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EAST in-vessel operation manipulator with failure recovery ability

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ABSTRACT

The Robotics Institute of SJTU has been involved in the development of an in-vessel maintenance operation manipulator system for China's Experimental Advanced Superconducting Tokamak (EAST) since 2007. Previous work primarily focused on the basic operating principle and extreme environment endurance. In this paper, the failure recovery feature is introduced for the first time for an in-vessel manipulator system. Based on a summary of previous research, we propose a new serial link structured manipulator with failure recovery ability. The main structure of the new manipulator is presented, including the baking cask, manipulator deployment platform, serial link manipulator main body and dual-drive push-rod structure, which gives the manipulator its failure recovery ability. Additionally, the manipulator in-vessel deployment process is simulated on a computer, and basic kinematics analysis is performed to evaluate the feasibility of the proposal.

1. Introduction

The remote-control in-vessel operation manipulator is a type of maintenance tool for the EAST tokamak vacuum vessel during high-energy plasma research (Fig. 1). The manipulator is stored outside the tokamak vacuum vessel during the high-energy plasma discharge process. After several cycles of the experiment, the plasma discharge activity is shut down while the in-vessel environment remains in the ultra-high vacuum and high temperature state. The manipulator is deployed under such conditions into the tokamak vacuum vessel for maintenance work, which primarily involves completeness examination of the first wall structure. This type of in-vessel operation is desirable for its rapidity and the absence of a time-consuming in-vessel state transition between the ambient environment and the high vacuum environment.

In our previous research, we developed an in-vessel inspection process with a long stretching manipulator carrying inspection cameras as an end effector [1–3]. The manipulator can enter the toroidal vessel through the tokamak horizontal observation windows and stretch out inside the toroidal vessel to access full coverage of the in-vessel workspace. High temperature environment endurance and ultra-high vacuum environment compatibility in the manipulator design were studied in detail for integration feasibility research.

Reliability design is an important aspect in remote control manipulator system research, especially for the in-vessel maintenance manipulator system, which is intended to facilitate the continuous operation of plasma research work inside the tokamak. However, reliability is a matter of probability, and the unit might still fail at times. If the in-service manipulator system fails during the in-vessel operation process, the entire tokamak system might need to be shut down completely and disassembled to rescue the failed manipulator in the worst case. Therefore, we believe that the failure recovery feature should be introduced to cope with such failures as a backup for safety concerns. However, these concepts were minimally considered in our previous research work on the EAST in-vessel maintenance manipulator.

The situation varies among other researchers on this topic. The articulate inspection arm (AIA) from the Atomic Energy Commission (CEA) in France is one similar serial link manipulator [4,5]. This unit has a comparable operation mechanism similar to that of our current solution for the EAST tokamak. In the AIA, servo-component hardening is one consideration for increasing system reliability under an extreme environment, but no explicit solution for failure recovery is addressed. The EAST articulated maintenance arm (EAMA) is one of the latest updated versions of AIA originating from the collaboration of the Institute of Plasma Physics Chinese Academy of Science (ASIPP) and CEA [6]. The improvement tasks include optimization of the dimensions and upgrade of the end effector design but do not cover treatment of failure recovery. The in vessel viewing system (IVVS) for the ITER program is another example of in-vessel operation devices [7,8]. The IVVS has been in development for quite a long time, since 1998, and researchers have begun considering the addition of failure recovery features to the system in the future. However, no further information has been disclosed on these failure recovery features. One available reference work on remote handling failure recovery was published recently by The

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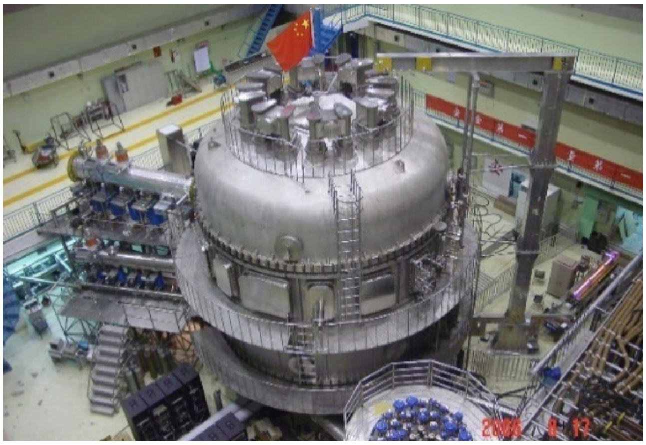

Fig. 1. The EAST in Hefei, China.

National Institutes for Quantum and Radiological Science and Technology (Japan) in which the researchers performed a thorough analysis of the types of remote handling system failures and proposed dedicated rescue operations with a dexterous manipulator for the recovery process [9].

The outline of this paper is described as follows. First, we analyze the manipulator failures based on reliability concerns, and the new proposed manipulator structure is subsequently described in detail to illustrate the failure recovery design for an in-vessel operation scenario. Finally, we analyze the kinematics performance of the new manipulator structure based on the results of several computer simulations of the in-vessel operation process.

2. Manipulator failure analysis

2.1. FMEA analysis on the in-vessel manipulator

The failure mode and effects analysis (FMEA) of the previous manipulator is shown in Table 1 below. An effective FMEA can help to systematically summarize the failures and offer guidelines for system improvement. FMEA has become an important procedure for reliability-featured design in current research and development. Control software-related questions are not addressed in this paper.

In the FMEA analysis, we categorized these failures into three types based on the extent of their effects on the normal functioning of the manipulator system: 1) failures that do not affect the basic functioning of the manipulator but block selected supporting functions, e.g., joint motor brake failure will undermine the manipulator emergency protection ability and component overheating may temporarily prevent manipulator operation; 2) failures that interfere with the servo-control capability of the manipulator but do not affect some low-level manual control capabilities, e.g., manual visual surveillance of the manipulator posture can substitute for some joint position sensor under an emergency situation; and 3) failures at the structural level that completely immobilize the manipulator, e.g., joint reducer failure or main power system failure.

The first two types of failures do not impede the basic motion ability of the in-vessel manipulator, and thus, the manipulator in the failure position can still be retrieved from the tokamak vessel by emergency manual control of the joint motors, which are driven directly by bypassing the servo-control system. As a result, these failures usually do not result in much damage to the tokamak system. Most of these failures can be avoided by system condition monitoring or by selecting system components that have stronger extreme environment endurance, and thus, these failures are relatively easier to cope with. Selected work has already focused on these aspects. For example, the coolant circulation-monitoring system and vacuum-sealing completeness detection system are integrated into the manipulator to monitor the real-time running status, and resolver encoders and mechanical position switches are selected as servo-control sensors to improve the extreme environment endurance.

However, the third type of failures completely disables the manipulator structure if it occurs during the in-vessel operation process. The situation can be so severe that irreversible damage could be caused to the entire tokamak system. Additionally, it is difficult to retrieve the failed manipulator from its failure position inside the tokamak vessel entrance window. Manipulator improvement at the component level and reliability design focused on these failures on the system level are necessary for safety concerns. However, failure recovery features should still be considered as a backup because of the possible severity of the failure consequences.

2.2. Failure recovery development for the in-vessel manipulator

Two main requirements apply for the in-vessel maintenance manipulator: the ability to be deployed from outside the tokamak and coverage of a large operation space inside the toroidal-shaped vacuum vessel. In addition, the manipulator system should be fail-safe first before considering a viable failure recoverability implement. Several general design criteria are applied to the fail-safe requirement for remote control manipulator development [10]:

(1) The manipulator joints should contain auto-locking devices to lock the joint movement after power loss such that the manipulator cannot move without control commands from the operator;
(2) The manipulator joints should have movement limitations to ensure the safety of the manipulator itself and prevent possible damage to the environment;
(3) The manipulator should have the ability to be operated under safety protection status or loss of power;
(4) The failure of fail-safe-related structures should not impede the normal functioning of the overall system.

In the development of failure recoverable features for the in-vessel

Table 1
FMEA of the EAST in-vessel manipulator.

Category	Failure	Cause	Effect
Supporting function failure	Motor brake failure	Overload or mechanical fault	Inability to hold joint position
	Coolant leakage	Coolant circulation system fault	Active cooling loss, vessel contamination
	Vacuum leakage	Vacuum sealing structure fault	Vacuum vessel contamination
	Component overheating	Servo control fault	Component breakdown
Servo control capability failure	Motor encoder failure	Connection fault	Inability for servo control
	Joint position sensor failure	Connection fault	Inability to obtain joint position
System structure failure	Joint motor failure	Overload or connection fault	Lost drive ability
	Joint reducer failure	Overload or mechanical fault	Joint stuck in failure position
	Manipulator joint locking	Mechanical fault	Joint stuck in failure position
	System loss of power	Connection fault	System total shut down