Fusion Engineering and Design 118 (2017) 25–33

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Conceptual design of EAST multi-purpose maintenance deployer system

Hongtao Pan [a,c], Kaihui He [d,*], Yong Cheng [a], Yuntao Song [a,c], Yang Yang [a], Eric Villedieu [b], Shanshuang Shi [a], Songzhu Yang [a]

[a] *Institute of Plasma Physics, Chinese Academy of Sciences, 350 Shushanhu Rd, Hefei, Anhui, China*
[b] *CEA-IRFM, F-13108 Saint-Paul-Lez-Durance, France*
[c] *University of Science and Technology of China, Hefei, Anhui 230022, China*
[d] *China International Nuclear Fusion Energy Program Execution Center, Beijing 100862, China*

HIGHLIGHTS

- A redundant 11-DOF articulated robot for EAST in-vessel maintenance is presented.
- A new modular joint developed to optimize the yaw joint actuator for the robot is described.
- A 3-DOF gripper integrated with cameras and torque sensor is developed.

ARTICLE INFO

Article history:
Received 22 August 2016
Received in revised form 20 January 2017
Accepted 13 February 2017

Keywords:
EMMD
Kinematics
CASK
Gripper
Vacuum
High temperature

ABSTRACT

EAST multi-purpose maintenance deployer (EMMD) system, being collaboratively developed by ASIPP and CEA-IRFM, is built as upgrades for EAMA. Updated kinematics parameters such as DOF distribution and joint angle for EMMD robot are performed and verified in a simulation platform. A new modular joint has been developed to optimize the yaw joint actuator for easy assembly and flexibility reduction. A 3-DOF gripper with cameras and torque sensor has been designed to provide inspection and dexterous handling of small fragments inside the EAST chamber. A conceptual upgrade for EAMA-CASK has been developed for the purpose of protecting the end-effector's sensors which do not have temperature-resistant qualification. The high temperature and vacuum compatible solutions and validation experiments have been presented in this paper.

1. Introduction

EAST, a non-circular advanced steady-state plasma experimental device, aiming at long pulse, H-mode and divertor configuration plasma operation, has provided valuable data for ITER and CFETR (China Fusion Engineering Test Reactor). However, the plasma facing components (PFCs) in the vacuum vessel (VV) are easily damaged during experiments as shown in Fig. 1, which greatly affect the physical experiment or even stop the experimental activities [1,2]. Remote handling technology has been identified as an effective solution for the in-vessel maintenance in EAST tokamak and the future fusion reactor [3].

The articulated inspection arm (AIA) developed by the CEA aims to be demonstrated close inspection of PFCs in Tore Supra without breaking Vacuum and temperature conditioning [4]. Within the frame of a Joint Laboratory between CEA-IRFM and ASIPP, the AIA robot was successfully validated its vacuum and temperature performance during the EAST experimental activities [5]. Meanwhile, a new version of the robot called EAMA (EAST Articulated Maintenance Arm), dedicated to EAST in-vessel maintenance, is being collaboratively developed from 2014 [6]. Then, the development of EAST multi-purpose maintenance deployer (EMMD) system was performed after EAMA prototype tests, consisting of main mechanical improvements and new technologies application on the motor and sensors, etc. It provides the means for deployment and handling of in-vessel tools inside the vacuum vessel for inspection, leak detection, broken tiles grasping and neutron source calibration.

This paper describes the conceptual design of the EMMD system as shown in Fig. 2. The main part of the EMMD is the articulated

* Corresponding author.
E-mail address: hekh@iterchina.cn (K. He).

http://dx.doi.org/10.1016/j.fusengdes.2017.02.042

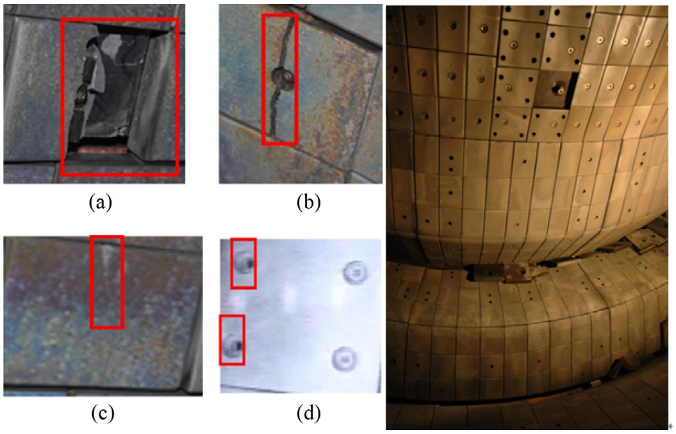

Fig. 1. Left: (a) tile missing, (b) crack, (c) fissure and (d) bolt missing; right: damaged PFCs after plasma.

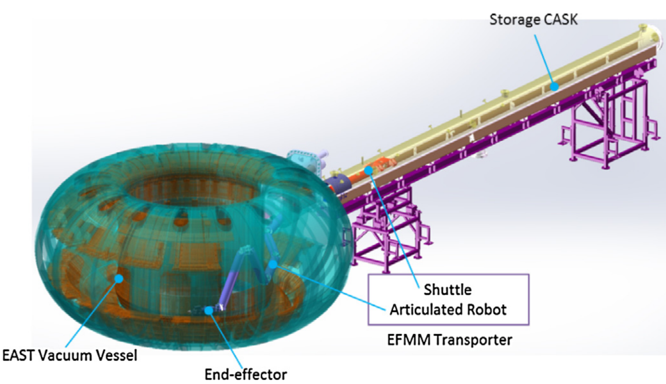

Fig. 2. EMMD arm deployed in EAST vacuum vessel.

robot arm with seven degrees of freedom, which provides transportation and positioning of the end-effectors. A new modular design joint was developed to optimize the yaw joint actuator of EAMA robot, which has the benefit of easy assembly and flexibility reduction. The new technologies application on the motor and sensors were implemented. Also the carbon fiber/epoxy composites introduced as a potential application for the tube was presented in this paper.

Among a set of specialized end-effectors, the gripper is a 3 degrees of freedom manipulator, which provides inspecting and dexterous handling of small fragments inside the EAST chamber. A torque sensor was installed between two-finger claw and rotation joint to perform force feedback handling. Due to the 9-m-long cantilever arm, the large flexibility of the robot causes limited accurate positioning. The vision system mounted on the gripper, consists of two cameras and LED lights in sealed boxes, is able to accomplish in-vessel inspection and target tracking. Considering the temperature constraint on the sensors in the end-effectors, a conceptual upgrade for EAMA CASK was developed to protect them during baking stage without using active cooling system applied on AIA robot [7].

2. System description for EMMD

Before the start of design study, a detailed analysis of the requirements and constraints for the EMMD has been done:

- The temperature and vacuum conditions: working temperature is 80 °C and baking temperature is 120 °C, vacuum is 10^{-5} Pa.
- The geometric constraints: EAST parameters (R = 1.94 m, a = 0.45 m), the access port (D = ϕ250 mm).
- Workspace: The full deployment of the arm should be able to inspect the whole chamber and pick up the broken tiles fallen at the bottom of the vacuum vessel.
- Function extensibility: Standard interface between robot and end-effectors.
- Safety: Do not damage or pollute the operating conditions in the vacuum vessel.

3. Kinematics and simulation

The kinematics of the robot includes forward kinematics and the inverse kinematics analysis. Forward kinematics analysis is to calculate the position and orientation of the end-effector with respect to the base frame according to the geometric parameters and a serial of joint angles. Inverse kinematics analysis computes the joint angles according to the position and posture of the end-effector. The rotation range of yaw joint, acting as one of important parameters to affect robot kinematics performance, varied from ±90° to ±62° caused by mechanical improvement. Meanwhile the updated DOF distribution and geometric dimension were implemented on EMMD robot to increase its mobility, i.e. it makes the robot easier to enter the chamber through the narrow port as well as pick up the targets dexterously.

The common used Denavit–Hartenberg (DH) convention is adopted to describe the EMMD robot kinematics, as shown in Fig. 3 and Table 1.

Due to the parallelogram mechanism in arm segment 4 and 5 (the last two segments), the robot joint, 7 and 10, are set up as dependent joints corresponding to joint 6 and 9, respectively, i.e. $\theta_7 = -\theta_6$ and $\theta_{10} = -\theta_9$. The d_i, i, a_i and i represent the link offset, the joint angle, the link length and the link twist, respectively, according to the name conventions in [8]. The upper limits and lower limits of the joints are given as U and L in Table 1, and the initial joint angles for joint 2 and 12 are both −90°.

Prior to qualifying the kinematic performance of robot such as workspace and dexterity in real work scene, a validation experiment was demonstrated in a simulation environment developed on RobWork [8], which is integrated with the functionalities of kinematics, visualization and motion planning.

Fig. 4 shows the robot unfolding movement along optimized planning path integrated with collision avoidance from the original position in storage cask to the farthest location in the EAST chamber. The planned path shows the kinematics performance, and the path could be a reference path when the robot performs the inspection task manually.

Table 1
Link parameters of the EAMA robot.

Link i	d_i/mm	θ_i/°	a_i/mm	α_i/°	θ_U/°	θ_L/°
1	d_1	0	0	−90	0	9.8 (m)
2	0	$\theta_2(-90)$	1200	0	−62	62
3	0	θ_3	1200	0	−62	62
4	−27.5	θ_4	1200	0	−62	62
5	0	θ_5	102	90	−62	62
6	0	θ_6	1048	0	−45	45
7	0	$\theta_7 = -\theta_6$	100	−90	−45	45
8	0	θ_8	102	90	−62	62
9	0	θ_9	1048	0	−45	45
10	0	$\theta_{10} = -\theta_9$	118	90	−45	45
11	−27.5	θ_{11}	132	90	−90	90
12	0	$\theta_{12}(-90)$	0	−90	−95	95
13	380	θ_{13}	0	0	−180	180