WEST regular in-vessel inspections with the Articulated Inspection Arm robot

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Currently on fusion devices, diagnostics are mainly aiming at plasma analysis and control. However, operational and programmatic needs have appeared for regular in-vessel components monitoring during plasma campaign. Light robotics systems could meet this requirement and may be a way as well to replace human interventions to fix damaged in vessel components. To minimize the impact on machine operation, the robotic system has to be mini-invasive and compatible with operating conditions (vacuum, temperature…).

To fulfill this goal, CEA has developed a multipurpose carrier able to be operated inside WEST vessel between plasma pulses. A prototype of this robot, called Articulated Inspection Arm (AIA), was tested in 2008 in Tore Supra vacuum vessel. A major upgrade was performed in 2014-2015 with the aim of converting this prototype into a reliable tool in support to WEST operation. During the WEST components manufacturing and installation (2014-2016), the robot was integrated and tested in the EAST Tokamak.

Since 2017, the AIA has been regularly used during the WEST plasma campaigns. Movies provided by the embedded camera allow to assess the evolution of Plasma Facing Components surface state and the effects of plasma loads, runaways and disruptions.
The robot operation was also very helpful to assess the needs for maintenance, to assist mechanical assembly without man entry and to perform diagnostics calibration under relevant conditions.

Keywords: WEST, assembly, operation, robotics.

1. Introduction

Fusion machines in development, construction or exploitation push the boundaries in terms of materials and physical knowledges. The machines configurations and sizes will increase the possibility to engender damages on the inner components, even generated water leakages on the actively cooled ones.
Many diagnostics precisely assess the sensitive Plasma Facing Components (PFCs) status during the plasma experiments. However, if something seems abnormal, the need for checking and visualizing the damages becomes elementary.
With its strong experience on Tokamak operation, CEA has felt this need and has developed a mini-invasive robot equipped with a high resolution camera able to be deployed under vacuum and temperature without polluting the vacuum vessel conditioning. Following different project phases from the prototype to the qualification in EAST Tokamak, the Articulated Inspection Arm (AIA) robot is now connected to WEST Tokamak during the plasma experimental campaigns (Fig. 1). The AIA is performing regular in vessel inspections and provide numerous information about PFCs status (Fig. 2).

2. The AIA robot

The robot called Articulated Inspection Arm (AIA) is a 8 meter long multi-link carrier with 5 modules of 160 mm diameter [1]. Modules include pitch (±45° in the vertical plane) and yaw (±90° in the horizontal plane) joints for a combination of elevation and rotation motions witch gives to the robot 8 degrees of freedom.; this design is consistent with a complete close inspection of ITER's 60° toroidal part of blanket and divertor.
With a payload of up to 10 kg, the poly-articulated arm total weight is about 130 kg and can be introduced through a remarkably small port of 250 mm diameter (Fig. 3).
To create such a slender beam, it has been necessary to minimise the gravity effect on the mechanical structure. Thus, the 2 fixing clevis of each module are linked by a parallelogram structure with a screw-jack embedded to operate the elevation. This arrangement also presents the advantage to keep joints fixing always horizontal for any given configuration. The angular module displacement in the horizontal plane is set in motion by the actuators through cables and pulleys system.
The first diagnostic plugged at the front head of the carrier is the viewing system able to do visual inspection of Plasma Facing Components. Its concept is based on a CCD colour sensor with zoom and LEDs light hold in an airtight stainless steel box and a glass dome.

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Fig. 1 - AIA connected to WEST Tokamak

Fig. 2 - AIA robot in WEST Tokamak

Fig. 3 - CAD view of the AIA robot performing a deployment in a Tokamak

3. New developments

3.1 The major upgrade

In order to prepare the robot for WEST routine inspections and support WEST operation, the robot sub-systems reliability has been improved. The major upgrade performed in 2014-2015 was focused on the mechanics and the electronics [2].

One of a key issue on robotics is the wires management. To reduce the number of wires, a CAN© 2.0 bus has been, retained associated with specific embedded and remote controllers.

The robot position is given thank to two position sensors on each axis (Fig. 4). One is attached to the motor-reducer and another one is linked to the articulation. Sensors are either confined in air tight boxes, either potted inside stainless steel boxes.

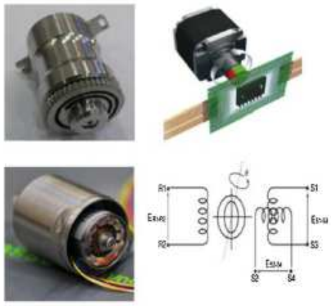

Fig. 4 - AIA sensors

3.2 Operation in EAST Tokamak

During the WEST components manufacturing and installation (2014-2016), the robot was integrated and tested in the EAST Tokamak [3] (Fig. 5), in the frame of a joined laboratory between CEA-IRFM and CAS-IPP.

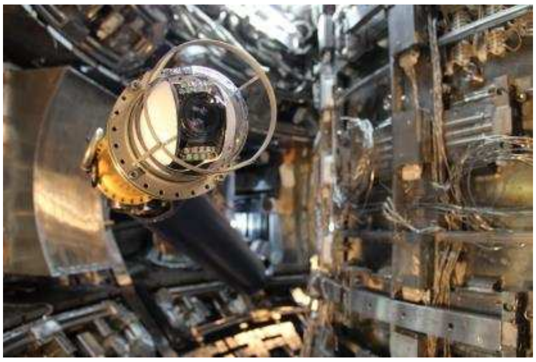

Fig. 5 - AIA robot in EAST Tokamak

The robot has been used for calibrating diagnostics (Fig. 6) as well as providing images from the inner vessel (Fig. 7).

Fig. 6 - Diagnostic calibration in EAST Tokamak

Fig. 7 - Broken tile observed in EAST vacuum vessel [5]

During that period, the AIA robot has been duplicated [4] and a new tool, the gripper [5] (Fig. 8), has been developed to answer EAST Tokamak needs.

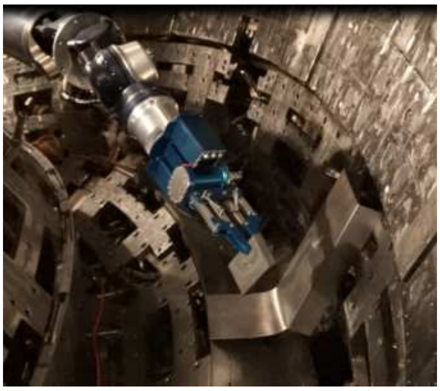

Fig. 8 - EAMA gripper [7]

Thanks to these experiences the robot returned at CEA with a grateful feedback. It has been prepared for WEST integration with a major objective: to upgrade the camera resolution to assess the tungsten Plasma Facing Units (PFUs) status.

3.3 The HD camera

Previously, a low resolution camera was used that required an actively cooled system with a path along the robot.

The camera, based on a nuclear inspection camera from HYTEC Company was embedded in a sixth segment able to perform rotations in a horizontal plan. The camera head proposed the complementary movements (360◦pan and ±90◦tilt). Unfortunately, without dedicated software, the operator could get lost by following the image and requires resetting frequently to the original position. The camera definition also was too poor in view of the low Tokamak lighting.

The cooling pipes were supplying nitrogen gas to the camera CCD sensor. The pipes were integrated below the robot segments.

The feedback from the AIA experiences shown that these pipes put significant constraints on the robot in terms of assembly, leakage and “spear-phishing” risks but also for the robot control. Moreover, the inspection of the Tokamak inner components at the entrance port was impossible due to the lack of flexibility.

In order to use the AIA as a diagnostic for WEST, a new High Resolution camera has been integrated on the robot (Fig. 9). It proposes a 1080p/60 image with 10x optical zoom (Fig. 10). It allows, as basic human head movements, dissociated azimuth and elevation trajectories thanks to three accurate dedicated joints. The three accurate joints offer two rotations and one elevation movements making possible the inspection from the port outset. The minimum object distance is from 10mm (wide) to 800mm (tele). These parameters allow getting a fast overview of the inner components as clear details definition when needed.

The camera temperature is kept within an adequate range by a Pelletier module and multi-layer insulation. The camera lighting is improved by placing it outside of the camera module and combined with powerful external lights around the Tokamak.

Fig. 9 - CAD view of the HD camera and the accurate joints

Fig. 10 - AIA HD camera module

3.4 The supervisor

The simplicity of the human machine interface is a key to propose a robot as a friendly tool to the operators. AIA control system use ACTIN software bricks, developed by Energid Company. It enables steering thanks to a 3D graphical interface of the inner vessel. The robot driving is performed using a real time flexible model and collision avoidance algorithm. Deployment can be controlled either by giving a reference to each actuator or by setting a target position only, then computed by the supervisor (Fig. 11).

The main upgrades performed on the supervisor were to prepare it to WEST environment by integrating the fifth segment, the new HD camera with it three joints and a detailed environment display. The detailed view of the inner vessel is helpful for the operator to identify the component that the camera is following (needles…).

Thanks to these upgrades, the collision avoidance mode and the motion constraint dragger are now fully operational.

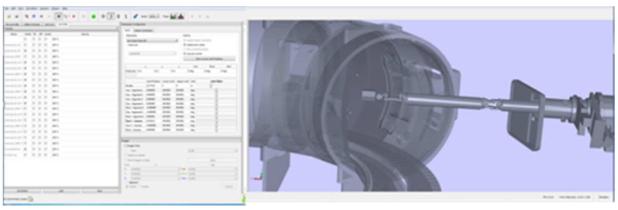

Fig. 11 - Snapshot of ACTIN supervisor, with the AIA starting it deployment in WEST

4. WEST in-vessel inspections

Since December 2017, 15 deployments (13 under vacuum) have been achieved in WEST for monitoring inner components (Fig. 13, Fig. 14, Fig. 15, Fig. 16), enabling to assess status of PFCs without opening the vessel (Fig. 12). The robot was also used for diagnostics assembly, assisting the introduction of the wide angle IR camera under nitrogen atmosphere or checking reciprocating Langmuir probes proper operation.

Fig. 12 - AIA with the low resolution camera observing the W PFUs

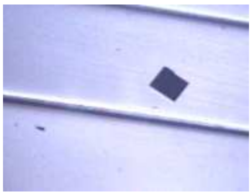

Fig. 13 - Material samples and dusts found on the divertor after the first campaign. A more robust sample holder has been developed since, and no further loss of samples was observed.

Fig. 14 - Shadows observed after the ITER like W monobloc

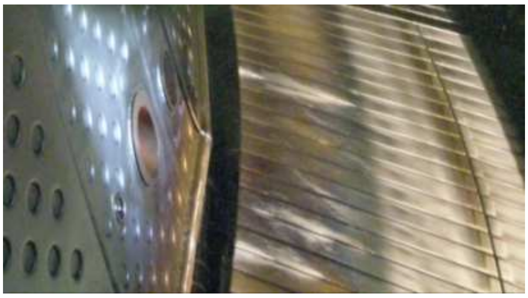

Fig. 15 - Image of WEST bottom divertor

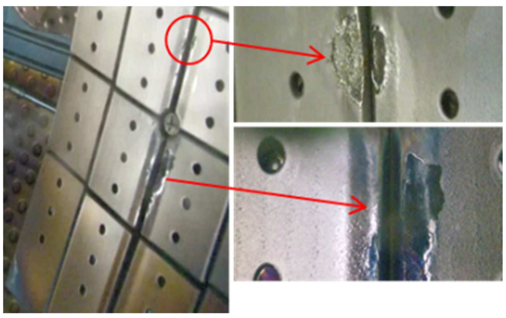

Fig. 16 - Runaways impacts on WEST outer limiter after the 1stcampaign. Damaged tiles have been swapped and no further damage was observed after runaways avoidance schemes were developed

5. Perspectives and conclusion

The WEST tokamak operation now benefits from an integrated robot which performs regular in-vessel deployments. It serves the scientific program by assessing the PFCs state, facilitates the technical operations conducted without in-situ personal access and prepares the tokamak shutdown by damages pre-identification.

On longer term, automatic inspections could be envisaged to compare data from the previous inspection.

Other embedded diagnostics helpful for the exploitation could be integrated on the AIA robot such as Leak localization, diagnostics calibration, Laser Induced Breakdown Spectroscopy.

Besides bringing a relevant proof of principle, lessons learned on WEST with such a multipurpose robotic device will give very helpful information for future ITER, CFETR and DEMO remote handling activities.

Acknowledgments

The CEA/IRFM team, the CEA/LIST team, the ASIPP team, involved in different development phases of the AIA robot project.

Part of this work is supported by EUROFUSION

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