Development and operation of an ITER relevant inspection Robot

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Abstract. Robotic operations are one of the major maintenance challenges for ITER and future fusion reactors. In particular, in vessel inspection operations without loss of conditioning will be mandatory. In this context, an Articulated Inspection Arm (AIA) has been developed by CEA within the European work programme framework, which aims at demonstrating the capabilities of a multi-purpose in-vessel Remote Handling inspection system. In September 2008, the AIA robot carried out a complete deployment into Tore Supra under relevant conditions (Ultra High Vacuum and 120°C). With this full scale demonstration, the robot constitutes a promising tool for generic applications: indeed, different diagnostics are being developed by CEA to be plugged at the front head of the carrier. One, currently in operation consists of 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.
This paper describes the AIA project and the recent operations carried on Tore Supra.

1. Introduction

ITER [1], the world's largest nuclear fusion research facility will rely heavily on remote handling operations to accomplish its scientific mission while minimizing the risk of ionizing radiation exposure to its personnel and to maintain high plant availability. To that purpose, one of the ITER major challenges is to manage a hard Remote Handling programme.
In particular, inspections and treatments should be required inside the vacuum-vessel between sessions dedicated to the experiments. In this prospect, a multipurpose carrier called Articulated Inspection Arm (AIA) was developed by the CEA with the aim to be deployed into a tokamak vacuum vessel without breaking in-vessel conditioning. Tokamak vessel conditioning is a major prerequisite for plasma performance; it requires many weeks of preparation before starting effective plasma experiments. Interventions "between pulses" and "under vacuum and temperature", allow significant time and cost saving for maintenance operations, and therefore enhancement of the overall machine availability.
For this purpose, all the AIA components are compatible with Ultra High Vacuum (10-6 Pa) and temperature (120°C) environment operations and supported baking phase at 200°C for the out-gassing. Operations under magnetic field and nuclear ambiance are not yet considered in the implemented technology for the AIA.

In view of ITER applications, the CEA has also engaged developments on associated diagnostic tools to be plugged on the front head of the AIA. For the moment, tools considered are vision, leak detection, and surface analysis and treatment.

2. The Articulated Inspection Arm

The AIA is an 8 meters long multi link cantilever arm composed with 5 modules of 160 mm diameter made in titanium. The length of the AIA robot is consistent with ITER full vacuum-vessel surface close inspection. The 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 give to the robot 8 degrees of freedom [2, 3, 4].

With a payload of 10 kg, the poly-articulated arm total weight is about 150 kg and can be introduced through a remarkably small port of 250 mm diameter.
To create such a slender beam, it has been necessary to minimize 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.

All electronic systems are embedded in each AIA module. These components are enclosed on neutral gas atmosphere pressure in tight boxes while the mechanical structure is under vacuum. To cope with the high temperature requirements, all electro-mechanical components are qualified up to 120°C in use and 200°C when switched off. To overcome pollution issues with using grease, the design of free lubricant joints is based on thermal treatment with Teflon coating.

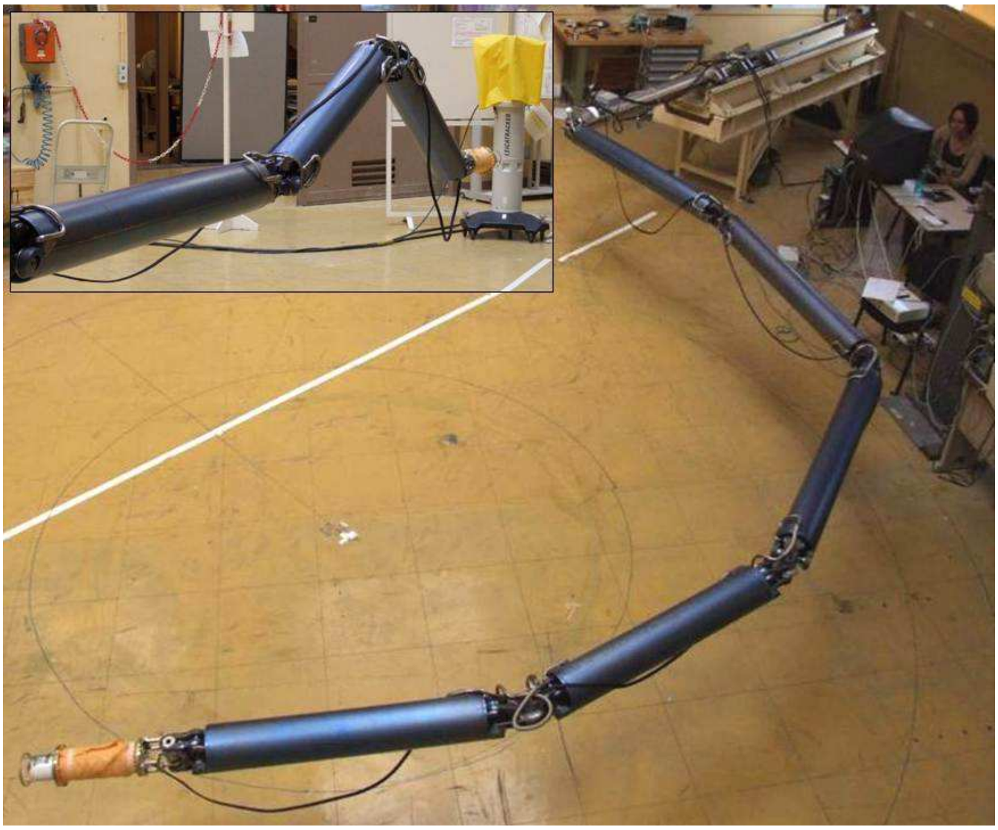

FIG. 1. AIA robot assembled, CEA-LIST Laboratory, June 2007.

3. Interchangeable Diagnostic Tools

The AIA robot is designed to allow accurate displacements of the head in front of the Plasma Facing Components (PFC). Several tools are in development to be implemented at the front end. All these tools shall be interchangeable; this specificity will offer flexibility in the operation tasks.

The first developed tool is a viewing system to make close visual inspection of PFC. The video process is designed with a CCD sensor embedded in a tight box made of stainless steel and glass (see Fig.2). It's linked to the head of the robot through a vertical joint actuated with the same concept of the robot modules. The electronic components and sensor are actively cooled by nitrogen-gas circulating in umbilicus in order to keep the temperature below 60°C for operation and baking phase. Currently, the system has been successfully tested up to a 170°C. Future improvements of the cooling system will allow ceaseless standing at 200°C.

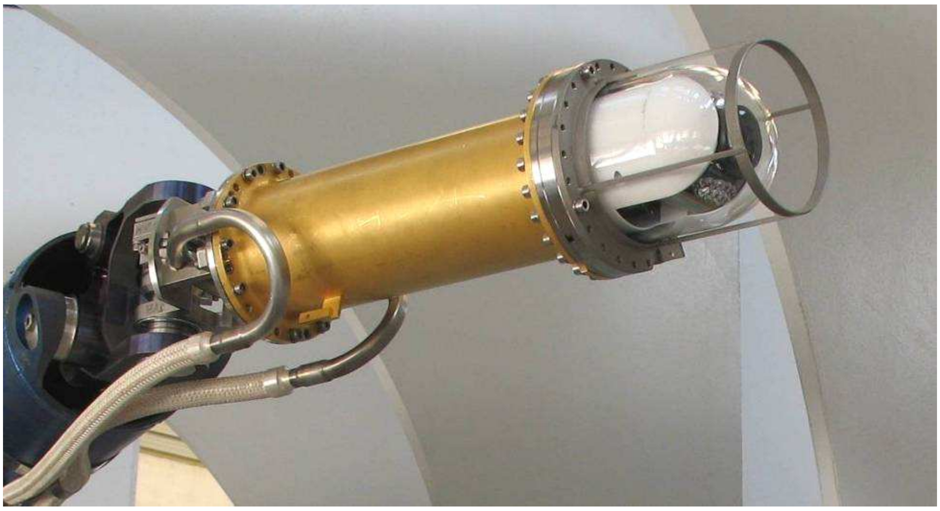

FIG. 2. The viewing system plugged on the front head of the AIA robot.

A diagnostic for water loop leak localisation is currently in development. It based on helium sniffing with outside spectrometer connected via an umbilical and could operate under dry nitrogen atmosphere.

Associated with the viewing system for accurate operation, the system could offer significant time reduction for (very) small leaks localisation with no need to insulate and pressurize independently each component.

Treatments and analysis of tokamak in-vessel components will be performed by laser systems [5]. During tokamak operation, eroded material is deposited on top of the PFC and the thickness of these deposited layers could increase up to several hundreds of µm. Co-deposited carbon are a huge reservoir of plasma fuel trapped in these layers. For safety, laser applications might be considered for tritium recovering, that concern:

1. Films removal by laser ablation.

As already demonstrated successfully at JET, an Ytterbium fiber laser (1064µm, 120ns, 20 W of mean power) could be used for layers ablation. This technique is considered for recovering the tritium trapped into the ITER vacuum vessel.

2. Chemical analysis of the deposited layers.

Their chemical composition will 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.
In order to implement these laser techniques, 2 optical fibres integration is foreseen on the AIA, one for the laser pulse, the other for the analysing spectrometer.

4. The housing

For the robot integration in the tokamak environment, a long storage cask has been defined for its conditioning and for its precise guiding during the deployment inside the plasma vessel. This large stainless steel cask (11m long, 3m height, 5 ton) is moved by 2 rolling support frames and can be (dis)connected from the dedicated port in less than 1 day. For this purpose, the cask is equipped with a double valve that allows connection and disconnection of the vessel without loss of vacuum conditions of the tokamak. Moreover, all electro-technical equipments are embedded to realize a compact and autonomous system (see Fig. 3).

FIG. 3. The Housing of the AIA (white cask on the left) connected to the Tore Supra tokamak.

5. Developments and operations

5.1 AIA project milestones

2 CEA institutes (robotic and fusion) undertook in 2002 the realization of the AIA robot. Six years of developments have been necessary to obtain the successful qualification of the first prototype arm.

In 2003, principles of integration on Tore Supra are validated. During the next 2 years the efforts were concentrated on the development and the qualification of the first segment prototype. Fatigue tests under representative loading, ultra high vacuum and temperature conditions were carried on (several weeks of cycles at 120°C during operating and 200°C for the out-gassing). The final vacuum residual gas analysis has confirmed the adequate behaviour of the device allowing operation without degradation of vessel conditioning [3]. However, the experience collected during these tests campaigns pointed out the necessity to upgrade some mechanical and electro-technical parts. The full AIA robot manufacture, based on the upgraded module design, was delivered in the beginning of 2007.

In parallel of the robot developments, the housing was designed, realized and qualified in the space of 2 years and the viewing system, manufactured by an industrial partner, is delivered.

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 (light wood structure) allows command control adjustments and scenario repeatability measurements.
- A large vessel (1/6 of the Tore Supra vessel) with a port plug fit to the storage cask enables the robot behavior checking under nominal UHV and temperature conditions [4].

5.2 Inspections in Tore Supra

In the second half of year 2007, the AIA robot and its viewing system operated for the first time in Tore Supra under atmosphere conditions (FIG. 4).
After this important milestone and one working year to achieve the airtight assembling and qualification, a second complete deployment was performed in Tore Supra plasma vessel under high vacuum (10^{-4} Pa) and at 40°C.
After the last phase of qualification and conditioning, in September 2008, the AIA robot performed for the very first time a complete deployment and close inspection of PFC under ultra high vacuum conditions **and** at 120°C (FIG. 5).

FIG. 4. On the left: AIA with the viewing system inside Tore Supra tokamak (atm. Pressure and 20°C).

FIG. 5. Visual inspection of a Plasma diagnostics (under ultra high vacuum and at 120°C
On the left: control of the shutter movement of an upper infrared endoscope
On the right: close tracking of the bottom limiter surface and carbon tiles macroscopic analysis (the gap between the vision tool and carbon tile's limiter was kept at 10 cm)

6. Perspectives

Following these successful demonstrations, the next step will consist in bringing the AIA to a high level of reliability and prepare for routine operation on Tore Supra.

This mainly requires improving kinematics, control enhancements and overall reliability improvements.
Further developments are in progress on robot modelling, motion simulation and geometric calibration taking into consideration the structure flexibilities. For a complete robot monitoring, operator assistance will be increased by the integration of a CAD graphic interface and anti-collision management.

7. Conclusion

The successful deployments of the AIA robot inside Tore Supra under relevant conditions (vacuum and temperature) close the important prototype demonstration phase and open the way for in-vessel maintenances and remote handling activities for fusion reactor like ITER.
The project is entering a second phase aiming at routine operation of the AIA robot on Tore Supra. This will mainly requires to further enhance the reliability of the components and the evolution of the command-control in order to increase the performances

In parallel, diagnostic tools relevant for ITER maintenance and safety are foreseen to be associated on the AIA robot carrier, capable to inspect, diagnose or treat Plasma Facing Components. These might be relevant for ITER maintenance and safety issues.

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