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Operation of an ITER relevant inspection robot on Tore Supra tokamak

Laurent Gargiulo[a,*], Pascal Bayetti[a], Vincent Bruno[a], Jean-Claude Hatchressian[a], Caroline Hernandez[a], Michael Houry[a], Delphine Keller[b], Jean-Pierre Martins[a], Yvan Measson[b], Yann Perrot[b], Frank Samaille[a]

[a] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[b] CEA, LIST, Service de Robotique Interactive, F-92265 Fontenay aux Roses, France

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ABSTRACT

Robotic operations are one of the major maintenance challenges for ITER and future fusion reactors. CEA has developed a multipurpose carrier able to realize deployments in the plasma vessel without breaking the Ultra High Vacuum (UHV) and temperature conditioning. A 6 years R&D programme was jointly conducted by CEA-LIST Interactive Robotics Unit and the Institute for Magnetic Fusion Research (IRFM) in order to demonstrate the feasibility and reliability of an in-vessel inspection robot relevant to ITER requirements.

The Articulated Inspection Arm robot (AIA) is an 8-m long multilink carrier with a payload up to 10 kg operable between plasma under tokamak conditioning environment; its geometry allows a complete close inspection of Plasma Facing Components (PFCs) of the Tore Supra vessel.

Different tools are being developed by CEA to be plugged at the front head of the carrier. The diagnostic presently in operation consists in a viewing system offering accurate visual inspection of PFCs. Leak detection of first wall based on helium sniffing and laser compact system for carbon co-deposited layers characterizations or treatments are also considered for demonstration.

In April 2008, the AIA robot equipped with its vision diagnostic has realized a complete deployment into Tore Supra and the first closed inspection of the vessel under UHV conditions. During the upcoming experimental campaign, the same operation will be performed under relevant conditions (10^{-6} Pa and 120 °C) after a conditioning phase at 200 °C to avoid outgassing pollution of the chamber.

This paper describes the different steps of the project development, robot capabilities with the present operations conducted on Tore Supra and future requirements for making the robot a tool for tokamak routine operation.

1. Introduction

Robotics and remote operations are one of the main challenges for ITER and future fusion reactors; in particular, first wall inspection and treatment between pulses will be required for exploitation and for safety purpose. Since 2003, two CEA laboratories have initiated developments to demonstrate the feasibility and reliability of an ITER relevant inspection robot.

A multipurpose carrier called Articulated Inspection Arm (AIA) was manufactured with the aim to be deployed in the plasma vessel of Tore Supra tokamak [1] without breaking plasma vessel conditioning. For this purpose, all the robot components were consistent with Ultra High Vacuum (10^{-6} Pa) and temperature (120 °C) environment operations and sustain baking at 200 °C for the outgassing phase.

Tokamak vessel conditioning is a major factor for plasma performance, it requires many weeks of preparation on tokamaks before starting operating with plasmas. Interventions “between pulses” and “under vacuum and temperature”, allow significant time and cost saving for maintenance operations, and therefore improvement of the overall machine availability.

In view of ITER applications, the CEA engaged also in development of plugged diagnostics needed for exploitation and safety. For the moment, tools considered are vision, leak detection and surface analysis and treatment.

2. From developments for hot cells inspection to application for fusion machines

During the 1990s the Interactive Robotic Unit of CEA-LIST developed a mini-invasive long reach Arm for Areva hot cells inspection [2]. The robot was actuated by electronic components hardened to bear high radiation. In 1999, based on the same architecture, CEA started studies on principles and characteristics of a robot able to

* Corresponding author. Tel.: +33 4 42 25 46 84; fax: +33 4 42 25 26 61.
E-mail address: laurent.gargiulo@cea.fr (L. Gargiulo).

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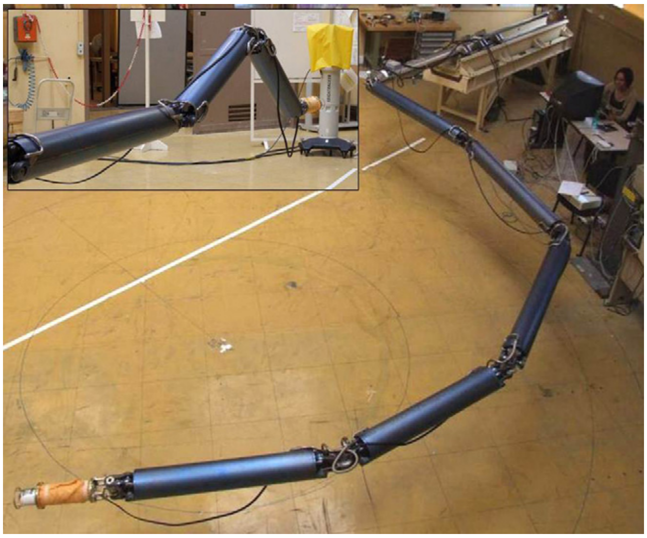

Fig. 1. AIA robot assembled, CEA-LIST laboratory, June 2007.

realise ITER in-vessel complete close inspection under EFDA Work programme.

In 2002 it was decided to launch the fabrication of an arm segment prototype and the first studies of the robot integration in Tore Supra.

The first single arm segment prototype was assembled in 2004. Fatigue tests under representative loading, UHV conditions and cycles of temperature (120 °C during operating and 200 °C for outgassing phase) were carried during several weeks to qualify the module concepts. The final vacuum residual gas analysis has confirmed the adequate behaviour of the device allowing operation without degradation of vessel conditioning [3].

After this important milestone, the full robot manufacturing and Tore Supra integration studies started in 2005.

3. Robot main characteristics

The AIA robot carrier (Fig. 1) is an 8-m long multilink arm with 5 modules of 160 mm diameter made in titanium. Modules include pitch (±45° in the vertical plane) and yaw (±90° in the horizontal plane) joints for a combination of elevation and rotation motions which gives to the robot a total of eight degrees of freedom; this design allows the full close inspection of Tore Supra plasma vessel components from a single median port.

With payload up to 10 kg and a total weight of 150 kg the poly-articulated arm can be introduced through a small port of 250 mm diameter. To create such a slender and light beam, it has been necessary to minimise the gravity effect on the mechanical structure. Thus, the 2 fixing clevis placed at the extremity of each module are linked by a parallelogram structure with a screw-jack embedded to operate the elevation. This arrangement presents also the advantage to keep joints fixing always horizontal for any given configuration and to reduce the size of the electrical actuators. Differently, angular module displacement in the horizontal plane is set in motion by the actuators through cables and pulleys system. To cope with the high temperature requirements, all AIA articulations are actuated by specific electrotechnical components embedded in tight boxes and qualified up to 120 °C in use and 200 °C when switched off.

At this stage, the robot monitoring is managed by position control of each module's joints. A real time command control model taking into account the flexibility of the arm and the full geometry of the environment is under preparation to increase steerage and performances.

During the deployment, the robot is set in translation by a trolley built to bear high forces and torques of the high cantilever structure (9.5 m). A storage cask was designed for the Tore Supra port connexion, the conditioning of the robot and the trolley precise guiding. This large stainless steel vessel (11 m long, 3 m height and 5 ton in service) is moved by 2 rolling support frames and can be placed or removed to the dedicated port in about 1 h (Fig. 2). For this purpose, all electrotechnical equipments are embedded to realize a compact and autonomous system; in particular the head wagon integrates the vacuum system, the heating and temperature regulation components while the second one includes the robot and process drivers. The connection on the tokamak is carried out by a double valve insulation system witch allows to abide vacuum conditions of the two vessels.

A viewing system able to make accurate visual inspection of Plasma Facing Components (PFCs) under darkness conditions is installed at the front head of the carrier (Fig. 3). It was designed and built by the ECA/Hytec Company and delivered in spring 2007. The concept is based on a CCD colour sensor with zoom and LEDs light hold in an airtight stainless steel box and a glass dome. The vision system has three degrees of freedom: one on the diagnostic envelope and two on the video camera. The viewing system is cooled with Nitrogen gas to keep the embedded electronic temperature below 60 °C.

Fig. 2. The storage cask overview and Tore Supra integration.

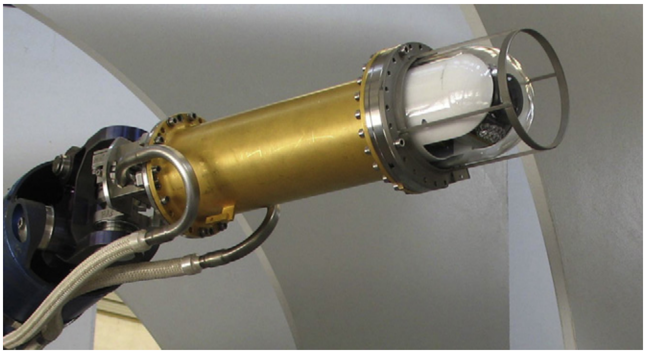

Fig. 3. The plugged viewing system.

4. Deployments and Tore Supra in-vessel inspections

Before operating inside Tore Supra, qualification, training and rehearsal of the robot deployment were performed inside two complementary test bed facilities:

- A scale 1 mock-up of the full vessel shape allows command control adjustments and scenario repeatability measurements (Fig. 4).
- A large vessel (ME60 facility) with a port plug fit to the storage cask enables the robot behaviour checking under nominal UHV and temperature conditions [4].

In April 2008, after airtight assembling qualification and command control adjustment, the robot with its vision diagnostic plugged has realized a complete deployment inside Tore Supra plasma vessel under UHV conditions and 40 °C (Fig. 5). The very first time in-vessel remote inspection of PFCs was performed then; video capture examples: control of the shutter movement of an upper infrared endoscope, close tracking of the bottom limiter surface and carbon tiles macroscopic analyse (the gap between the vision tool and carbon tile's limiter was kept at 10 cm) (Fig. 6).

Deployments and video inspection under nominal temperature were performed in August 2008 in the ME60 test benches (Fig. 7). To complete the demonstration, operations of the AIA robot in the plasma vessel of Tore Supra under ITER relevant conditions are planed in September 2008.

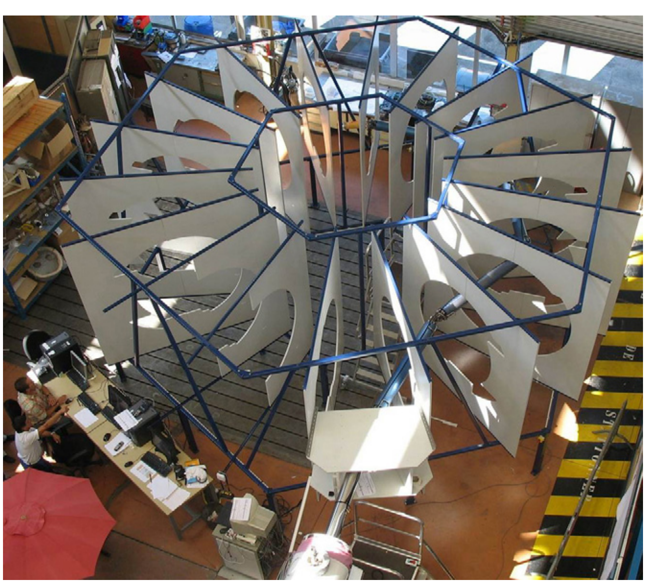

Fig. 4. Robot rehearsal into Tore Supra scale 1 mock-up.

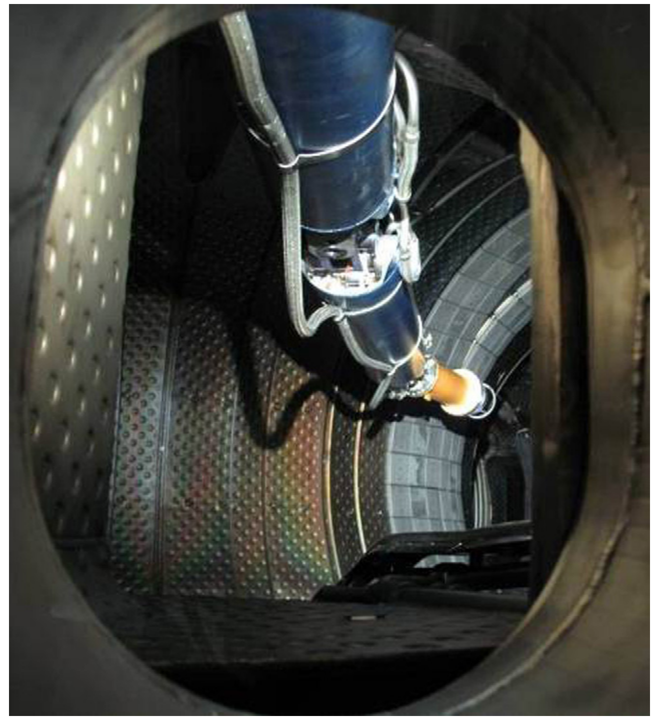

Fig. 5. AIA deployment into Tore Supra under UHV conditions.

Fig. 6. Tore Supra in-vessel inspections under UHV conditions.

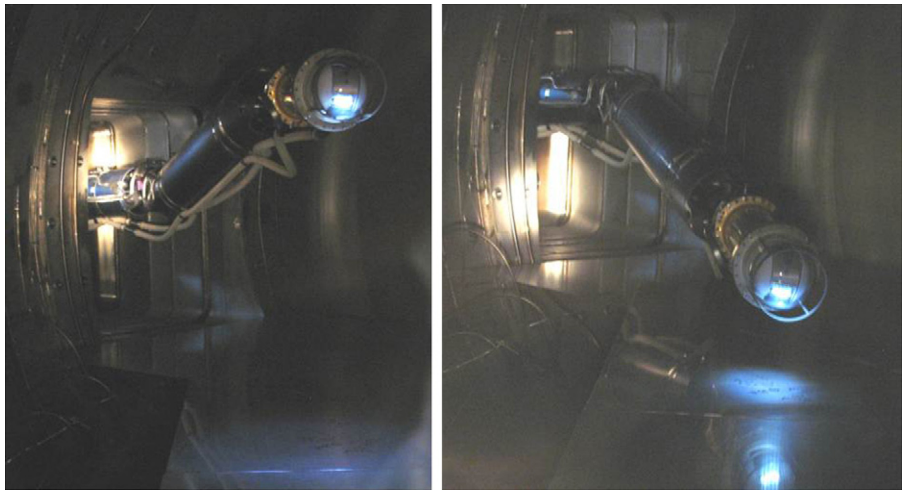

Fig. 7. Robot qualification into ME60 facility under UHV and temperature conditions.

5. Next steps

The next step will consist in bringing the AIA to a reasonable level of reliability and prepare for routine operation of the robot. This mainly requires to improve kinematics, control enhancements and overall reliability improvements.

Several developments are presently in progress on robot modelling, motion simulation and geometric calibration taking into consideration the structure flexibilities [5]. For a full robot monitoring during operation, operator assistance will be added by the integration of a CAD graphic interface and anti-collision management performed by the mean of a supervising software.

In parallel of these R&D programmes, new plugging tools are being developed by CEA for tokamak in-vessel diagnostic: a leak detection system and a laser compact system for carbon co-deposited layers characterizations or treatments.

The AIA is designed to allow accurate displacements of the head, close to the first wall. Associated with a viewing system, a leak testing tool can be implemented, which will operate under limited dry nitrogen atmosphere. Using a specific sensor for helium sniffing, the process would enable failure component localisation with a global loop helium pressurisation. This principle should allow a significant maintenance time reduction with no need to insulate several components before the leak localisation.

During tokamak operations, eroded carbon material is deposited by layers which are huge reservoir for hydrogen and isotopes. In situ analysis and surface treatment of the PFCs can be performed by laser systems:

- Deposited layers removal. As already demonstrated successfully at JET, an Ytterbium fibber laser (1064 μm, 120 ns, 20 W of mean power) will be used for films ablation. This technique is considered for recovering the tritium trapped into the ITER vacuum vessel [6].
- Chemical analysis of the co-deposited layers. Their chemical composition can be assessed using the Laser-Induced Breakdown Spectroscopy (LIBS) analysis technique. This in-line analysis permits also to have an End Point Detection during laser ablation operations and preserve the substrate integrity [7].

6. Conclusion

CEA is being developing an Articulated Inspection Arm aiming at satisfying requirements in term of availability for maintenance and in-vessel components inspection for tokamak.

Demonstration of the AIA behaviour and reliability in real temperature and vacuum tokamak environment has been achieved on Tore Supra in 2008. Experience gained with such a multipurpose robotic device will give very helpful information for future ITER remote handling tools for in-vessel operations.

Several diagnostics to be installed on the AIA robot carrier are under development. They range from leak detection module to sophisticated laser tools for plasma facing components characterisation, considered like very important functionalities for ITER maintenance and safety issues.

Acknowledgements

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