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An ITER Relevant Robot for Remote Handling: On the Road to Operation on Tore Supra

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1. Introduction

In the context of Fusion, several experimental reactors (such as the International Thermonuclear Experimental Reactor (ITER)), research aims to demonstrate the feasibility to produce, on earth, the plasma that occurs on the sun or stars. Fusion using magnetic confinement consists in trapping and maintaining the plasma in a magnetic container with torus shape (Tokamak), under Ultra High Vacuum (10^{-6} Pa) and high temperature (100 millions °K).

During plasma burning, the severe operating conditions inside the vacuum vessel apply high thermal loads on the first wall Plasma Facing Components (PFCs). Therefore, regular inspections and maintenance of 100% of the first wall surface is highly required. When considering the maintenance between two plasma shots, the conditions to perform maintenance tasks, without breaking the vacuum, exclude human intervention and require use of remote means based on robotic technologies that enable extension of human capabilities into the machine.

The technologic research on robotics and remote operations is called the Remote Handling (R.H.) activity. The Interactive Robotics Unit of CEA-LIST has been working on Remote Handling for Fusion for more than ten years. Experience on JET reactor maintenance has proven the feasibility to maintain an installation with robots controlled by distant operators (A.C. Rolfe et al., 2006), (O. David et al., 2000).

When considering generic Tokamak relevant conditions such as we can find in the CEA Tore Supra Tokamak, the set of major challenges we selected for the Remote Equipment is to sustain the following severe operating conditions: ultra high vacuum (10^{-6} Pa), temperature (120°C), baking (200°C). The limited number of machine access ports and the very constrained environment complicate the introduction of a robot into the machine. These issues impose an major step in term of technologic research for R.H.: innovation in robot conception, new kinematics, new actuator technologies, hardened electronic components were designed, simulated and tested to cope with the ultra high vacuum and the temperature constraints.

Since 2000, under EFDA (European Fusion Development Agreement) support, the Interactive Robotics Unit of CEA-LIST and the CEA-DRFC of Cadarache collaborate on a potential ITER relevant Remote Handling Equipment (RHE). The main challenge of the project is to demonstrate the feasibility of close inspection of a plasma chamber In Vessel

first wall with a long reach robotic equipment, under some ITER requirements: Ultra High Vacuum (10^{-6} Pa), temperature 120°C and 200°C during the outgassing phase to avoid pollution chamber. The proof of feasibility is performed on the existing CEA facilities called Tore Supra (TS), which is an experimental fusion machine using superconducting coils and water cooled plasma facing component (like ITER) located in Cadarache facilities ($R=2.3\text{m}$, $r=0.8\text{m}$ for torus dimensions).

The Remote Handling Equipment (RHE) designed for this application is composed of a Robotic Equipment called Articulated Inspection Arm (AIA), a video process and a Tokamak Equipment which enables conditioning and a precise guiding of the robot. (Fig. 1)

Fig. 1. View of the Remote Handling Equipment (RHE) in Tore Supra

Since the first conceptual design in 2000, succession of mock up, tests campaigns, tuning and design enhancements lead, in 2007, to the prototype module qualification under real operating conditions, Ultra High Vacuum (10^{-6} Pa) and temperature (120°C). The full robot is then manufactured, assembled and tested under atmospheric conditions on a scale one mock up in Cadarache facilities. The robotic equipment is assembled to the Tokamak Equipment for the complete qualification of the RHE connection on Vacuum Vessel.

In September 2007, 12th the successful feasibility demonstration of close inspection with a long reach poly-articulated robot carrier in Tore Supra is proved under atmospheric conditions.

Next milestone is the complete robot qualification under real operating conditions. At this step of the project, the robot prototype needs or could need further developments to meet 100% of the ITER operational requirements.

The RHE has to be used in real operating conditions to collect knowledge on the system behaviour. The design and command control has to be enhanced toward robustness and reliability. Further developments on command control and modelling taking into consideration the structure deformation are still necessary to have good confidence on the robot position in the 3D environment. Reliability of the complete RHE and control modes will have to be proved before the final RHE could be qualified as operational on Tore Supra. This chapter presents the complete RHE including the Robotic Equipment (RE), the Tokamak Equipment (TE) and the Video Process. An overview of the mechanical and control design principles is presented. Then, technologies selected for the robot to sustain vacuum and temperature are detailed and a presentation of the prototype module and full

RHE qualification tests and successful deployment demonstration in Tore Supra are depicted. The last part presents further developments that could be done in order to enhance the robot performances and manoeuvrability.

2. The AIA RHE design

2.1 Summary of the requirements

Toward the final objective to use the AIA Robotic Equipment on Tore Supra as an inspection tool, and with respect of the ITER relevant conditions, several requirements have to be met and taken into consideration during the robot design:

- Small penetration hole: equatorial port dedicated not larger than 250mm
- Operational full extension, able to reach any point inside the Tokamak, high mobility in the environment.
- Payload: Possibility to plug various processes (up to 10kg); the first process developed is a video camera for inspection.
- Functioning conditions: Ultra High Vacuum (10^{-6} Pa) and temperature: 120°C in use (baking phase 200°C for vacuum conditioning)
- In-Vessel requirement: do not pollute the Tokamak Equipment.

2.2 General design and control

First conceptual designs started in 2000. Simulation results and first computations converge toward the following kinematics structure: a poly articulated robot formed by 5 identical segments and one precise guiding and pushing system at the base, called "Deployer", able to push the robot into the machine. Each module includes up to two degrees of freedom, two rotary joints (one in the horizontal plane and one in the vertical plane) (Y. Perrot et al., 2004).

Main characteristics:

- Cantilever length: 9.5 meters.
- Weight: ~300 kg (5 modules + Deployer).
- Payload: 10 kg.
- 6 modules Ø160 mm, up to 11 degrees of freedom (d.o.f.), (10 rotary joints, 1 prismatic joint at the base).
- Rotary joint (vertical axis): $\pm 90^\circ$.
- Rotary joint (horizontal axis): $\pm 45^\circ$.
- Prismatic joint at the base: 10m range. (Fig. 2)

Fig. 2. Simplified AIA kinematics model with 11 d.o.f.

In Fig. 3, the elevation axes are represented with a simple revolution axis whereas, in fact, it is a parallelogram structure that performs the elevation motion in order to minimize the impact of the cantilever structure and keep the axis vertical.

Fig. 3. AIA kinematics model with parallelogram structure

The AIA articulations are actuated by electrical motors. Each module includes on-board temperature hardened control electronics qualified up to 120°C in use and 200°C switched off. The robot can carry a payload of 10 kg at its end effector. At the moment, the AIA can be piloted by programming the desired angles of the robot’s joints (articular control mode). Limited access of viewing in the Vacuum Vessel requires developing assistance to steering that could be developed in the next phase of the project.

2.3 Mechanical design

The AIA robot carrier is composed of a set of 5 modules and a pushing system (Deployer). The payload is supported by the end effector. Because of the high cantilever structure (9.5 m), the robot elements are submitted to high forces and torques. Tubes and clevis are made of titanium for its mechanical properties even under high temperature, rods are made of bearing steel for its high mechanical resistance in traction. Each module is a two DOF mechanism: 2 rotary joints (horizontal and vertical axis) with a four-bar mechanism (the parallelogram) composed of the rods, the base clevis, the tube and the head clevis (Fig. 4).

Fig. 4. View of a AIA module

The parallelogram plays a major role in reducing the gravity effect over the joints of the structure by keeping the clevis vertical. Thus, if the parts deformations are neglected, the rotation axis between two modules will also be kept in a vertical position for any given configuration. This property is an advantage for the design because it tends to reduce the

size of the electrical actuators that provide the modules rotation motion. As far as no dynamic motion is required, high ratio gearbox with D.C. motors are satisfactory. The angular displacement in the horizontal plane is set in motion by the actuators through a cable and pulleys system as shown in (Fig. 5).

Fig. 5. Rotation cable system

The forces and tensions due to gravity over one of the modules of the AIA robot are represented in Fig. 6. The segments of the robot that follow the current one are modeled by a weight $\vec{P}$ and a moment $\vec{C}$ applied over the clevis. When performing a structural analysis to define the tensions created in the parallelogram structure, we find that:

$$\begin{aligned} T_1 &= \frac{C}{\ell \cos \alpha} \\ T_2 &= P \cdot \frac{d}{\ell_1} \\ T_3 &= \frac{C}{\ell \cos \alpha} + P \cdot \frac{L}{\ell_1} \end{aligned} \tag{1}$$

Fig. 6. Gravity forces repartition in the parallelogram structure

Since $l = l_1$ in (1), and considering the basis module, the maximal forces supported by the elements are 64000N in the tube, 40000N in the rods and 25000N in the jack. The issues of the final Robotic Equipment design are represented in Fig. 7.

Fig. 7. View of the complete Robotic Equipment design

2.4 Tokamak Equipment design and integration on Tore Supra

As the final objective is to demonstrate the feasibility to use a Robotic Equipment has an inspection tool between two plasmas, the equatorial port of Tore Supra is dedicated to receive the AIA RHE. It means that the robot must be already conditioned under the same vacuum and temperature level as the Tokamak ones to avoid any perturbation during the robot introduction into the machine. In this context, a long storage cask has been designed. It is provided to allow the robot conditioning and precise guiding of the Deployer (Fig. 8). This large structure: 11m long, 3m height and about 5 tonnes in operating mode is carried by 2 rolling wagons operated by winches and guide rails on the ground. One of the initial integration objectives is to connect or fold up the entire device in about 1 hour. For this purpose, all electro-technical equipment is embedded to realise a compact and an autonomous system. In particular the head wagon integrates the vacuum pump group, the heating and temperature regulation components while the second one includes the robot and process drivers. The cask is also equipped with a double valve that allows disconnection of the vessel without loss of the vacuum condition (L. Gargiulo et al., 2006, 2007).

Fig. 8. Schematic view of the AIA integration on Tore Supra (side view)

2.5 Video process design

The initial objective of the project is to demonstrate the feasibility of close inspection task. Therefore, the first process developed and integrated in 2007 on the AIA robot is a video process. It was designed and assembled by ECA/HYTEC.

Principal characteristics:

- CCD color sensor with zoom and LEDs lights
- gas cooled system (temperature below 60°)
- 3 degrees of freedom (1 body rotation + 2 camera rotations)

The video process is designed with a fixed CCD camera embedded in a tight box made in stainless steel with a bright coating. This box is linked to the head of the robot through a vertical joint actuated from inside with the same system as the yaw joint of the robot. All the components and more particularly the CCD sensor located inside this box are actively cooled by the means of a small diameter flexible umbilical.

The AIA is designed to allow accurate displacements of the head, close to the first wall. A water loop leak testing process could be performed under dry nitrogen atmosphere. It will use a specific sensor able to sniff helium placed at the head of the AIA carrier or positioned at the extremity of a 20m sniffer umbilical.

3. The AIA RHE prototype and proof of feasibility

3.1 Vacuum and temperature technologies – Experimental measurements

As the robot is dedicated to be introduced in a Tokamak without breaking the vacuum, several technologies were selected to be used under ultra high vacuum:

- The structure materials in metallic alloys, like titanium.
- Some other non organic materials could also be used like Vespel and Viton.
- No organic materials.
- Use of welding for assembly of the structure parts.
- Gearbox will use standard reducers. Roller screw and gearbox should be lubricated and embedded in tight sealed boxes with the motors.
- Use of needle bearings with dry lubricant but significant regular maintenance will be required.
- Electronics will be embedded in tight boxes with tight connectors and linked by flexible tubes. (Fig. 9)

Fig. 9. Rotation tight boxes embedded on the Robotic Equipment

In parallel of the Robotic Equipment design, tests campaigns, components characterizations under temperature and, if needed, specific developments have been performed at CEA-LIST laboratory facilities. For instance, no manufacturer's standards actuators cope with the vacuum and temperature requirements. Specific temperature hardened motors and gold coated electronic boards using HCMOS military electronic boards have been developed and tested.

Fig. 10. Temperature tests on motors

Fig. 11. Gold coated electronic boards qualified under temperature (baking 200°C and 120°C in use)

3.2 First prototype module

Since overall vacuum and temperature technologies are selected and qualified, the prototype module can be manufactured and tested.

In 2004, a vacuum and temperature test campaign was performed in CEA DRFC test facility ME60. This test has shown a good functioning under ITER representative conditions 120°C temperature and vacuum. The baking of the robot at 200°C was performed during one week and the final spectrum has shown a good behaviour of the system (Fig. 12).

These first results give confidence in the technologies developed for the AIA to be used in a Tokamak conditioning. An endurance testing was also performed at room conditions to qualify the module performances under representative payload (Fig.13).

Fig. 12. Final outgassing spectrum before and after baking

The final pressure obtained at the end of the test campaign was $9.7 \cdot 10^{-6}$ Pa which are good results to use the AIA robot in a Tokamak vessel.

Fig. 13. Endurance tests on the prototype module in CEA-LIST facilities

The experience collected during these tests campaigns pointed out the necessity to upgrade some mechanical parts toward a new prototype design. On that base, this module is considered as the first of series constituting the whole robot.

3.2 First prototype module qualification under Vacuum & Temperature

The February 2007 test campaign was a significant milestone of the project as it represents the final design of the prototype module qualification under real operating conditions in ME60 facility (Fig. 14):

- Ultra High Vacuum (10^{-6} Pa)
- Cycles between 200°C for outgassing, 120°C and 20°C .

The successful results of this test campaign qualify the entire prototype module and also all the components and technologies developed since the beginning of the project to cope with the severe operating requirements: Ultra High Vacuum (10^{-6} Pa) and temperature (200°C for outgassing, 120°C in use).

Fig. 14. Test campaign on the ITER relevant module in real functioning conditions (February 2007)

3.3 Complete assembly of the Robotic Equipment and preliminary tests

The full AIA robot manufacture was based on the same design than the upgraded module. All these parts were delivered before the end of 2006 and were integrated beginning 2007. The command control of the robot is deployed on the system and tuned.

Fig. 15. Robotic Equipment preliminary tests at CEA-LIST robotics laboratory facilities

The video process assembly is achieved in June 2007 and integrated on the AIA Robotic Equipment (Fig.16).

In August 2007, the complete AIA robotic equipment is achieved and tested at CEA - LIST Robotics laboratory facilities (Fig. 17) under ambient pressure and temperature conditions for:

- Robot mechanical and electronic functional validation,
- Command control tuning and validation,
- Robot integration on the deployment system and functional validation,
- Video process integration and functional validation
- Performances measurements,
- AIA robot qualification under atmospheric conditions in free environment,
- Definition of deployment trajectories in free environment
- Tuning of security modes

Fig. 16. Video process integration on the AIA robot carrier

Fig. 17. AIA robot and Deployer tuning in CEA-LIST laboratories.

In the meantime, the Tokamak Equipment is assembled and tested at CEA-DRFC facilities for the functional validation and its integration on the Tokamak.

Qualification tests of the guiding system and leak tests are performed under high temperature. Connection to Tore Supra is validated (Fig. 18).

Fig. 18. Tokamak Equipment integration on Tore Supra

3.4 Tests on a Tore Supra scale one mock up

Qualification campaigns with a deployment on the Tore Supra scale 1 mock-up of the port and slices of the vessel (Fig. 19) were carried on for:

- AIA robot qualification rehearsal under atmospheric conditions in free environment
- Deployment trajectories rehearsal under atmospheric conditions in free environment (as defined in CEA-LIST labs)
- Deployment trajectories rehearsal under atmospheric conditions on the scale one mock up for :
 - trajectory validation,
 - distance measurements between the robot and the Vacuum Vessel mock up
 - Deployment scenario validation before the robot introduction in Tore Supra.
- Security modes rehearsal and validation of safety procedures.

Fig. 19. AIA introduction scenario rehearsal in Tore Supra mock up

3.5 Deployment on Tore Supra under atmospheric conditions – Proof of feasibility

In September,12th 2007, the Remote Handling Equipment is connected on Tore Supra and deployed into the machine by following the same scenario as rehearsed on the mock up (Fig. 20).

Fig. 20. AIA deployment scenario rehearsal in TORE SUPRA under atmospheric conditions

The tests enabled to validate the operational performances of visual inspection process. Close inspection of the machine first wall components gives sufficient quality images to accurately analyze the state of the installation. These tests bring confidence to draw sustainable analysis of the inner surface state and diagnostic of possible events. The test has still to be rehearsed under real operating conditions. Thus, the robot reliability and controllability must be enhanced to have confidence in close teleoperation trajectories.

3. Development to maturity toward In-Service use on Tore Supra

This RHE tool from its prototypical nature has still to prove its reliability, robustness and controllability for its In-Service use. Therefore, several tests campaigns are planned on the Tore Supra scale one mock up and ME60 test bed facility to collect knowledge on the system behaviour. Some mechanical upgrades could be necessary to enhance the RHE reliability.

Also, due to its large structure and flexibilities the accuracy of the AIA robot is perfectible. Therefore, a calibration method of the flexible model taking into consideration the flexibilities of the structure and geometric imperfections could improve the robot performances (J. Chalfoun et al., 2007). Once calibrated, the robot model could be computed in real time by the controller in order to locate the robot position in the 3D environment.

Limited access of viewing in the Vacuum Vessel requires on line monitoring of the robot. Next developments concern a teleoperation control system enabling steering thanks to a passive 3D device (space mouse), a 3D graphical interface for 3D realistic display of the manipulator. The robot position in the 3D environment is computed by the real time flexible model. On line collision avoidance and real time dynamic simulation are functionalities provided by the graphical interface tool.

The on line monitoring could also be used for fault detection while it could detect robot deviation or component fault in real time. This steering interface will provide all the functions necessary to remotely control manipulators. (Fig. 21).

Fig. 21. AIA's control through on line monitoring system

Several tools to be installed on the AIA for various in vessel operations are being studied. In particular water loop leak testing, laser ablation for wall detritiation and surface characterization are foreseen as utilities to be placed at the AIA end effector. All these various systems are currently in development in different laboratories of the CEA.

4. Conclusion

The first lessons learned on the preliminary results on testing a scale one RHE prototype in a scale one in service Tokamak facility is extremely important to show real results on Remote Handling which stands for 50% robotics and 50% tokamak integration technology. The demonstration on Tore Supra helps in the understanding of operation issues that could occur in the tokamak vacuum vessel equipped with actively cooled components.

Tore Supra operates with similar vacuum and temperature conditions as ITER (120°C to 200°C). Integration and rehearsal operation of the AIA demonstrator in this tokamak facility will give essential results when considering in-vessel inspection routine capabilities and reliability of the system.

In-Service use of a RHE as a routine inspection tool on a Tokamak will provide a lot of lessons very precious to follow up the demand for high performance remote maintenance required to operate the next Tokamaks expected to support the future Fusion experiments.

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This book consists of 18 chapters about current research results of service robots. Topics covered include various kinds of service robots, development environments, architectures of service robots, Human-Robot Interaction, networks of service robots and basic researches such as SLAM, sensor network, etc. This book has some examples of the research activities on Service Robotics going on around the globe, but many chapters in this book concern advanced research on this area and cover interesting topics. Therefore I hope that all who read this book will find lots of helpful information and be interested in Service Robotics. I am really appreciative of all authors who have invested a great deal of time to write such interesting and high quality chapters.

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