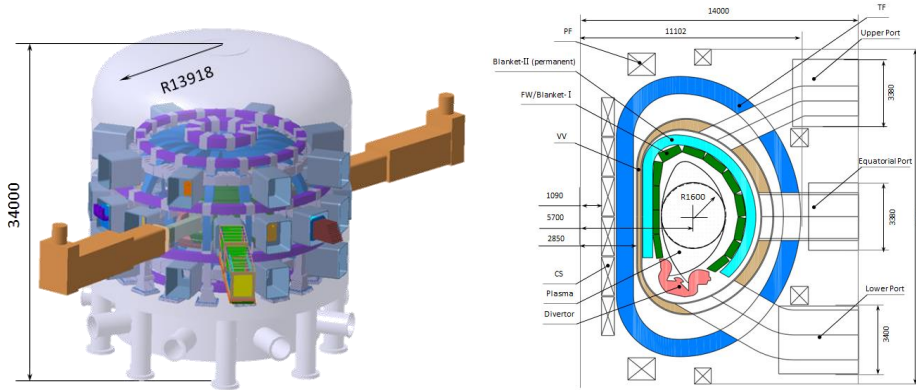
Figure 2.8: Schematic diagram of maintenance scheme of ITER-like port (Kumar 2013).

The maintenance scheme of the ITER-like port, as shown in figure 2.8, presents 8 upper ports, 16 middle ports, and 8 lower ports. All ports are symmetrically distributed along the track: 1) the upper ports are mainly used for the inlet and outlet of the cooling system piping, tritium extraction, and diagnosis; 2) the 16 middle ports are: 2 NBI tangential ports, 5 diagnostic ports, 3 auxiliary heating ports, 4 maintenance ports, and 2 spare ports; 3) the lower ports are the water cooling passage and maintenance pass of the divertor (Kumar, et al. 2013)..

The ITER-like maintenance scheme adopts the existing technology from the ITER machine to reduce the risk of the maintenance system design as ports have smaller openings, and consequently have better shielding performance for preventing neutron leakage. However, each sector contains 18 blanket modules and each weighs about 5.8t. Meanwhile, the internal cooling pipes for each module need cutting (or welding) during maintenance, which leads to lower efficiency of maintenance. It will be difficult to meet the requirements of maintenance efficiency in future fusion reactor. In addition, RH

operation has complicated actions in limited maintenance space. The main maintenance system is shown in the figure 2.9 (Shibanuma, K., & Honda, T. 2001):
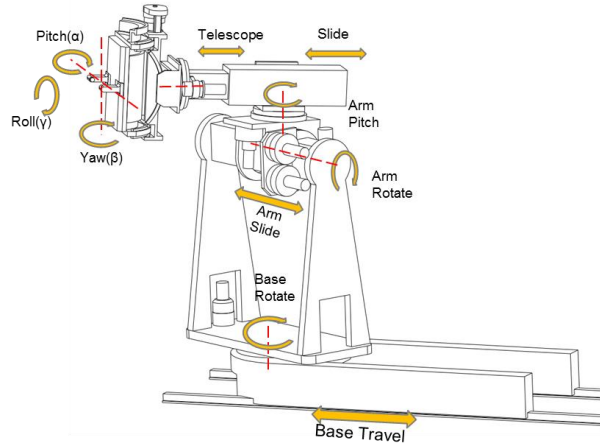
Figure 2.9: Structural design of a maintenance system with an ITER-like port.

2.3.4   Maintenance scheme of the integrated port

In this scenario, the vacuum vessel is divided into 16 sectors along a circular track. Several horizontal ports are arranged for heating, diagnosis and rescue, as shown in figure 2.10. At the lower position are 8 divertor ports for the cooling pipes and RH maintenance. Considering the detachable blankets and the difficulty of removing the NBI, blankets will be removed away from the upper ports to avoid removing complex equipment, such as the NBI and the diagnostic system. This happens before transporting the blankets through the equatorial ports in order to reduce the difficulty and the workload of assembly and disassembly.
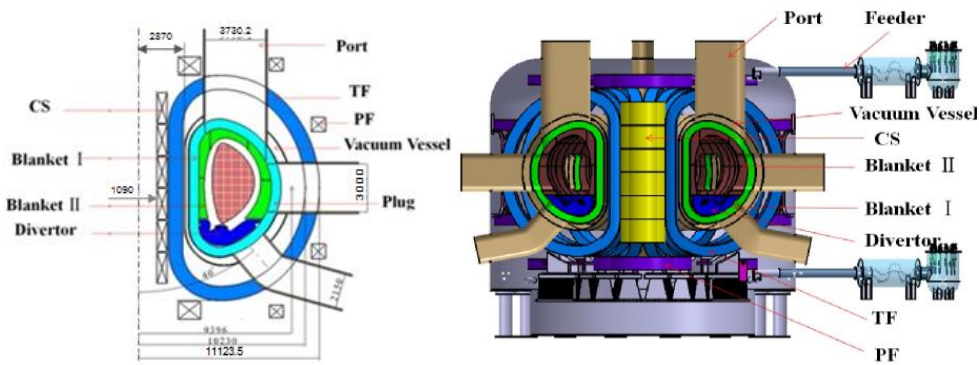
Figure 2.10: Structural diagram of a maintenance scheme with an integrated port.

The track is set at the bottom of the vacuum vessel and the RH systems for the blanket are similar to the ITER. This proposal has a significant feature: the upper ports are for the accessing blankets during the machine assembly and the maintenance process. The main part of the RH system is shown in figure 2.11.
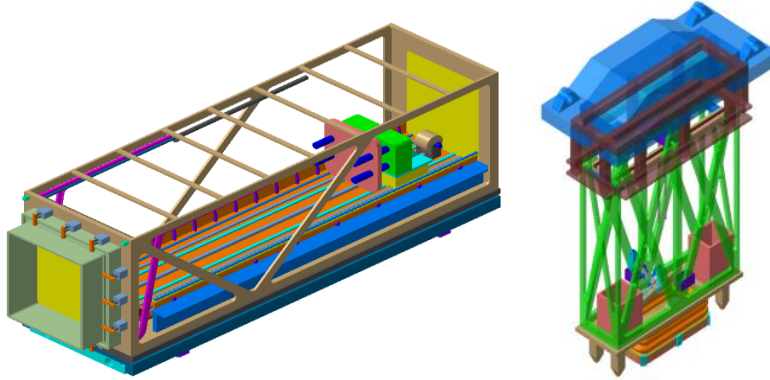
Figure 2.11: Structural design of the maintenance system using an integrated port.

The RH tools in the integrated port maintenance scheme include the blanket manipulator, the equatorial port CASK and the upper port CASK.

The equatorial port CASK transports the vacuum vessel track and the blanket manipulator, both of which are similar to the ITER. The CASK system includes the smart manipulators. The bottom of the manipulator is rotary and can rotate 90 degrees; the effectors of the manipulators are replaceable. The replacement toolbox is placed on the locker and the rotatable manipulators can disassemble the bolts, cut and weld pipes, and so on. The driving system on the top transfers the blanket modules from the vacuum vessel to the CASK. The CASK is transferred between the Hot Cell and the tokamak ports through the external hall of the fusion reactor.

In this proposal, the maintenance process is simple, and the maintenance work of the blankets and divertors can be done in parallel in the upper and lower ports. This proposal include using 16 ports for maintenance, refining blanket segmentation (thus lowering the maintenance efficiency of the blankets), and taking up more ports for maintenance operations.

Based on the above maintenance schemes, comparison results of the weight of the maintenance components, maintenance efficiency, the complexity of the maintenance equipment and the number of maintenance ports are shown in table 2.4.

Table 2.4: Comparison of maintenance schemes for the CFETR machine.

Maintenance scheme	Weight of the blanket	Maintenance time	Advantage	Disadvantage
Large port maintenance scheme	~ 340t	Maintenance integrally assembled using 16 sectors, the shortest time	Maintenance is simple: easy overall disassembly maintenance RH simple equipment: the number required is less;	Preparation is long: need to remove many machine peripherals Maintenance is high: maintenance system load The port occupies 16 sections, and usability is reduced
Equatorial port maintenance scheme	~ 113t	Each sector proliferated blanket has three parts; independent maintenance; longer maintenance time	Components are light weight; Maintenance of equipment is relatively simple	Occupy more ports: 16 equatorial ports; Long reparation time; need to remove a large number of machine peripherals
IITER-like port maintenance scheme	~ 5. 8t	Each sector is divided into 18 pieces; the inner pipe cutting (or welding) procedures are complicated; longer maintenance is needed	The existing ITER already mature; reduce risk; Fewer ports are used: only four are needed; Port opening small: helps prevent neutron leakage	Maintenance procedures are complex: the blanket module is divided into too many pieces; more RH equipment involved, and work space is limited
The integrated port scheme	~ 20t	Breeding blanket layer is reduced to 64 pieces; the blanket inside the vacuum vessel needs to change the direction; longer maintenance	Easy maintenance: vertical lifting; Short time preparation: no need to remove the peripherals of the equatorial ports	Long operation time: too many pieces of the blanket block. More ports: 16 maintenance ports

This proposal combines the advantages of both maintenance schemes using the upper and equatorial ports; it symmetrically sets up four upper ports, four equatorial ports and four lower ports at the top of the vacuum vessel for the removal of blankets, diagnostics,

divertors and the maintenance of the NBI. The structural diagram of the maintenance scheme is shown in figure 2.12.
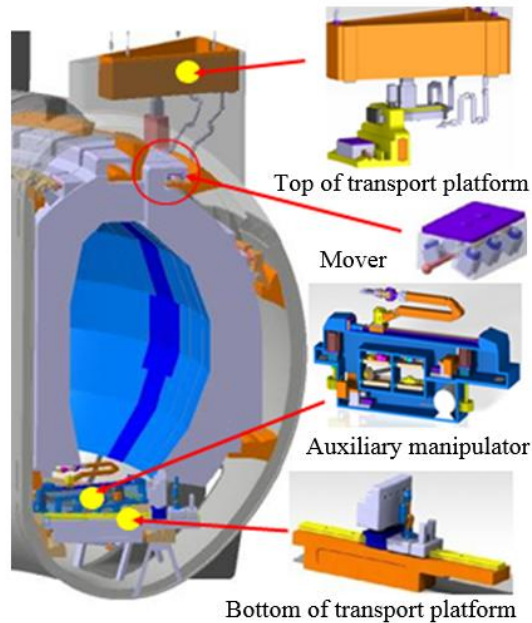
Figure 2.12: Schematic diagram of the integrated port maintenance scheme.

When comparing the current ITER remote maintenance of small modules of blanket and divertor to the new scheme for the CFETR advantages are:

i.   It uses only fewer ports so that the maintenance operation does not require the use of other diagnostic ports, and the maintenance operation is relatively simple;

ii. Maintenance operations can be carried out from the upper and lower port, thus no need to remove the peripheral diagnostic system at the equatorial ports, therefore improving maintenance efficiency;

iii. It is convenient to carry out maintenance work on the blankets by the upper lifting system. The proposal does not require complex manipulators, which reduce the difficulty of maintenance system design and improve the inherent safety and reliability of the reactor maintenance systems;

iv. In reference to the ITER divertor maintenance (Muhammad, et al. 2007), we adopt the bottom lift and toroidal driven move system to carry out the cassette which will obtained much more capability and reliability compared with the ITER CTM side grabbing and CMM front end lifting scheme.

2.4   CFETR divertor RH maintenance system design

2.4.1   Functional requirements of a Divertor RH System (DRHS)

The RH equipment provides the maintenance for divertors and associated components inside the reactor, a system for port plug removal, and various types of maintenance inside the cryostat (Zhou, 2015).

There are eight lower ports, four of which are maintenance ports for divertors, and the other four ports are for diagnostic. Eleven divertors will be transferred through each maintenance window with an operating range ±45°.

The divertor RH System should perform the following functions:

1) Install and remove divertors from the lower maintenance port;
2) Install and remove the diagnostic system from the lower maintenance port;
3) Transport the divertors and diagnostics system between the tokamak and the Hot Cell by the transfer CASK system;
4) Clean the dust and debris generated during the divertor maintenance operation;
5) Support the load of the maintenance system (a single large cassette weighs about 20 tons and a small cassette about 10 tons).
6) Insure that the clearance between the two cassettes is less than 20 mm and the drive speed is about 20 mm/s.

The divertor RH maintenance system can remove the divertors and transfer them to the Hot Cell for repair, replacement and disposal with high efficiency during the CFETR lifetime (Zhao, et al. 2015).

A divertor consists of 44 cassettes, accessible through four RH ports. Each port allows the remote replacement of 11 cassettes. The cassette number and the transported ports are defined as shown in figure 2.14.
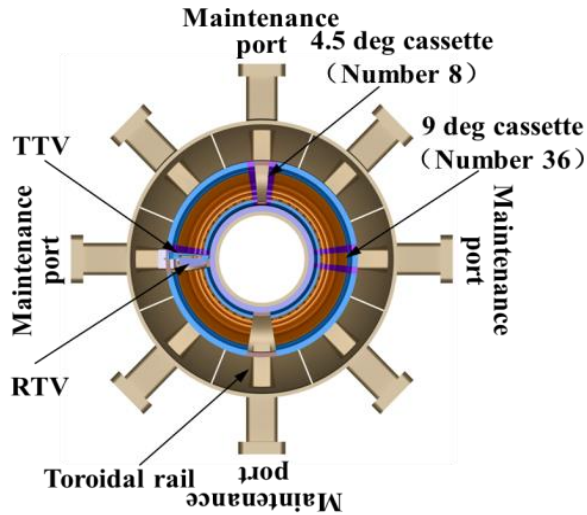
Figure 2.14: Divertor cassette maintenance port scheme.

The following outlines the main operating conditions of the DRHS (Zhao, et al. 2015; Gironimo, et al. 2013):

1) In-vessel elements of the Divertor RH were operated under the nitrogen protected atmosphere;

2) The divertor RH system operates under an absolute pressure of one bar;

3) The temperature during RH operations can be up to 50 ℃

4) In-vessel elements of the divertor RH system operate with gamma radiation of up to 500 Gy/h;

5) In-vessel elements of the divertor RH system can operate in an environment contaminated with tritium and activated dust (C, Be and W);

6) The Divertor RH system operates within a magnetic field of up to 1 mT;

The defined operational requirements of the divertor RH are:

1) Reliability: The in-vessel part can regularly work under radiation of 500Gy/hr;
2) Capability: the RH system has a high load capability (20 tons) and a security coefficient;

3) Material: Must be highly radiation-resistant and have high structural strength material.

4) High efficiency: The time for replacing the whole divertor system should not exceed 6 months.

All components of the RH system should be standardized and easy to be decontaminated. Recoverability is also important during RH design (Maisonnier, 2001).

The divertor remote handling equipment comprises, as shown in figure 2.15:

1) 3-DOF platform: driven by a rack, pinion and hydraulic actuator, three degrees of freedom, equipped with a manipulator to realize the divertor radial moving to the maintenance port.

2) Toroidal mover system: performs the bottom grabbing, lifting the divertor cassette and moving along the toroidal rail to the maintenance port for quick replacement.

3) Auxiliary manipulator assembled at the side of the 3-DOF platform with the toolbox: performs bolting, cutting, welding, and inspecting operations inside the VV.

4) Dexterous manipulator assembled on the top of 3-DOF platform: conducts connecting, handling, positioning, and locking/unlocking of the supports and removable rail.
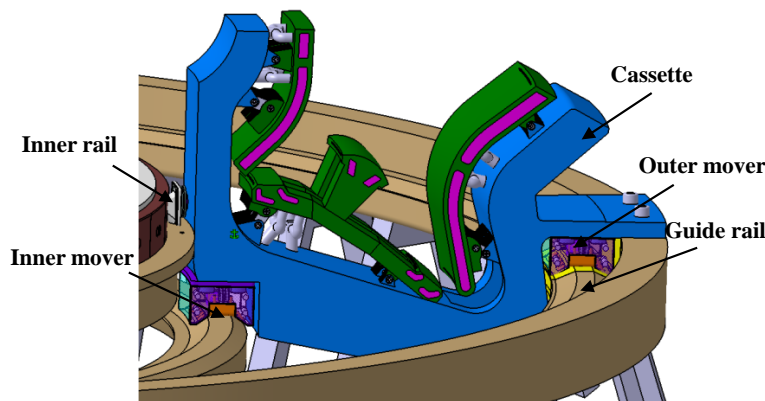
Figure 2.15: Overview of divertor RH maintenance system.

2.4.2 Design of the 3-DOF platform

The 3-DOF platform, as shown in figure 2.16, is used for transporting the toroidal mover system and the auxiliary manipulator from the transfer cask into the VV and carrying the

divertor cassette from inside the VV to the HC for refurbishment and replacement, and vice-versa. The 3-DOF platform is driven by the rack & pinion through the VV tunnel rail. There are four hydraulic actuators inside the 3-DOF platform for lifting the divertor cassette and two hydraulic cylinders at the side of the platform for position adjustment. Purified water is the hydraulic medium for preventing pollution inside the VV. A dexterous manipulator is mounted on the 3-DOF platform for pre-installing and locking the removable rail to the VV.
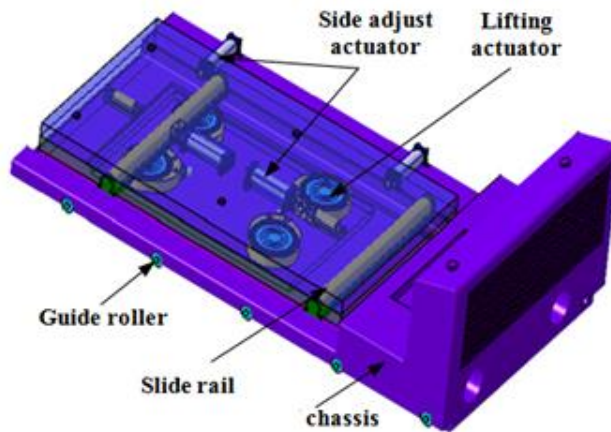
Figure2.16: Overview of the 3-DOF platform.

2.4.3   Design of the toroidal mover system
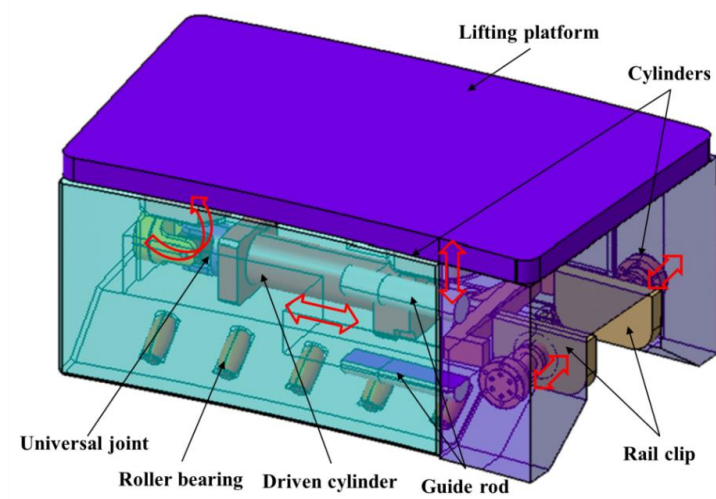
Figure 2.17: the toroidal mover system.

The toroidal mover system is designed to transport and install divertor cassettes as shown in figure 2.17. It is driven by the water hydraulic cylinder to move along the toroidal rails to the bottom of the divertor cassette and then transform the cassette to the lower port area on to the 3-DOF platform and then removed out of the tunnel of the vacuum vessel for refurbishment and replacement.

2.4.4   Design of the divertor cassette transfer cask

The DRHS transfer cask system is devoted to the transportation of contaminated in-vessel components between the VV and Hot Cell, as shown in figure 2.18. A double cask system scheme is adopted to increase the efficiency of the maintenance procedure (see figure 2.18 b). The cask system mainly includes: a locking mechanism between the cask flange and the VV port flange used after docking, a double seal door for the prevention of contamination spreading outside during docking or undocking, and a self-propelled air transport system (ATS).
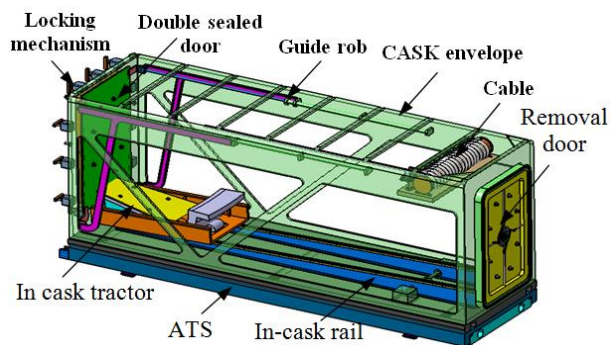
(a)

(b)

Figure 2.18: the transfer cask: (a) structure of the transfer cask (b) Second cask containing 3 cassettes.

2.4.5   Design of the end-effectors for the cassette

A set of end-effectors are designed to perform cutting, welding, the removing the diagnostic system; to inspect the divertor cooling pipes (two pipes per cassette), and to lock/unlock the cassette pins and bolts. This dexterous manipulator is mounted on the 3-DOF platform, and the end-effectors are shown in figure 2.19:

(a)

(b)   (c)
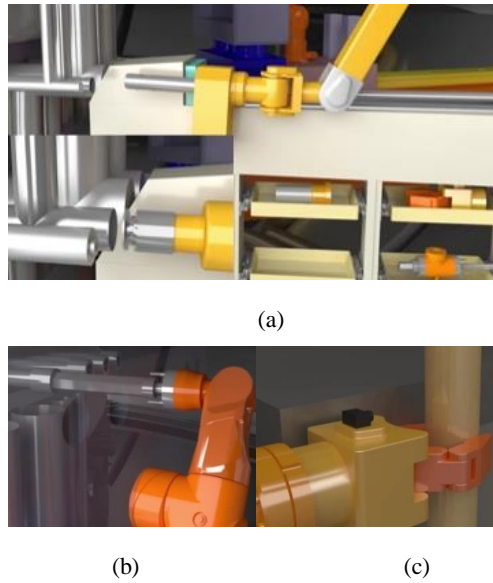
Fig. 2.19: (a) Different tools with box; (b) Bolt disassembly tools; (c) Pipe cutting tools.

2.4.6   Operational sequences of the DRHS

The maintenance sequences for divertor replacement involve the removal of the cassettes at the divertor level using two types of remotely controlled cassette vehicles: the 3-DOF platform that travels along radial rails and toroidal mover system that moves toroidally inside the VV. The divertor cassettes are accessed via four of the lower ports. Removal of the divertor cassette involves five main phases, as shown in figure 2.20:

Phase1   Phase2   Phase 3   Phase 4   Phase 5
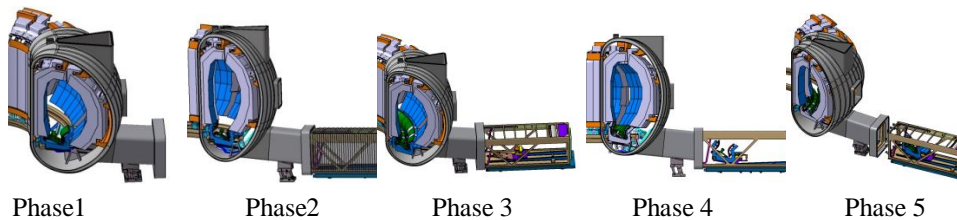
Figure 2.20: Operational sequences of the DRHS.

Phase 1: Prepare the port cell for maintenance configuration. This mainly concerns the outer vessel diagnostics and pipe cutting and removing the seal primary closure plate.

Phase 2: Removal of the components at RH port area: the RH operations take place inside the RH port with a primary closure plate, diagnostics rack, and the central and second cassettes. The auxiliary manipulator with various end-effectors mainly achieves these operations.

Phase 3: Handle the in-vessel remote operations: RH operations take place inside the VV (cassette replacement and dust removal) by the toroidal mover system and 3-DOF platform with the manipulator. The cassette's cooling pipes can be accessed from their adjacent port cells with RH pipe tools.

Phase 4: Handle in-cask remote operations: the 3-DOF platform carries the cassette with movers to the transfer cask with the bottom rack of the vacuum port and closes the cask port by its manipulator.

Phase 5: Transfer cask transport the divertor cassette and the diagnostics system of the RH port and dock with the HC for refurbishment and disposal.

2.5   Summary

Different maintenance schemes were (the large port scheme, the equatorial port scheme, the ITER-like port scheme, and the integrated port scheme) presented in compliance with the different structures of the in-vessel components. Compared with different maintenance schemes from the load capability, maintenance efficiency and difficulty level, the integrated port maintenance scheme, the 3-DOF platform and mover system instead of the ITER maintenance, which have the innovative advantages of the simplified design, high load capability, safety and functional reliability. For the CFETR is under the concept design, so we just give a qualitative comparison from the load capability and its functional reliability.

3 RAMI based reliability analysis for RH system

3.1 Introduction

The RH maintenance system is a multi-disciplinary complex system involving mechanics, power electronics, hydraulics, computer and control systems. Any approach would be imperfect if the study of the reliability of the robot system only focused on the components of reliability and manufacturing technology, regardless of the effect of system design on reliability. Especially when the maintenance system becomes increasingly complex, it cannot adequately solve the reliability problem. In this part of the study, the failure mode and effect analysis (FMEA) and the fault tree analysis (FTA) are first applied to the reliability analysis of the RH maintenance system. With the FTA method applied to the RH maintenance system, the failure modes are built up and the effect relations are established, and they are both beneficial to the analysis of each operation phase and to obtaining failure information. The operator can then clearly understand the situation of the RH system operation and maintenance. In this research, the intelligent optimization algorithm is utilized for the reliability analysis of the 3-DOF-platform, for determining the optimum parameters.

3.2 RAMI analysis and optimization procedure

We used the RAMI method (Reliability: continuity of correct operation; Availability: readiness for correct operation; Maintainability: ability to undergo reparations and modifications and inspectability: ability to undergo visits and controls). This is a combination of methods and dedicated software tools that allows definition requirements for operational functions and provides the assurance that they are met (Van Houtte, et al. 2010). Because corrective actions are still possible at the system design phase, the RAMI analysis is most effective in terms of design changes and tests before assembly, allowances for accessibility and inspectability in system integration, input for the operation or definition of the frequency of maintenance, and list spare parts. The process has four steps:

1) Functional analysis (FA): functional breakdown describing the considered system from its main functions and components;

2) Failure Modes, Effects & Criticality Analysis (FMECA): establishment of a list of function failures, their causes & effects, according to their importance to machine operation availability; evaluation of the severity of the effects and occurrences of the

causes of main failure modes; discrimination between major, medium and minor risks by using a criticality chart;

3) Risk mitigation actions: initiation of actions in terms of design, tests, operations and maintenance to reduce risk levels. A new criticality assessment is made to evaluate the benefits of the risk mitigation actions. Then, consistency between the expected RAMI results and the assigned RAMI targets for the system's main functions are checked;

4) RAMI requirements: integration of the RAMI targets and the required risk mitigation actions into the system specifications.

The following sections realize this process and perform the analysis on the divertor RH System.

3.2.1   The Fault Tree Analysis (FTA) method

The FTA was studied for system reliability analysis (Carfora, 2015). FTA sees a system failure as one top event and branches were generated downward according to the causes of this failure. The number of failures for each smallest system obtains the corresponding failure probability; then, the minimal path set method and the minimum cut set method are used for solving the system fault probability and analyzing the importance of each component to the system.

The failure mode, effects and criticality analysis was introduced for the system reliability analysis: 1) evaluate the impact of potential malfunctions or hardware failures on the application effects and the system performance; 2) sort failures according to the severity of their impacts; 3) suggest design, maintenance and improvement of the system. The key is to obtain rich data to form a reliability database.

The RAMI method is for a reliability analysis of the CFETR RH maintenance system. Regardless of the types of reliability work, the common purpose is to evaluate the reliability of a system's normal operation (Voronov, & Alzbutas 2014).

In this section, the RH maintenance system of CFETR is studied: system overview, functional analysis, reliability block diagram (RBD), reliability and applicability, risk matrix showing risk levels of different failure modes, failure's occurrence probability and impact, and recommendations and measures for reducing and responding to failure mode risks. The CFETR machine is currently in the conceptual design phase. The specific parameters of a few components were not fully defined yet, and therefore, their parameters and structures were referred to those of ITER.

Meanwhile, the usability planning and reliability prediction of the CFETR machine are not yet established. The analysis of the CFETR RH maintenance system first makes use of the usability planning, reliability prediction of ITER, namely the usability planning of the RH maintenance system in the reactor is 99.43%, and reliability is estimated as 99.57%. The internal usability of CFETR is the ratio of the system's available working hours and the system's normal working hours (excluding unplanned delays and maintenance) (Dongiovanni, 2015):

$$A_i = MUT / (MUT + MDT_{NSi}) \tag{3.1}$$

where, MUT represents the Mean Up (or operation) Time available for operation time, while MDT_{NS} is the Not-Scheduled Mean Down Time of the system.

The internal availability of the machine is as follows:

$$A_i = 1 / (1 + \sum_{i}^{n} (\lambda_i \cdot MDT_{NSi})) \tag{3.2}$$

where, λ_i means the failure rate of the system or the main functions failure rate of the system. The system's internal reliability and usability can only reflect the system itself, whereas availability and reliability of other peripheral systems or peripheral equipment are taken as 100%, because they are decided independently and separately in their respective systems.

3.2.2 Failure modes and reliability analysis

The RH maintenance system of CFETR consists of the blanket RH system, the divertor RH system, the tele-operated transfer vehicle (CASK), the Hot Cell RH system, and so on. This analysis focuses on CFETR's divertor remote system operation and maintenance, including the related mechanical structure, electrical hardware, sensors, control software systems, and so on. A detailed design of the system is in progress. The following assumptions are made:

1) Standards of failure severity and occurrence frequency are referred to those of ITER.
2) Usability of the RH maintenance system is 99.43%, while the estimated reliability 99.97%.
3) Mechanical structures and electrical systems of the RH system have no defects; the reliability and usability of control motors, sensors and control software system are evaluated.

3.2.3   Functional analysis for reliability

Functional analysis, as the first step in reliability analysis, provides a comprehensive understanding of a system from the perspective of system functions, and it describes the measures to be taken to achieve the ultimate functions of the system. Functional analysis begins with the main functions, then the intermediate functions, the basic functions, and finally the ability to make a full and complete decomposition.

Functional analysis mainly uses IDEFØ (Integration Definition Function modelling-0). IDEFØ is not a software but a group of modeling languages used to implement systems and software engineering, building on structured analysis and design techniques (Kitazawa, et al. 2014). IDEFØ is used for analyzing the performance and structure of the completed preliminary conceptual design of the CFETR RH maintenance system (Qin, S., et al. 2014). RAMI Analysis Program Design and Research for CFETR (Chinese Fusion Engineering Testing Reactor) Tokamak Machine. *Journal of Fusion Energy*, *33*(5), 516-522.). The detailed designs of the CFETR RH maintenance system are presently in progress that is why the preliminary analysis results are obtained based on the functional analysis of the ITER conceptual design in the remote handling maintenance systems.
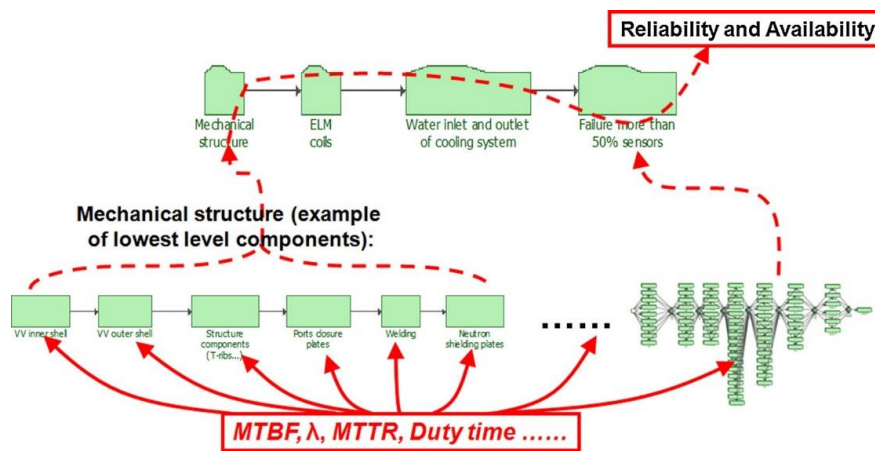
Figure 3.1 Diagram and calculation of system reliability and availability

Several principles are important for functional analysis, as shown in figure 3.1:

1. Functional analysis is the first step of the CFETR RAMI analysis: first find the most important top system functions, i.e., what needs to be done.

2. The top overall function can be broken down into three to six main functions requirements. These are the system requirements and the goals of RAMI reliability and usability. It is best if the number of function levels does not exceed five.

3. Each main function is further broken down till the bottom functions which are functions directly performed by indivisible components. There are intermediate functions between the bottom and main functions. Under each of the main functions, the number of sub-functions may vary.

The main function of the divertor RH system is to maintain the divertor module throughout the life cycle of reactor, assemble the manipulator system of the VV, lay the rail inside the VV, perform cutting and welding on pipelines of the divertor module inside the VV, transport the divertor modules, and so on. The functional analysis of system is shown in the figure 3.2.
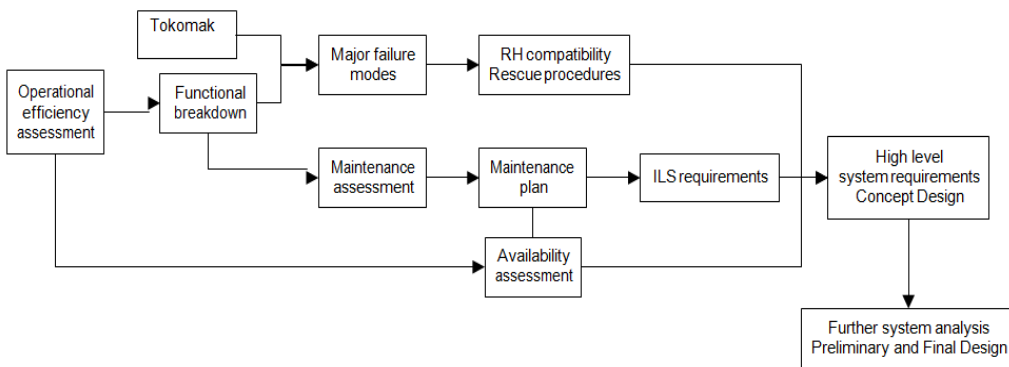
Figure 3.2: Functional analysis of the CFETR divertor RH system.
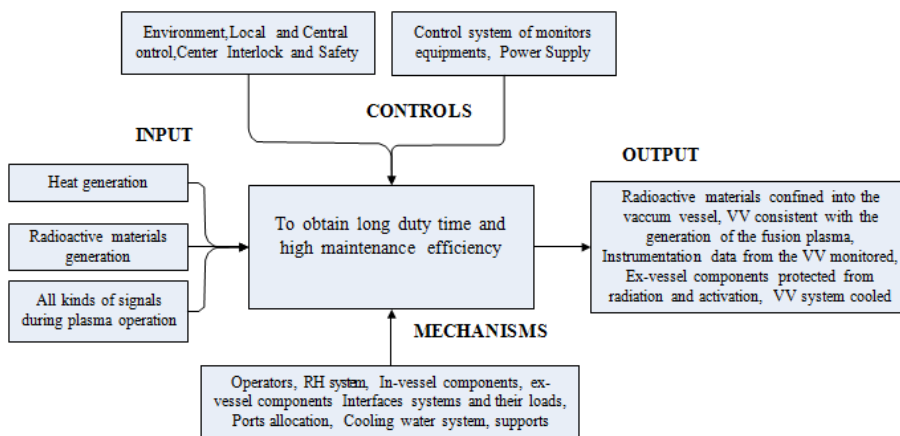
Figure 3.3: Model of the RH maintenance system by IDEFØ.

Figure 3.3 shows the features of the IDEFØ method where each feature is given an overall functional decomposition. Table 3.1 lists the functions and associated components or structures.

Table 3.1: Functions and associated basic parts or structures

Function	Components/structures corresponds to functions
Docking with VV, sealing	CASK docking systems
Cassette transportation	RH maintenance platform
Internal component maintenance	Multi-DOF-manipulator
Pipe cutting, welding, testing	Effector
Neutron/radiation shielding	Radiation protection structures and circuit boards
Reliability, maintainability	Redundant architecture design, quick-replacement system
Real-time feedback and monitoring	Sensors for pressure and vision, etc.

The functional analysis results are input to BlockSim Software; then data, such as the failure rate λ, MTBF, the Mean-Time To Repair (MTTR), the duty cycle, and so on, are collected.

Based on the functional analysis, the availability and reliability of VV are under the influence of the following subsystems:

1) RH maintenance platform;
2) CASK docking system;
3) Multi-DOF-manipulator;
4) Effector;
5) Radiation protection board;
6) Sensors for pressure and vision.

3.2.4   Reliability block diagram

Following the first step where the system reliability and usability was evaluated, the next step was taken. With RBD, reliability parameters and usability parameters can be

obtained by failure modes plus their effects and causes; then the system reliability and availability can be calculated, see figure 3.4.

Input of RBD included the accepted system functional analysis; failure modes; components; reliability parameters: MTBF, duty cycle, failure rates λ; maintainability parameters (MTTR and spare components). Output included reliability and its features, availability and its features, optimization recommendations, and the corresponding technical solutions.

(a) Top lasyer

(b) Bottom layer
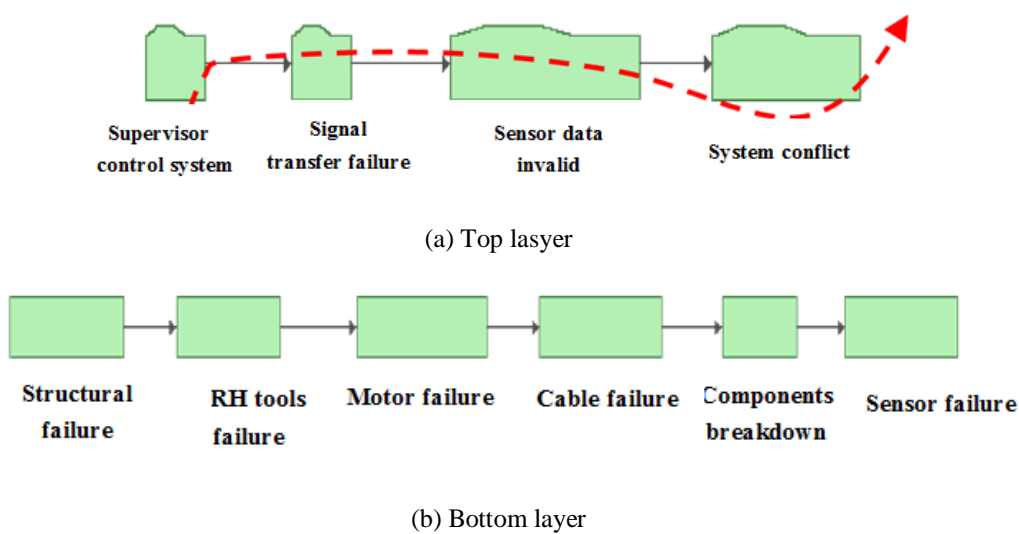
Figure 3.4: Reliability block diagram of the RH system.

General assumptions:

a) The availability and reliability calculation does not consider anything other than the reactor, including the power supply system, heating and cooling systems.
b) The calculation assumes that the system will serve for 20 years and operate for 100000 hours by simulation (The 20 years' service period is in accordance with that of ITER).

The reliability block diagram of mechanical structures

Mechanical failure will result in failure of the maintenance system:

- Reactor's structure
- Motor system

- Sensor system
- Cooling system
- …...
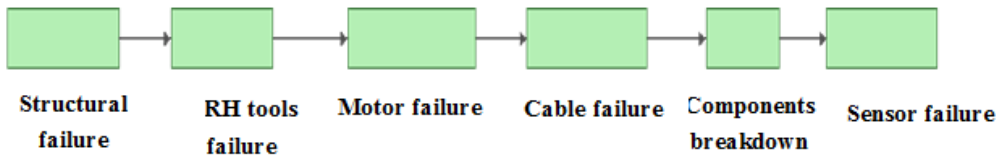
Figure 3.5: Reliability block diagram of mechanical structure of RH system.

In simulation with BlockSim, parameters are set as in table 3.2 for calculating reliability and availability.

Table 3.2: Parameter setting for calculating reliability and availability with BlockSim

Component	Failure rate (per year)	MTTR (years)	Notes
Main body	$5.00E^{-4}$	0.25	Reference to ITER requirements; port tests every four years. Occurrence frequency taking the upper limit of Level 1 based on the VV design and the standard of structure RCC-MR.
Motor system	$5.0E^{-4}$	0.5	Occurrence frequency of Level 1; upper limit ≥ 50%
Cooling system	$4.12E^{-3}$	0.5	Sum the failure rates of pipe breaking and leaking; occurrence frequency as Level 2; severity of Level 5
Sensor failure	$5.0E^{-4}$	1/6	Occurrence frequency of Level 1; upper limit ≥50%

Cooling system

Currently, there is no data for the failure rate of the tokamak maintenance system water cooling pipes. The failure rate of the external pipe is set at $7.0E^{-10}$/m/h. The length and

material type used in ITER are almost same as in CFETR, and the overall failure rate of the cooling system is $4.12E^{-3}$/y, as shown in table 3.3.

Table 3.3: Overall failure rate of the cooling system.

Component	Failure rate (per year)	MTTR, plus leak checking (years)	Notes
Cooling system	$4.12E^{-3}$	0.5	Sum of failure rates of breaks and leaks of external cooling pipes; the occurrence frequency of Level 2; severity of Level 5

Sensor system

The RH maintenance system runs inside the tokamak and it is needed to monitor various sensors, e.g., monitor the operation states of the manipulator joints through displacement sensors, the acceleration sensors, and the strain sensors. These sensors do not affect the system operation but should be maintained and tested on a regular basis, until automatic checking during the next maintenance period. From a conservative point of view, if the failure rate is over 50%, the corresponding sensor should be replaced. This replacement should be done after the shutdown of the tokamak reactor before the maintenance procedures in order to reduce the impact of failure mode on the tokamak and to increase the availability of the entire system. Otherwise, sensor replacement normally takes every two months.

Sensors are exposed to a harsh environment, and failure rates in the existing database are not applicable. The occurrence of frequency of event "sensor failure rate over 50%" is of level 1 with the failure rate less than $5.0E^{-4}$/y, as shown in table 3.4.

Table 3.4: Overall failure rates of a sensor system.

Components	Failure rate (per year)	MTTR (In years)	Notes
Sensor failure rate over 50%	$5.0E^{-4}$	1/6	Occurrence frequency: Upper limit of Level 1

The detailed RBD of the sensor is given in the figure 3.6.
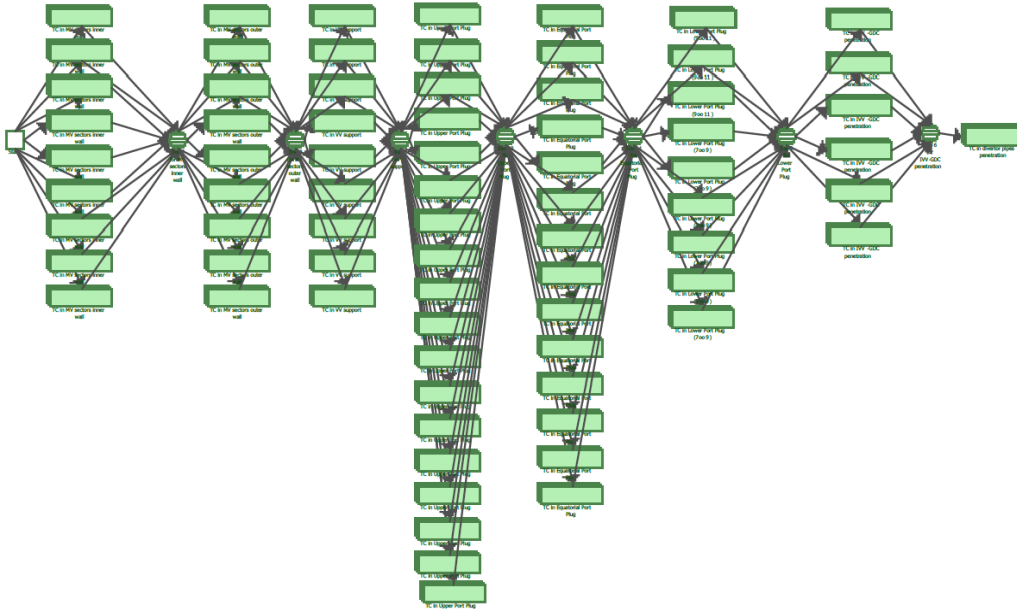
Figure 3.6: RBD of the RH sensor system.

To calculate inputs is shown in table 3.5:

Table 3.5: Calculation of various input conditions for RBD.

Block	Duty cycle (%)	Reliability			Maintain-ability	Notes
		Failure distribution function	MTBF (hours)	Λ (1/h)	MTTR (hours)	
Welding	100	EXP	6667	1.50E-04	8760	In strict accordance with the RCC-MR standard. Welding failure rate 1.50E-05, adding a conservative error factor 10

Radiation damage	100	EXP	2000	5.00E-04	17520	Occurrence frequency: Level 1 with upper limit. So far no record of such a failure rate
Cooling pipe	100	EXP	200	5.0E-03	6480	Occurrence frequency of Level 2 with upper limit
Sensor failure rate over 50%	100	EXP	2000	5.0E-04	1440	Displacement sensors, acceleration sensors, and strain sensors. Occurrence frequency of Level 1 with upper limit

We decompose the main functions of the RH system, calculate the availability and reliability of each basic function by BlockSim, give boundaries and inputs to the RBD, and obtain the results.
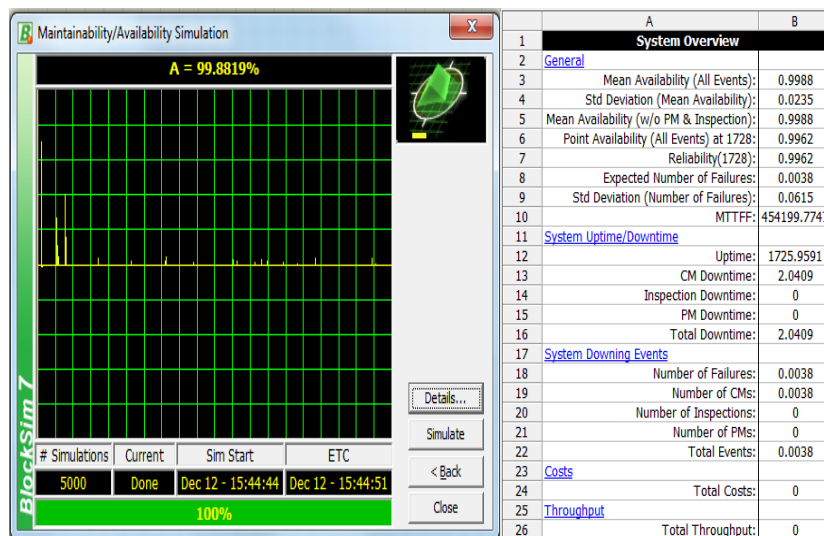
Figure 3.7: Calculation results of RBD on the CFETR RH System.

Figure 3.8: Graph of failure rate over time for the CFETR RH system.

Referring to the ITER assumptions, the availability of ITER is expected to be 99.43% and reliability 99.57%. Seen from results in figures 3.7 and 3.8, the availability of CFETR's RH maintenance system is 99.88% under the current design and boundary conditions and the reliability is 99.62%. The calculation results principally meet the desired goals and requirements.

3.3 Summary

RAMI based reliability analysis of the RH maintenance system design was presented. The theoretical calculation of the RAMI was illustrated. Functional analysis, reliability block diagrams, results of availability and reliability, a risk matrix diagram showing the risk levels under different failure modes. Occurrence probability of failures, the impact of failures, and recommendations to reduce risks. The curve of failure rate over time of the system provides the theoretical foundation for reliable system operation and prompt maintenance.

4 Reliability based optimization design of RH system

4.1 Introduction

Reliability based design has been receiving more and more attention and has become an important research direction for the rapid development of the mechanical engineering industry (Cadwallader. 2006). The reliability design of the remote handling maintenance system can help in many ways: 1) save the resources, material and financial resources; 2) improve design capability; 3) shorten the design cycle. Therefore, it plays an important role in reasonably arranging the pilot projects, verifying the rationality of the reliability design, and discovering weaknesses of a structure (Youn, 2003).

In reliability-based design optimization of the RH maintenance system, many design variables and parameters are uncertain. When used for reliability calculation, there will be significant defect resulting from the large error of failure probability, and the inability to provide explicit expression of random variables and reliability. In addition, the structural system often has multiple failure modes among which are certain correlations. These circumstances add more difficulties to reliability-based design optimization (Sibois, & Määttä, 2013). Therefore, it is necessary to find a better way to solve this problem (Su, & Chen. 2004).

There have been great improvements in structural reliability theory and methods, and the analysis methods include the First Order and Second Moment (FOSM) method, the Second Order and Second Moment (SOSM) method. Intelligent algorithms are methods, which search and calculate by employing natural or biological phenomena, and they can adapt to the environment. Currently, research on intelligent algorithms and new intelligent tools are being actively researched. The Differential Evolution (DE) algorithm is a stochastic parallel optimization algorithm based on swarm intelligence. It guides optimization searching by simulating heuristic swarm intelligence generated during cooperation and competition among individuals within a population (Vesterstrom, & Thomsen, 2013). DE is a stochastic global optimization method, robust, easy to use, and has been widely used in many fields (Liu, 2002). The DE's specific memory capacity makes it possible to dynamically track the current search, to adjust its search strategy, to realize the adaptive optimization, and thus has good global convergence and robustness. It is suitable for solving optimization problems in complex environments which cannot be solved by conventional mathematical methods (Ning, & Zhou, 2007; Gamperle, 2002).

In this dissertation, the FOSM and the DE algorithm were studied for the RH system reliability optimization analysis and compared with the other optimization algorithm such

as PSO and the traditional ANSYS to explore the solution for the higher reliability and lower cost system.

4.2 State of the art of reliability analyses methods for RH system

The safety and reliability of the RH maintenance system of a fusion reactor are the key technological issues, which the future design of a fusion reactor will face. This is because once the RH maintenance system fails. It will not only cause damage to the structure itself, but also have a significant and immeasurable impact on the fusion reactor (Chowdhury, 1988). Therefore, it is essential that the RH maintenance system meets design requirements and performs the designed operational roles within the specified period without the excessive maintenance. During the operation of the reactor, the reliability of the structure cannot be precisely predicted, due to uncertainty in the analysis and computational aspect of the structure. In order to ensure different design conditions and different limiting conditions (when the structure meets the safety, reliability, durability and overall stability requirements), the structure should satisfy a certain degree of reliability. The extreme state variables are the measurements of the structure's functions and mainly used to identify the reliability of the structure. In general, the factors that affect the reliability of structure are two comprehensive quantities, i. e., resistance, R, and load effect, S (Selvik, & Aven, 2011):

$$Z = g(R,S) = R - S \tag{4.1}$$

$$Z = R - S = 0 \tag{4.2}$$

Load resistance R and the actual load effect S of real engineering structures are random variables, thus Z is also a random variable and the following three cases may occur:

a) Reliable of structure;
b) Failure of tructure;
c) Structure in extreme state.

It is possible to determine if the structure meets a certain functional requirement based on the Z values. Variable Z is called the utility function and equation (4.2) is the extreme state equation.

Load effect S and resistance R both have many random variables (e.g., cross-sectional geometric characteristics, structural dimensions, material properties, etc.). The probability of extreme state must meet the following condition:

$$Z = g(R,S) = R - S \geq 0 \tag{4.3}$$

From the reliability theory, we can see that the reliability of a structure is the probability of an extreme state by the function $Z = g(R) \geq 0$. Reliability (i.e. the reliable probability) p_r and failure probability p_f are obtained from the extreme state equitation. The failure probability p_f can be expressed as:

$$p_f = \int_{z<0} \int f_x(x_1, x_2, ..., x_n) dx_1, dx_2, ..., dx_n \tag{4.4}$$

where, $f_x(x_1, x_2, ..., x_n)$ is the joint probability density function of n variables. If the basic variables are independent of each other, there are:

$$p_f = \int_{z<0} \int f_{x_1}(x_1) f_{x_2}(x_2) ... f_{x_n}(x_n) dx_1, dx_2, ..., dx_n \tag{4.5}$$

The failure and reliability of the structure are two mutually incompatible events; therefore, based on the probability theory, the relationship between the failure probability and reliability is complementary:

$$p_f + p_r = 1 \tag{4.6}$$

The probability density function of z is:

$$f_z(z) = \frac{1}{\sqrt{2\pi\sigma_z}} e^{\frac{1}{2}(\frac{x-u_z}{\sigma_z})^2} \tag{4.7}$$

where, $u_z = +u_R - u_S$ is the standard means and $\sigma_z = \sqrt{u_R^2 + u_S^2}$ is the standard deviation.

The reliability of structure is:

$$\Pr = P\{Z > 0\} = \int f_z(z) dz = \int \frac{1}{\sqrt{2\pi\sigma_z}} e^{\frac{1}{2}(\frac{X-u_z}{\sigma_z})^2} d_z \tag{4.8}$$

When the mean and variance of the function are known, the structural reliability is known, and the coefficient of the variation is obtained as the measure of structural reliability and is called the reliability index.

4.3   Differential Evolution Algorithm

An optimization problem solved by DE can be expressed as the following:

$$Min = f(x) \tag{4.9}$$

Restrictions:

$$\begin{cases} g(x) \le 0 \quad k = 1, 2, ..., m \\ h(x) = 0 \quad l = 1, 2, ..., q \\ \qquad X^L \le X \le X^U \end{cases} \tag{4.10}$$

where, $f(x)$ is the objective function, $g(x)$ and $h(x)$ respectively the inequality and equality constraints, m and q respectively the numbers of the inequality and equality constraints, while $X = (X_1, X_2, ..., X_n) \in R^n$ represents an n-dimensional decisional variable, which is in the range of $[X^L, X^U]$.

(1) Generating an initial population

DE uses a real-valued population, each individual is represented as:

$$Xi, G(i = 1, 2, ..., Np) \tag{4.11}$$

where, i is the sequence of individuals in the population, G is the generation of evolution, and Np is the population size, which remains unchanged during the minimization process.

To establish the initial point of optimization, the population must be initialized. A method generally used to construct the initial population is randomly selected from within the given boundary. In a DE study, it is generally assumed that all random initial population individuals are uniformly distribution probability. The boundaries for the variable parameters:

$$X_j^{(L)} < X_j < X_j^{(U)} \tag{4.12}$$

and then:

$$X_{ji,0} = rand(0,1)(X_j^{(U)} - X_j^{(L)}) + X_j^{(L)} \tag{4.13}$$

where, $rand(0,1)$ is a generated uniform random number in the range of [0, 1]. $i = 1, 2, ..., Np$; $j = 1, 3, ..., D$.

If preliminary solutions can be obtained in advance, the initial population may be produced by adding the normally distributed variations to the preliminary solutions in order to improve reconstruction effects.

(2) Mutation

For each target vector X_i, $G(i = 1, 2, ..., N_p)$, a mutant vector is generated as follows:

$$v_{i,G+1} = X_{r1,G} + F \cdot (x_{r2,G} - x_{r3,G}) \tag{4.14}$$

Herein the randomly selected numbers r_1, r_2, and r_3 are different from each other, and $N_p \geq 4$. The mutation operator $F \in [0,2]$ is a real constant amplification factor and controls deviation.

(3) Crossover

In order to increase the diversity of parameter vectors, a crossover operation is introduced. The test vector becomes:

$$u_{i,G+1} = u_{1i,G+1}, u_{2i,G+1}, ..., u_{Di,G+1} \tag{4.15}$$

$$u_{ji,G+1} = \begin{cases} v_{ji,G+1} & \text{if } randb(j) \leq CR \text{ or } j = rnbr(i) \\ X_{ji,G+1} & \text{if } randb(j) > CR \text{ and } j \neq rnbr(i) \end{cases} \tag{4.16}$$

where, $rand\ b(j)$ is a generated random number in the range of [0, 1]; $rnbr(I) \in 1,2$, D is the sequence selected. $i = 1,2...,Np$; $j = 1,3,.....,D$. The crossover makes sure that at least one trial parameter from the mutant is inherited and CR is the crossover operator in the range of [0,1].

(4) Selection operation

When DE determines if a test vector $u_{i,G+1}$ will become a member of the next generation, it compares a target vector in the current population with the corresponding trial vector; the trial vector has an equal or lower objective function value than that of the target vector. It replaces the target vector in the next generation. Note that the trial vector is not compared with each individual of the population.

(5) Boundary conditions

Every trial parameter value must be in the feasible region of the problem at hand; if a newly generated random individual in the feasible region replaces a trial individual outside the boundaries.

That is if,

$$u_{ji,G+1} < x_j^{(L)} \text{ or } u_{ji,G+1} > x_j^{(U)}, \tag{4.17}$$

Then:

$$u_{ji,G+1} = randj[0,1](x_j^{(U)} - x_j^{(U)}) + x_j^{(L)},$$

$$i = 1,2\ldots,Np; \quad j = 1,3,\ldots\ldots,D \tag{4.18}$$

Another method is to re-produce the trial vector and then perform the crossover operation until a new feasible individual is obtained (Brest, et al 2007). The important parameters of the DE algorithm are mainly population size Np, mutation factor F and crossover probability CR. Parameter selection is critical for the algorithm to have good performance. Research results show that 1) the number of the population size, Np, is generally between 5xD and 10xD; if it is less than 4, DE cannot perform the mutation operation; 2) mutation factor F is typically between [0, 2]; 3) the crossover operator is generally in the range of [0, 1] and usually taken as 0. 5.

4.4   Reliability based optimization of the 3-DOF platform

Structure optimization design of the 3-DOF-platform allows some performance indicators of the structure, such as weight, stiffness or cost, to achieve the maximum under a variety of specifications or requirements (Yu, 2013). It is a combination of optimization techniques and mechanic computation. Optimization is a process, which requires the establishment of a mathematical model (the objective function) for optimizing the problem and then finding solutions for the problem. For establishing the mathematical model, there are three things that need to be done: 1) determine the objective function(s); 2) select design variables; and 3) list constraints. This chapter is devoted to the reliability based optimization of the 3-DOF-platform in the divertor RH maintenance for the CFETR system. Here the smallest weight of platform and hydraulic lifting system are the objective functions; strength and reliability are the constraints; and establishing a multi-objective optimization problem is the mathematical model for optimizing the reliability of the 3-DOF hydraulic lifting system.

4.4.1   Mathematical model of optimization design

A reasonable 3-DOF-platform structure should meet a variety of conditions: strength, rigidity, stability, weight, machining, assembling and so on. The objective function of optimization is to minimize structural weight, while meeting the requirements of structural stiffness and strength (Lopez, & Beck, 2012).

The reliability based design optimization model of the system with both probabilistic and interval variables can be generally expressed as:

$$Min \ W(X) = f(x) \tag{4.19}$$

$$X^L < X < X^U$$

where, $W(X)$ is the objective function, X represents the design variables (Cross section area A, thickness T, diameter of hydraulic cylinder rod D, hydraulic cylinder diameter d), X^L lower boundaries of design variables, X^U designates the upper boundaries of design variables.

If the concern is with the lifting platform and the hydraulic system weight, the design can be formulated as:

Minimize $\qquad f(X,P) = f_1 + f_2$ (4.20)

$$f_1 = \rho_1 \times B \times H \times T \tag{4.21}$$

$$f_2 = 4\rho_1 l_1 \frac{\pi d^2}{4} + \rho_2 l_2 \frac{\pi(D-d)^2}{4} \tag{4.22}$$

where, $f(X,P)$ the objective function of the minimum weight of the platform, f_1 the weight of mechanical lifting platform, f_2 the weight of hydraulic cylinder; P are the system parameters such as the B, H and T the platform width, length and thickness, respectively; d the diameter of the piston rod, D the diameter of the hydraulic cylinder and l the length of the cylinder. $\rho_1 l_1 \frac{\pi d^2}{4}$ and $\rho_2 l_2 \frac{\pi(D-d)^2}{4}$ respectively the weights of the hydraulic cylinder and the hydraulic rob.

If the basic variables are independent of each other, there are subjects to the reliability constraints:

$$p_r\left[g_i(X,P) > 0\right] \le \Phi(-\beta_i^T), \, i=1, 2 \tag{4.23}$$

$$p_r\left[g_1(X,P) = 1 - \frac{\sigma}{[\sigma_s]} > 0\right] \le \Phi(-\beta_1^T)$$

$$p_r\left[g_2(X,P) = 1 - \frac{\xi_i}{[\xi_i]} > 0\right] \le \Phi(-\beta_2^T)$$

where, $X \in R^{nr}$ is the random vector, $P \in R^{np}$ are system parameters, and $\Phi(\cdot)$ is standard cumulative function of the normal failure distribution. β_i^T is the target reliability index. The selection of a target safety index β^T is dependent and commonly used value is 3, σ mean value of yield strength, $[\sigma_s]$ yield point strength, the deformation constraint, ξ_i the mean value of strain constraint, $[\xi_i]$ the allowable strain. The other parameters as well

as the expected values of the stochastic variables can be optimization as geometric dimensions, material properties and boundary conditions can be considered in the optimization process.

Geometric constraints are:

400mm≤B≤800mm;   400mm≤H≤1200mm;   0mm<T≤50mm;   50mm≤d≤160mm; 60mm≤D≤180mm; 15mm≤l≤40mm.

The critical load value for pressure on the piston rod is:

$$F \le \frac{\phi \pi^2 EJ}{n_k l^2} \tag{4.24}$$

where, l is the cylinder length, ϕ the coefficient of the hydraulic cylinder supporting mode, n_k the safety factor of 2 to 4, E the elastic modulus of the piston rod, and:

$$J = \frac{\pi d^2}{64} \tag{4.25}$$

The moment of inertia of the section of piston rod.

The cylinder material is 316LN, Elastic modulus E =200Gpa, the Poisson's ratio μ= 0.3, yield point strength $[\sigma_s]$ is 245MPa.

4.4.2   System reliability based optimization with the DE algorithm

The differential evolution algorithm is a global search algorithm and it minimizes the nonlinear non-differentiable continuous function. It is robust, easy to use and has been widely used in nonlinear constrained optimization computation, clustering optimizations, control and neural networks and other fields. The general process of DE is shown in figure 4.9 (Dos Santos Coelho, 2009; Mallipeddi, et al. 2011).
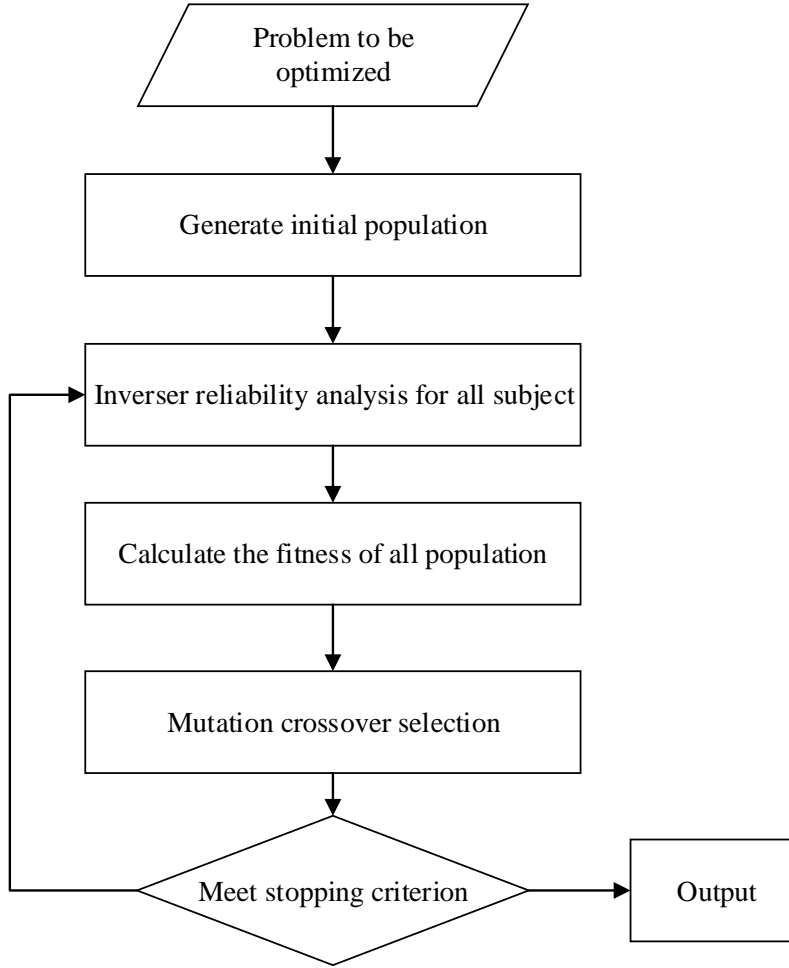
Figure 4.9: Differential evolution algorithm.

To overcome the problem of falling into local optimum, the concept of "center point of the population" was introduced in the DE algorithm. As the last individual of a population, this "center point of the population" only competes with the current best, and receives no operation on it; in contrast, the other (Np-1) individuals receive the mutation, crossover and selection operations. The "center point of the population" is defined as following:

$$C_p = \frac{1}{N_p - 1} \sum_{k=1}^{N_p - 1} x_k \qquad (4.26)$$

The center point has two functions in the DE algorithm: 1) this point only competes with the current best, therefore, accelerating the convergence speed; 2) the point is reliable and is still changing when some individuals are in the stagnation state. Thus, the competition between the centroid and the current best still exists, and the probability of early convergence is reduced. The reformed scheme is called the Adaptive Centre Differential Evolution algorithm (ACDE) and the steps are as follows:

① Determine the optimized parameters: 1) the population size Np; 2) the weight actor F; 3) the minimum value, Cr_{min}, and maximum values, Cr_{max}, of the crossover;

② Create the (Np-1) initial population individuals in the feasible region, and calculate their center point Cp as the last individual of the initial population;

③ Perform the reliability analysis of all subject for the Np-1 trial vectors;

④ Create the (Np-1) initial population individuals in the feasible region, and calculate their center point Cp as the last individual of the initial population;

⑤ Perform the mutation crossover operation to generate a mutant cluster h(g+1), in the feasible region, for each current population individual except the center point Cp;

⑥ Evaluate the process by the stopping criteria. If the evolution has reached the maximum number of generations or the convergence requirements, go to Step⑦; otherwise, increase the number of generations by 1, and go to Step ③;

⑦ Output the optimal solution and end the calculation process.

The above-discussed design variables, constraints and the objective function are used to establish the optimization model of the 3-DOF hydraulic lifting system in the MATLAB. The Adaptive Center Differential Evolution Algorithm (ACDE), the Particle Swarm Optimization Algorithm (PSO), and the ANSYS optimization algorithm are used to perform the optimization operation for comparative analyses. We need to set the parameters for the ACDE algorithm as Np = 10D, t_{max} =3 000, CR_{min} =0.1, CR_{max} =0.9, F =0.5. Thirty simulation experiments have been performed with the optimization methods. The simulation results are shown in table 4.1.

Table 4.1: Results of reliability based optimization on the 3-DOF platform by different methods.

Design variable	Initial value	Top limit value	Lower limit value	ANSYS optimization value	PSO optimization value	ACDE optimization value
B(mm)	600	400	800	600	575	530
H(mm)	1200	400	1200	1200	130	1120
T(mm)	400	20	50	400	38	31
D(mm)	180	60	180	180	178	160
d(mm)	110	50	160	110	80	90
l(mm)	300	15	40	300	290	270
t(min)	——	——	——	——	17.9	26.7
N	——	——	——	——	2265	1497
Weight (kg)	——			253.2	215.56	215.38

As seen from the table 4.1, the structural optimization results of the ACDE algorithm are better than that of ANSYS tool. The running time also shows that the convergence by the ACDE algorithms is faster than that of the PSO algorithm. The optimization results by the ACDE reliability analysis verify the correctness of the ANSYS results. The running time also shows that the search capability of the ACDE algorithm is better than other methods because the corresponding convergence speed is faster than other optimization algorithms.

4.5   Summary

In this chapter, the 3-DOF platform of divertor maintenance was taken for analysis to ensure the reliability of its structure. The reliability based analysis methods of RH maintenance systems, such as FOSM and SOSM were also presented. Meanwhile, the reliability based analysis methods of the intelligent algorithms such as the DE algorithm the PSO Algorithm. The running time shows that the convergence by the DE algorithms is faster than that of the PSO algorithm and result also is better than ANSYS optimization tool, which showed that the DE algorithm had the advantage in the reliability based system analysis and optimization.

5 Optimization control of the RH system

5.1 Introduction

Control of the CFETR RH maintenance system plays an important role in tokamak maintenance performance. In this section, the divertor RH maintenance control system is studied to perform the hydraulic servo control optimization, establish the servo control experimental platform, use control optimization with DE methods and compare its robustness, response and anti-interference ability with Fuzzy adaptive PID control. Feed-forward control method improves the performance over a simple feedback control system against the disturbances (Jones, D., & Mansoor, S. 2004). The feed-forward controllers has been studied in the previous works (Wu, et all, 2014) for suppressing the chatter of manipulator in ITER application, and neural network control has been studied by the team member(Mazin. et. all, 2014). In this research is to study the different intelligent control algorithms to handle the uncertain in the hydraulic servo system.

5.2 Design of servo control system for the 3-DOF system

Hydraulic servo-systems are widely applied due to their lightweight, small size and high torque (Kazuhisa, et al. 2012), as showed in table 5.1. With increasing requirements regarding precision control, the requirements on hydraulic servo-control technology have also become tighter (Lim, 2003).

Table 5.1: Comparison of transmission between water and hydraulic oil.

	Water hydraulic	Oil hydraulic
Advantages	Clean, pollution-free, safe, cheap, easy to obtain, high recycling rate and easy process.	High viscosity, good lubrication properties, antirust, compatible. lower ratio of price to performance
Disadvantages	Low viscosity, poor lubrication performance, high-saturated vapor pressure, high causticity, susceptible to contamination; water hydraulic component have problems: wear, corrosion, cavitation, erosion, leakage and other issues; worse	Flammable, leakage and emission pollution, easy oxidation and metamorphism, poor shear capacity, viscosity largely affected by oil temperature, recycling rate, difficult waste treatment, and decreasing oil resources.

	overall performance and shorter life expectancy.	

A hydraulic servo-system is normally nonlinear and has time-varying parameters, especially in valve-regulated power flow mechanisms. It is difficult for traditional PID control to achieve acceptable results (Dommel, 1971). Recently, there have been many different modern control strategies, such as fuzzy control, evolutionary control, neural network control, adaptive control, predictive control, etc., solving this problem. These control methods have made great progress in theory, but there are some practical problems to be addressed in hydraulic servo control. This chapter is devoted to the hydraulic servo control system design of the lifting system for the divertor RH maintenance system, including verification of its feasibility and reliability of the feedback control system. The structure is shown in figure 5.1.
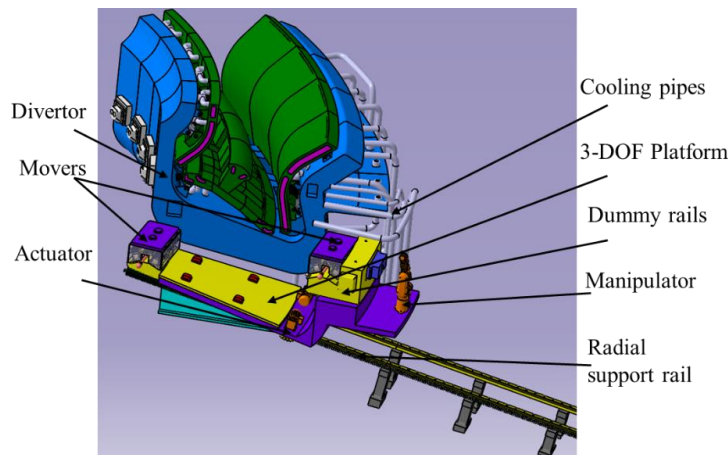

Figure 5.1: 3-DOF water hydraulic lifting system of the Divertor RH system.

A flow chart of the hydraulic servo-driven 3-DOF system is shown in figure 5.2.
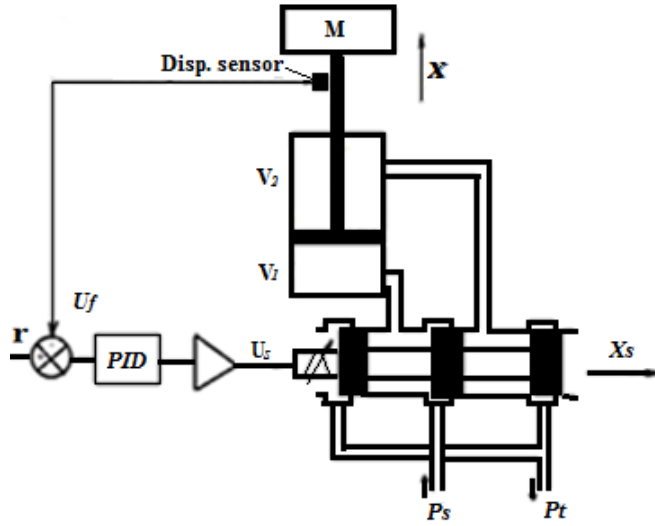
Figure 5.2: Flow chart of hydraulic servo-driven system.

5.2.1 Transfer function for the hydraulic cylinder

The feedback signal converted into voltage signal U_f by displacement sensor inside the hydraulic cylinder. The voltage signal is transmitted to the control system and compared with the system's given signal r, as shown in figure 5.2. Then, differential signal is obtained and converted to an electrical signal through the control amplifier and input to the servo valve solenoid for adjusting the valve displacement X_s. The relationship between U_s and X_s is expressed in the first-order transfer function (Jelali, & Kroll. 2003):

$$\frac{X_s}{U_s} = \frac{1}{1 + \tau_v s} \tag{5.1}$$

where, τ_v is a time constant determined by the frequency response of the servo valve. The phase delay is 45° when the frequency range is:

$$\tau_v = \frac{1}{\omega_{-45°}} = \frac{1}{2\pi f_{-45°}} \tag{5.2}$$

Therefore,

$$X_s = \frac{k}{150+s} U_s \tag{5.3}$$

For calculation and design convenience, the constant gained is k.

At the time of the initial state, the signal U_f of the feedback displacement sensor and the input signal r is 0; the deviation signal U_s value is 0, the spool is at the zero position and there is no flow output. When the error signal $U_s > 0$, the spool moves to the right under the influence of the deviation signal, and the flow output of the hydraulic system increases until $U_s = 0$. Then the forces of the two ends of the spool are balanced, and vise versa. Therefore:

(1) The work parameters of the hydraulic cylinder controlled by valve are:

$$p_L = \frac{F}{A_1} = p_1 - p_2 \frac{A_2}{A_1} \tag{5.4}$$

and:

$$Q_L = Q_1 + \frac{nQ_2}{1+n^2} \tag{5.5}$$

where:

$n = A_2/A_1$;

A_1, A_2 = areas for the rod and no-rod chambers of the hydraulic cylinder;

p_1, p_2 = pressure in the rod and rod-free chambers of the hydraulic cylinder;

P_L = load;

Q_L = load flow;

Q_1, Q_2 Respectively are flows into the rod and rod-free chambers of the hydraulic cylinder.

(2) Equations of servo valve flows:

$$Q_1 = \begin{cases} c_s \dfrac{u_s}{k} sign(p_s - p_1) \sqrt{|p_s - p_1|}, u \geq 0 \\ c_s \dfrac{u_s}{k} sign(p_1 - p_t) \sqrt{|p_1 - p_t|}, u < 0 \end{cases} \tag{5.6}$$

$$Q_2 = \begin{cases} c_s \dfrac{u_s}{k} sign(p_2 - p_t) \sqrt{|p_2 - p_t|}, u \geq 0 \\ c_s \dfrac{u_s}{k} sign(p_s - p_2) \sqrt{|p_s - p_2|}, u < 0 \end{cases} \tag{5.7}$$

where, p_s is the pressure of the water pump; p_t is the pressure of the water tank connecting with the external environment, i.e. atmospheric pressure; c_s is the flow coefficient;

(3) Flow continuity equation of the hydraulic cylinder

When the piston rod of the hydraulic cylinder moves at a constant speed, the flow rates into the rod and rod-free chambers of hydraulic cylinder are:

$$Q_1 = A_1 \dot{x} \tag{5.8}$$

$$Q_2 = A_2 \dot{x} \tag{5.9}$$

Where, $\dot{x}$ is the speed of the piston rod; linearized the formulas (5.7) and (5.8), then obtained:

$$K_q = \partial Q_L / \partial x_s \tag{5.10}$$

$$K_c = \partial Q_L / \partial P_L \tag{5.11}$$

By combining the formula (5.7) with (5.10), the linear flow equation of valve is:

$$Q_L = K_q x_s - K_c P_L \tag{5.12}$$

where, x_s is displacement of the servo valve, K_q is flow gain, and K_C is the flow-pressure coefficient.

Therefore, the flow continuity equation of the hydraulic cylinder is:

$$\dot{p}_1 = \frac{B_e}{A_1 x + V_1} (Q_1 - A_1 \dot{x} - C_{ic}(p_1 - p_2)) \tag{5.13}$$

$$\dot{p}_2 = \frac{B_e}{A_2(L-x) + V_2} (-Q_2 + A_2 \dot{x} + C_{ic}(p_1 - p_2)) \tag{5.14}$$

where, x is displacement of the piston rod of the hydraulic cylinder, B_e is the effective bulk modulus of water, C_{ic} is the hydraulic cylinder leakage coefficient, and L is the hydraulic cylinder stroke;

V_1— The initial volume of the rod-less chamber of the hydraulic cylinder;

V_2— The initial volume of the rod chamber of the hydraulic cylinder;

(4) The force equilibrium equations:

According to the Newton's second law of motion, the motion equation of the hydraulic cylinder piston is:

$$A_1 p_L = A_1 p_1 - A_2 p_2 = fe + m\ddot{x} + mg \tag{5.15}$$

where, m is the weight of load mass, b is the viscous friction coefficient of 400, generally, $\ddot{x}$ is acceleration of the cylinder rod, and fe the friction force (N).

The friction force fe is defined as (Canudas, 1995; Olsson , 1996):

$$fe = \sigma_0 \cdot z + \sigma_1 \cdot z \frac{dz}{dt} + b \cdot x_p \tag{5.16}$$

$$\frac{dz}{dt} = \dot{x}_p - \frac{|\dot{x}_p|}{g(\dot{x}_p)} z , \tag{5.17}$$

$$g(\dot{x}_p) = \frac{1}{\sigma_0} \left[F_C + (F_S - F_C) \cdot e^{-\left(\frac{\dot{x}_p}{v_s}\right)^2} \right], \tag{5.18}$$

where, σ_0 is the flexibility coefficient (N/m), σ_1 the damping coefficient (Ns/m), b the viscous friction coefficient (N/m), general values of 400, z the internal state, F_C the Coulomb friction level (N), F_S the static friction force level(N), and v_s the Stribeck velocity (m/s).

In the early work, the dynamic modeling and parameter identification was studied, which showed that the leakage coefficient is more sensitive to the system and coulomb friction has less impacts on the water hydraulic system (Liu, 2006). For the simplification and linearization, only viscous friction was concerned. Therefore, in the simulation only the linear model was set up without considering the nonlinear and time-varying parameters.

Equations (5.14) and (5.15) are substituted into equation (5.6) to give:

$$Q_L = A_1 \dot{x} + \frac{V_t}{2(1+n^2)B_e} \dot{P}_L + C_{tc} P_L \qquad (5.19)$$

where, V_t is the volume of the hydraulic cylinders and C_{tc} is the total leakage coefficient with $C_{tc} = ((1+n)/(1+n^3))C_{ic}$.

5.3 Servo control based on the differential evolution algorithm

5.3.1 Optimal control modeling with the DE Algorithm

The differential evolution introduced by Storn, & Price. (1996), has proven to be promising for minimizing real-valued, non-linear, and multi-modal objective functions (Melo, 2012). The flow chart is given in figure 5.10. The D is the number of variables and N_p represents the population size.
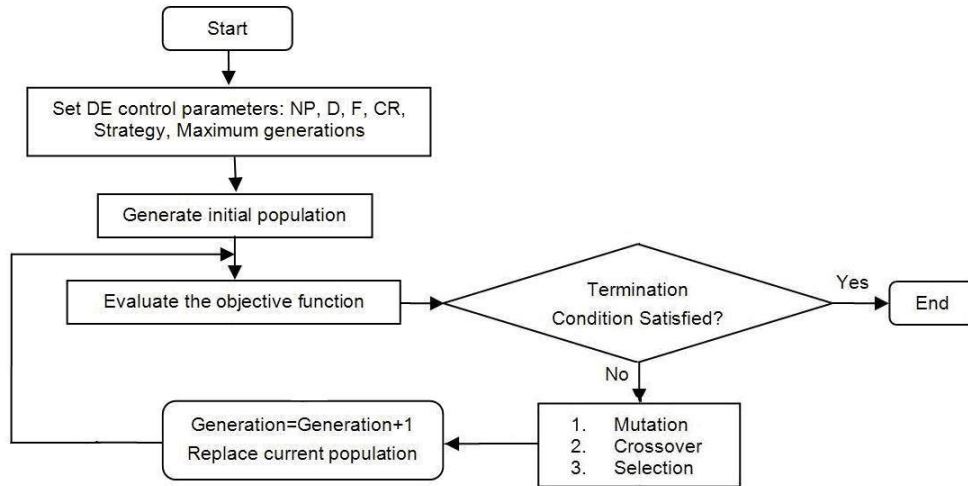

Figure 5.3: Flow chart of the DE algorithm.

The objective function of a DE algorithm is:

$$Min \quad f = \int_0^t (r - x)^2 \, dt \qquad (5.20)$$

Restrictions:

$$\begin{cases} g(x) \leq 0 \ \ k = 1, 2, ..., m \\ h(x) = 0 \ \ l = 1, 2, ..., q \\ \quad X^L \leq X \leq X^U \end{cases} \tag{5.21}$$

where, $f(x)$ is the objective function, $g(x)$ and $h(x)$ respectively the inequality and equality constraints, m and q respectively the numbers of the inequality and equality constraints, while $X = (X_1, X_2, ..., X_n) \in R^n$ represents an n-dimensional decisional variable, which is in the range of $\left[X^L, X^U \right]$.

with constraints of P_k, P_i, P_d given by the following:

$$\begin{cases} P_k^L \leq P_k \leq P_k^U \\ P_i^L \leq P_i \leq P_i^U \\ P_d^L \leq P_d \leq P_d^U \end{cases} \tag{5.22}$$

The parameters were set as $N_P = 10D$, $t_{max} = 3000$, $CR_{min} = 0.1$, $CR_{max} = 0.9$, and $F = 0.5$.

5.3.2   Servo valve-controlled hydraulic cylinder based on DE

The block diagram is given in figure 5.4. The simulation environments, such as step length, time and input signal, were the same as those when using the fuzzy adaptive PID.

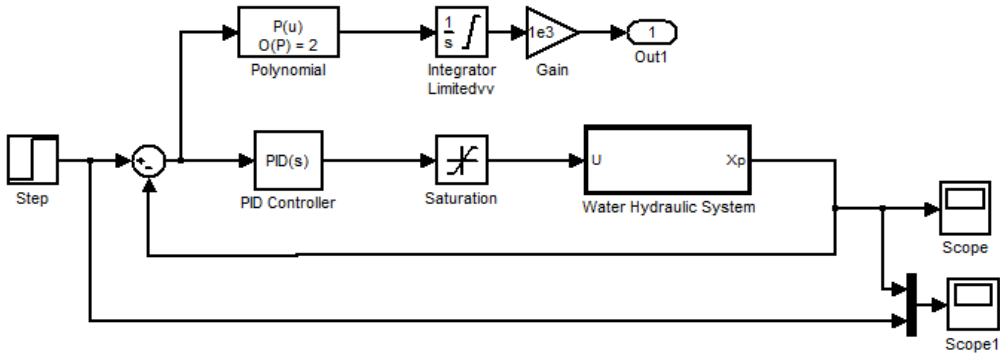Figure 5.4: Block diagram of the valve-controlled cylinder system using DE.

As seen from the simulation results, the optimal values of the parameters are $K_p = 1$, $K_i = 0,2$ and $K_d = 0.46$. The optimization process is shown in figure 5.5 and figure 5.6 (Yousefi, 2008; Subudhi, & Jena, 2011).
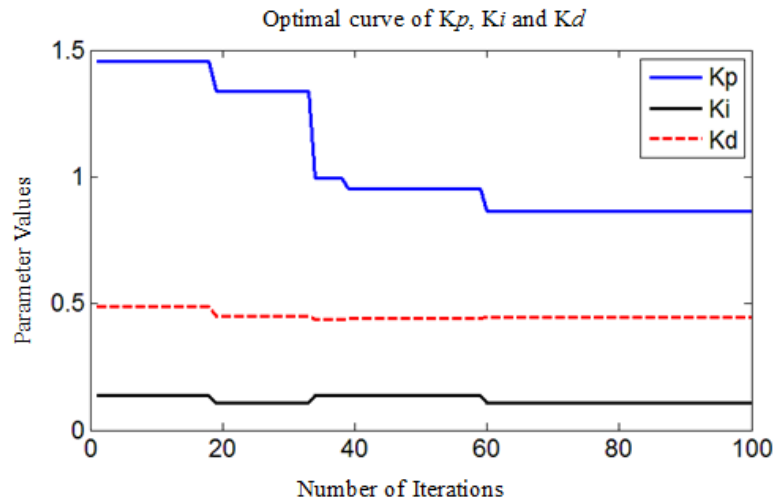

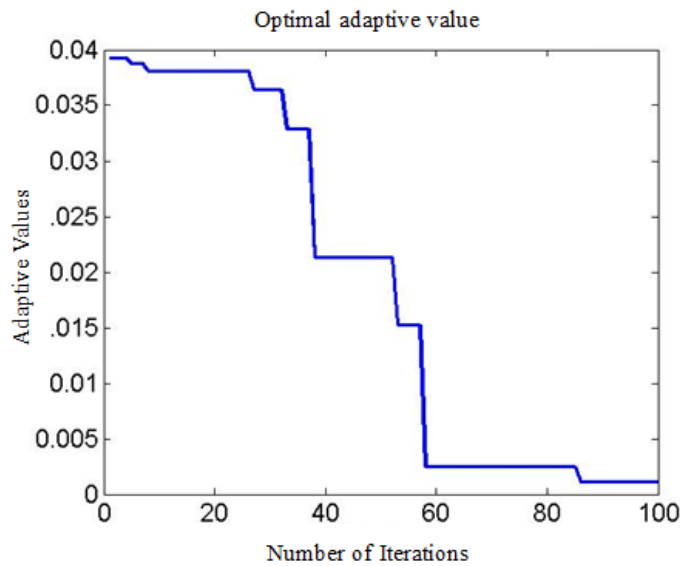
Figure 5.5: Parameter optimization process.

Figure 5.6: Best fitness of optimization process.

As we have studied that the fuzzy adaptive PID control has performed better than the conventional PID controller for the small overshoot, high robustness, quick response and strong anti-interference ability. So, in order to verify the optimization control of DE algorithm result we compared the DE control algorithm with the fuzzy adaptive PID control in the water hydraulic lifting control system.

5.4   Servo control based on Fuzzy adaptive PID

In the 1990's, with the rapid development of computer science, the use of artificial intelligence technology appeared. This constitutes a knowledge base with comprehensive expert knowledge and experience to imitate the thinking and decision-making process of a human and to realize the automatic adjustment of PID control parameters by fuzzy logic. The basic principle of fuzzy adaptive PID control is schematically shown in figure 5.7.
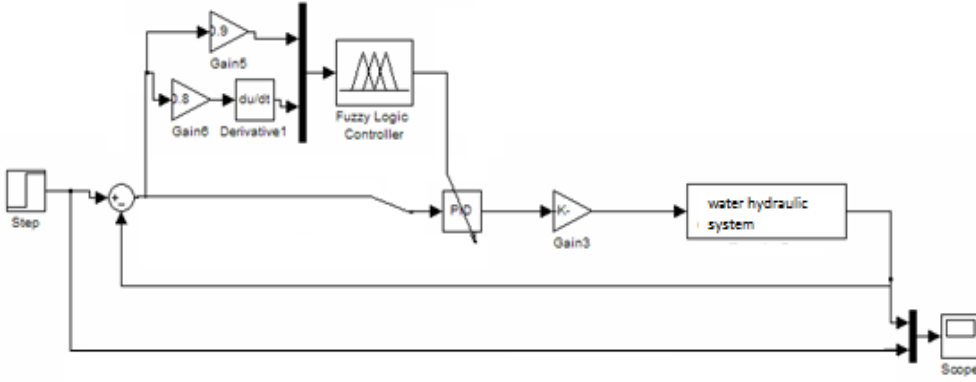
Figure 5.7: Schematic diagram of fuzzy adaptive PID control.

Fuzzy adaptive PID control consists of conventional PID control and the fuzzy inference system. The error e and the rate of error change $ec(de/dt)$ are inputs of the fuzzy controller; outputs of Δk_p, Δk_i and Δk_d are obtained based on fuzzy control rules and fuzzy inference reasoning; the PID parameters are then adjusted to meet the different requirements of e and ec.

The fuzzy adaptive PID controller realizes adaptive parameter adjustment according to the following formulas:

$$k_p = k_p' + \Delta k_p$$
$$k_i = k_i' + \Delta k_i \qquad\qquad (5\text{-}22)$$
$$k_d = k_d' + \Delta k_d$$

where, $k_p{}'$, $k_i{}'$and $k_d{}'$ are the initial values of the PID parameters; $\Delta k_p{}'$, $\Delta k_i{}'$ and $\Delta k_d{}'$ are outputs of the fuzzy controller; and k_p, k_i and k_d are the final output values of the control parameters.

Fuzzy control rulers of the Δk_p, Δk_i and Δk_d can be derived from the regulation rules.

Each variable defines a linguistic set of seven items {NB, NM, NS, O, PS, PM, PB}. A triangular membership function is selected for the input and output variables of the fuzzy controller, as demonstrated below in figure 5.8:

(a)

(b)

Figure 5.8: (a) error input and error change input membership function, (b) output membership function.

The corresponding fuzzy control general rules are:
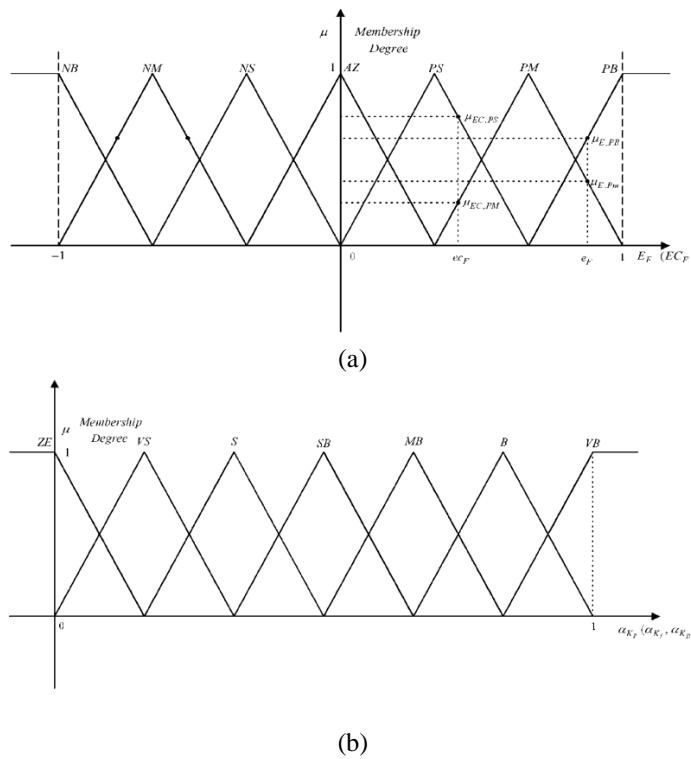
IF eF is NEm and ecF is NECn; THEN μKp is NK1; μKi is NK2; μKd is NK3.

The simulation results are shown in figure 5.9. The initial value of the PID parameters were given as $k_p{}'= 300$, $k_i{}'= 0.3$, $k_d{}'= 280$. The quantitative factors were $k_e = 0.005$ and

$k_{ec} = 0.005$; and the scaling factors of k_p , k_i and k_d were $k_1 = 0.001$, $k_2 = 0.05$ and $k_3 = 0.001$. A unit step signal was added as the system input. The response curves of conventional PID control and fuzzy adaptive PID control were obtained.
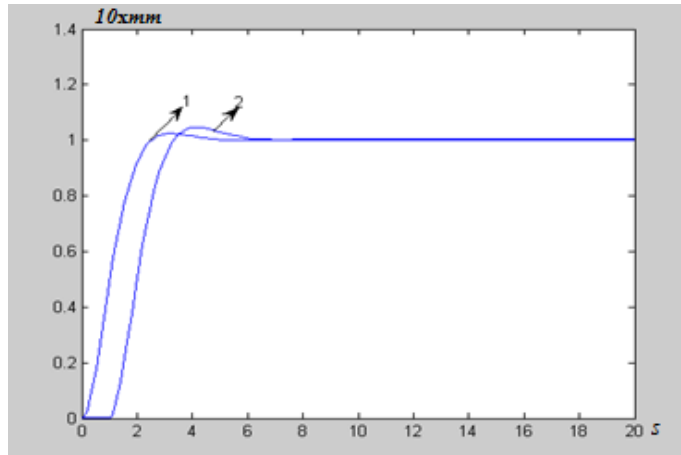
Figure 5.9: Step responses. Curve 1: Fuzzy adaptive PID control; Curve 2: Conventional PID control.

The results show that fuzzy adaptive PID control provides smaller overshoot and shorter response time than conventional PID control, thus, the system has stronger adaptability.

5.5   Experimental verification of different control strategies

The hydraulic test platform is for analyzing the performance of the water hydraulic component and for experimental verification of the pressure control system. This test platform was used for experimental verification of the control strategy of the valve controlled cylinder system (Hyun-Joon, 1997).

5.5.1   Experiment setup

The hydraulic test platform used a modular structure and usually included a power supply module, a valve-controlled hydraulic cylinder module, a digital signal conversion module and a computer monitoring module (Wu, 2005; Dubus, 2008).

(1) Power supply module

The power supply module provides flow and pressure for the hydraulic system (Trostmann, 1995). Separating the water tank and pump avoids pump vibration from being transferred to the tank, thus avoiding vibration impact on valve performance. The water treatment system performs ion sterilization to the tank water to prevent microbial pollution of the water hydraulic component, as shown in figure 5.10.

Figure 5.10: Water tank and control system.

(2) Valve-controlled hydraulic cylinder module

The hydraulic module is composed of the hydraulic cylinder, the servo valve and displacement sensors, as shown in figure 5.11. The displacement signals were converted to digital signals and sent to the control system. Then, the control system sent the control signal to the valve to realize displacement control of the hydraulic cylinder.
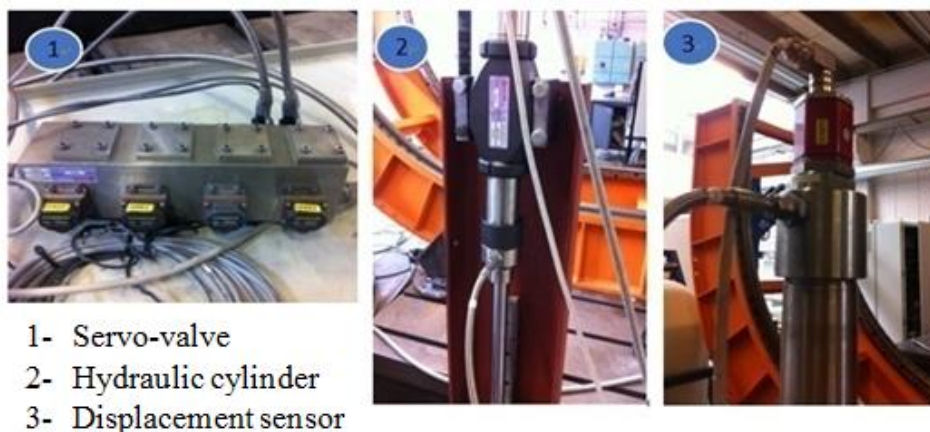
1- Servo-valve
2- Hydraulic cylinder
3- Displacement sensor

Figure 5.11: Valve-controlled hydraulic cylinder module.

(3) Digital signal conversion module

An A/D digital signal converter (showed in figure 5.12) converts the piston rod displacement signal into a digital signal for the computer control system, and similarly, a D/A converter converts the binary digital outputs from the computer control system to the voltage or current input to the servo valve solenoids to realize control of displacement of the hydraulic cylinder.
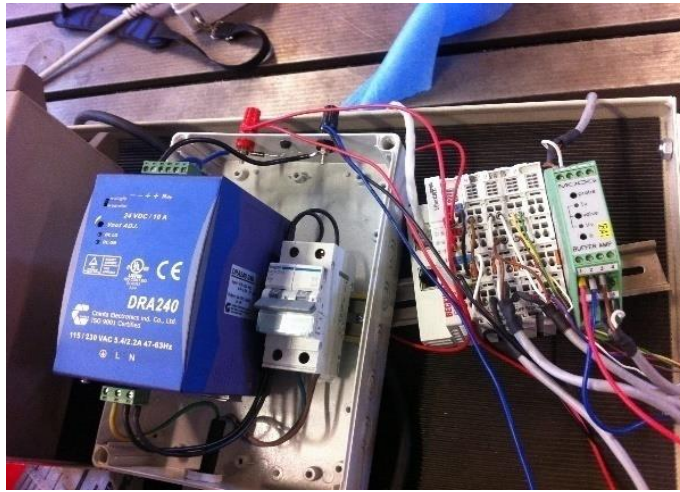
Figure 5.12: Digital converter module.

(4) The computer monitoring module

The computer monitoring system processes all data, signals, and produces graphics. The control system is developed in the twin/cat environment and sends commands from the computer to the PLC to control the servo valve. The control interface includes inputting three parameters of the PID controller, moving pistons (by setting displacement, restoring and stopping) and other operations.

All components of the hydraulic test platform components are shown in table 5.2.

Table 5.2: Physical parameters of the test platform components.

Parameter	Value	Unit	Item No
Load	50	kg	——
Working pressure	100	bar	——

Hydraulic cylinder	D=45m, d=30, L=450	mm	50/30-450AISI316
Displacement sensor	——	——	0.001mm/24Bitgray
Servo valve	——	——	Moog30-417
Data converter	Input=±10, Output=24	V	DRA240-24B

5.5.2   Experimental procedure

The operational procedure for the valve-controlled hydraulic cylinder on the water hydraulic test platform is:

1) Ensure the tank's water level between the lowest and highest limits;

2) Check the opening and closing status of each pipe valve to ensure the normal operating loop, and check the displacement sensors, D/A converters and other data connections to ensure normal transmission of the interface;

3) Turn on the control unit to observe whether each indicator lights up normally. If any abnormality occurs, immediately turn off the power and check it out;

4) Use the computer control interface to input the settings for displacement and the PID controller parameters, and then start the experiment.

5.5.3   Cooperation and verification of experimental results

The DE algorithm enabled optimal control and the fuzzy adaptive PID controller was applied to the water hydraulic control. Experimental results are shown in the figure 5.13.
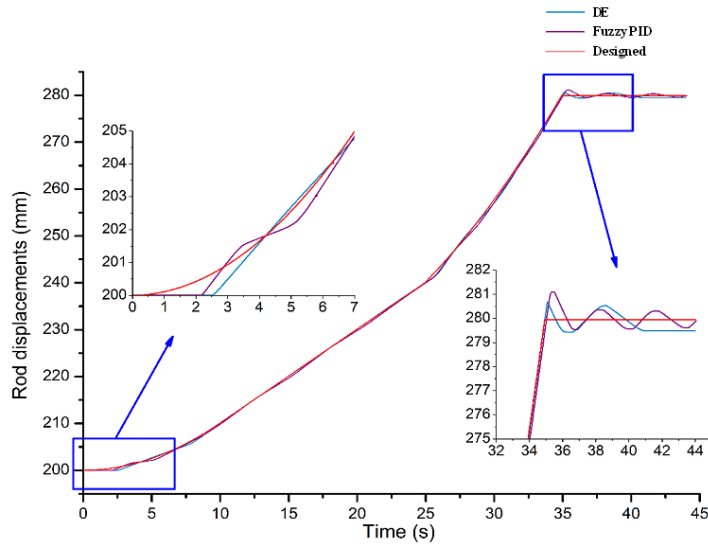
Figure 5.13 Motion curves by different control strategies

As shown in figure 5.13, the piston's motion curve with the DE optimization algorithm can better meet the essential requirements than that of fuzzy adaptive PID control. The specific characteristic parameters of the responses are listed in table 5.3.

Table 5.3: Characteristic parameters of the displacement curve by DE algorithm and fuzzy adaptive PID

Parameter	DE-based	Fuzzy-based
Kp	–	3
K_i	–	2.0928
K_d	–	1.6627
Response time	2.54s	2.18s
Maximum error	1.001mm	1.152mm
Overshoot	6.93%	11.02%
Steady-state error	0.474mm	±0.7mm

5.6   **Summary**

In this chapter the DE optimization control algorithm was adopted compared with the fuzzy adaptive control in the water hydraulic servo control of the 3-DOF divertor lifting system. First, the DE optimization control was applied through establishing the mathematical model of the controlled objects and simulation. Results have shown that the DE improves on response, stabilization time and the overshoot rate of the servo control system. The experimental results showed that the controller applying this algorithm has the advantages of smaller overshoot, quicker response and stronger anti-interference ability than fuzzy adaptive PID control.

6 Conclusions and recommendations

6.1 Summary and main achievements of the research

A Magnetically confined tokamak is the most promising experimental solution for nuclear fusion. At present, 35 nations are working together to build the world's largest tokamak, a magnetically confined fusion machine designed to demonstrate the feasibility of fusion as a large-scale and carbon-free source of energy in southern France. However, ITER has not been involved in some of the key scientific and technical issues related to the control of nuclear fusion, such as self-sustaining tritium, demonstrating fusion power generation. Therefore, during the construction of ITER, many countries have also started long-term planning for the development of magnetic confinement fusion. In 2011, the Ministry of Science and Technology of China decided to, relying on the University of Science and Technology of China (USTC), set up China's magnetic confinement nuclear fusion reactor research team for CFETR design. The goals of CFETR complement those of ITER, such as: 1) full cycle demonstration of fusion energy with minimum Pf=50~200MW; 2) full cycle demonstration of T self-sustained with TBR ≥1.2; 3) long pulse or steady-state operation with a duty cycle ranging from 0.3 to 0.5; 4) reliance on the existing ITER physical bases (k<1.8, q>3, H~1) and technical bases (higher BT, diagnostic, H&CD); 5) exploration options for DEMO blanket and divertor with an easy changeable core by RH; 6) exploration of a technical solution for licensing a DEMO fusion plant; 7) approach potential power plant gradually. The main objectives of the CFETR unit have been identified, including tritium self-sustaining, fusion power of 50MW-200MW, a high duty cycle ranging from 0.3 to 0.5. The main contents of this thesis are:

1) This work systematically illustrated the necessity and importance of RH maintenance of the reactor including the basic principles and introduced the particularity and research progress of RH technologies of fusion. The classification of RH maintenance systems and the characteristics of each subsystem. Key technical problems and the future development of RH maintenance were also discussed in detail.

2) Based on the design of the current CFETR superconducting tokamak machine and the maintenance requirements of the reactor, the main maintenance components and maintenance operations have been summarized and classified. The advantages and disadvantages of different reactor designs and maintenance schemes have been compared and the selection proposal of maintenance strategy for the reactor has been given. The design of an RH maintenance system for the reactor and its internal components were developed.

3) The structural design and kinematics analysis of the RH system were carried out. The kinematics model of the RH maintenance robot system was established and its simulation was analyzed. The mechanical structure, the drive system and the transmission mechanism were determined.

4) Overall control strategy of the RH maintenance system was studied for the control system architectural design. The large-scale heavy-duty hydraulic driven system was designed and the simulation model of the hydraulic drive system was established. The simulation and optimization analysis of the hydraulic servo driven system were carried out, and an experimental platform was built to verify the system reliability and safety.

5) The fuzzy adaptive PID and the differential evolution optimization algorithm were used to realize the high precision control of the hydraulic cylinder system. The water hydraulic servo control experiment platform was set up to verify the correctness of the simulation results.

6.2 Innovative work

The innovations of this work are as follows:

1) The main components, contents and basic principles of the RH of reactor were systematically analyzed. This work presents and compares the advantages and disadvantages of an integrated large window, a medium window, an ITER-like and integrated window of RH maintenance scheme. It draws the conclusion that the reactor shall adopt the integrated window maintenance scheme.

2) This dissertation systematically discusses the subsystems needed for remote operation of a reactor including the functional requirements. The preliminary structural design of each maintenance system (such as the VV endoscopic robotic arm, the divertor maintenance system and the structural design of transporter system) is given.

3) Based on the RH maintenance plan, the design and analysis of the RH maintenance system were carried out to verify the design feasibility and give a technical reference to the design and construction of a future reactor.

4) From the maintenance and reliability analysis, the reliability, usability, maintainability of the RH maintenance system were analyzed in detail by theoretical calculations and a numerical simulation.

5) The design and experimental studies of the water hydraulic servo control system of the large-scale heavy-duty divertor maintenance system were carried out. DE control algorithm compared with the fuzzy adaptive PID was demonstrated to verify the robustness and stability of the DE control algorithm.

6) The research work of this dissertation was summarized, and the outlook on several key issues that need to be solved in the RH maintenance system was presented.

6.3   Suggestion for the future work

Because the fusion reactor and its RH maintenance system are still in the phase of conceptual design, as well as the limited time of this dissertation and other reasons, we suggest that the problems need to be studied and solved for the RH maintenance system of a reactor are:

1) Further improvement on the study of various maintenance schemes need to be carried out by the quantitative analysis methods. In RH maintenance system, such as heavy load (several tons to tens of tons), high positioning accuracy (millimeter in dimension), and large operating range (more than ten meters) should be defined in more accurate numbers, the structural design of the RH system should be optimized on the basis of detailed engineering design and structural reliability analysis.

2) Research and development on key technology. Various tasks (such as the assembly and disassembly of the bolt, the welding and cutting of the cooling pipes, the grabbing and transferring of components, vacuum leak detection, non-destructive testing) and the relevant key technology research and development need to be carried out as early as possible. Other tasks (for instance the sensor technology in nuclear environment, visual system in nuclear environment, the RH maintenance technology, the RH leak detection and non-destructive testing technology) also need to be further studied.

3) Different areas should be taken into account in the design phase to solve the reliability to promote the reliability RH maintenance system. These include the wealth of engineering experience, macro reliability designing, test technology, the microscopic mechanism of material failure in its aging process, and practical designing.

4) A hydraulic servo-system is normally nonlinear and has time-varying parameters, especially in valve-regulated power flow mechanisms. The time-varying parameters and the nonlinearities should be considered in the simulation modelling and more advanced control algorithms should be studied, such as feedforward control, sliding model control and so on.

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Appendix A

A.1: Defined Severity rating scale (at the time of delivery)

Value	Description	Meaning
1	Weak <1h	Unavailable (less than 1 hour)
2	Moderate <1d	Unavailable (between 1 hour and 1 day)
3	Serious <1w	Unavailable (between 1 day and 1 week)
4	Severe <2m	Unavailable (between 1 week and 2 months)
5	Critical <1y	Unavailable (between 2 months and 1 year)
6	Catastrophic >1y	Unavailable (more than 1 year)

Appendix B:

B.1: Defined Occurrence rating scale (at the time of delivery)

Value	Description	Meaning
1	Very Low	$\lambda_{risk} < 5\times10^{-4}$/yr (less than once in 2000 years)
2	Low	5×10^{-4}/yr $< \lambda_{risk} < 5\times10^{-3}$/yr (less than once in 200 years)
3	Moderate	5×10^{-3}/yr $< \lambda_{risk} < 5\times10^{-2}$/yr (less than once in 20 years = ITER lifetime)
4	High	5×10^{-2}/yr $< \lambda_{risk} < 5\times10^{-1}$/yr (less than once in 2 years = experimental campaign)
5	Very High	5×10^{-1}/yr $< \lambda_{risk} < 5$/yr (less than five times per year)
6	Frequent	$\lambda_{risk} > 5$/yr (more than five times per year)

Appendix C:

C.1 Defined Detection rating scale (at the time of delivery)

Value	Description	Meaning
1	Very Easy	Easy failure detection by human, system, or high level coverage monitoring means (dedicated interlock/safety system, internal or external to the control system)
2	Easy	Automatic failure detection by control or monitoring system (medium coverage diagnostics)
3	Moderate	Failure detected by combined means of control or monitoring system (displays) and human intervention (within procedures)
4	Hard	Failure detected through external additional means (typically preventive maintenance operation)
5	Very Hard	No failure detection (cannot be detected)

Major risks are those that are in the "red zone" of the Criticality Matrix that is generated for each system. This relates to an Initial Criticality value (C_i) greater than 13:

$$C_i = S_i.O_i \geq 13$$

Where, C_i is the Initial Criticality, S_i the Initial Severity and O_i the Initial Occurrence.

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