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REMOTE HANDLING AT JET

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1 ABSTRACT

JET – the world's largest and most powerful operational nuclear fusion reactor – has employed teleoperation and other remote-maintenance techniques for over three decades to avoid human exposure to a potentially hazardous environment and to develop techniques for future power-generating fusion reactors where environments will be far too hazardous for any manned maintenance.

As a unique application of robotics, virtual reality and operations management systems, JET's remote handling unit, now a part of RACE, has driven the state-of-the-art with each upgrade programme in its history.

This paper presents the current capabilities of the JET remote-handling system, and the future capabilities being delivered by its latest upgrade programme, which makes use of cutting edge advances in electronics and software.

RACE aims to shape the technologies being developed for JET in such a way that they will have wider applications, such as in nuclear decommissioning.

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2 INTRODUCTION & BACKGROUND

The Joint European Torus (JET), located in Oxfordshire, UK, is currently the world's largest operational nuclear fusion reactor. Due to activation of the machine components, as well as the presence of various hazardous materials, regular maintenance and reconfiguration of the machine are conducted remotely using robotic devices. As JET is an experimental device, installation and removal of components, diagnostic devices, and actuation devices is required on a relatively regular basis.

When fusion experiments are taking place, the JET vessel is in a state of vacuum, with high temperature plasma, magnetic fields, and high neutron flux. These conditions are unsuitable for the majority of robotic maintenance activities, and so the machine is routinely shut down for periods of several months in duration. These shut-down periods are used to deploy maintenance equipment and conduct the required modifications. Due to the high cost of experimentation, it is essential that maintenance activities are conducted efficiently and do not cause extension to the planned shut-down duration. This creates the need for high reliability, highly dependable systems.

Because JET was designed to be remotely maintained from the outset [1], it has been at the forefront of remote handling systems technology for the past 2 decades, boasting state-of-the-art robotic systems and supporting technologies such as virtual reality and software planning tools.

The difficulties of maintaining JET are not all related to the environmental conditions. As discussed in [2], significant challenges are presented by the size and shape of the horizontal entry ports as well as the need to access all areas of the inside of the machines toroidal vacuum vessel and plasma-facing components. As such there are no trivial solutions to providing access, and as a result the remote maintenance equipment must be relatively sophisticated.

The primary remote handling equipment consists of two hyper-redundant articulated boom systems, each of which is able to access the entirety of the required workspace. These are posted through horizontal entry ports during shut-down periods and are able to use snaking motions to navigate the toroidal geometry. The typical operating mode is for one of these booms to transport components and tools to the work site, whilst the other is used to deploy a dexterous telemanipulator robot which can perform a wide variety of tasks.

All of the systems are remotely operated from a control room, located in a separate part of the same building. All actuation is achieved electronically, whilst visual feedback is provided via a low-latency CCTV viewing system. A suite of software tools, developed to support JET remote maintenance are deployed in order to assist operators in these complex and time-sensitive tasks.

This paper presents an overview of the main principles and systems involved with JET RH operations, as well as a view of the future developments that are planned to take place.

3 DESIGN PARADIGMS

The JET RH equipment is varied in both form and function – from small dexterous telemanipulator arms to 15-metre long snake-like Booms. However, it all shares common design paradigms which are essential for working in the JET environment.

Recoverability.
For a remote-handling system to be considered feasible, there must be no failure mode that leaves it stranded inside the JET reactor vessel. For example the JET Booms, discussed in sections 4.3 and 4.4, have redundant motors and mechanical disconnects to provide recoverability.

Maintainability.
At hundreds of thousands of pounds per day, any stoppage to JET is extremely costly. Therefore every way in which JET's systems can be more easily maintained is always investigated. All maintenance manuals are stored on JET's ODS database (see section 5.1) and all control systems are designed for quick access to diagnostics. Specialised data acquisition systems have been developed for JET's Booms, giving diagnostic access to motor voltages, currents, and controller following-error signals.

Flexibility, modularity, reconfigurability.
All of JET's RH equipment is designed to be flexible and adaptable to unknown future tasks, by having re-configurable modules. For example, MASCOT includes a special connector on its front, which includes 106 cores of cabling, plus Co-Ax for video, wired all the way back to the control cubicles outside of the JET vessel. This allows the development of a wide range of tools in support of the evolving JET programme. Even MASCOT itself is exchangeable for alternative end-effectors on Oct. 5 Boom.

Radiation tolerance
Since JET is a potentially radioactive environment, microelectronics such as optical encoders, digital multiplexers and on-board miniature servo drives are not used where their failure could cause the boom to require its recovery actuators. Therefore, all the joints use either resolvers or potentiometers instead of encoders, with the main Boom joints using both, for redundancy. Each motor and sensor is individually wired back to the controller, outside of the JET vessel. This requires large cable looms, with around 1,000 cores present inside each Boom.

Human-in-the-Loop.
While JET's Booms and MASCOT are capable of automatic and computer-guided movements, all operations are closely driven by a team of human operators. JET systems have not yet been upgraded to the stage where fully autonomous operations are possible.

Integrated Operation
JET Remote Handling consists of numerous machines all integrated and operated as a unified RH System. This co-operation between systems is key to JET's efficiency at RH operations.

Data sharing
In order to be able to implement JET's Virtual Reality (see section 5), ODS (section 5.1), Virtual Rail, and Condition Monitoring system (section 6.4), the different control systems for the JET RH equipment need to share as much data as possible. In the existing systems at JET, each system transmits status telegrams via TCP/IP to its PC-based HMI, which then relays the information on to other systems such as the VR.
Future systems being developed for JET share data using a publish-subscribe middleware standard called Data Distribution Service (DDS). This will enable flexible, scalable and

deterministic real-time data sharing, and eliminates the need for some of the dedicated data acquisition systems.

4 OVERVIEW OF THE JET REMOTE MAINTENANCE SYSTEM

JET has many different remote handling tools which have been integrated to work as one unified system. These are illustrated in the diagram below.

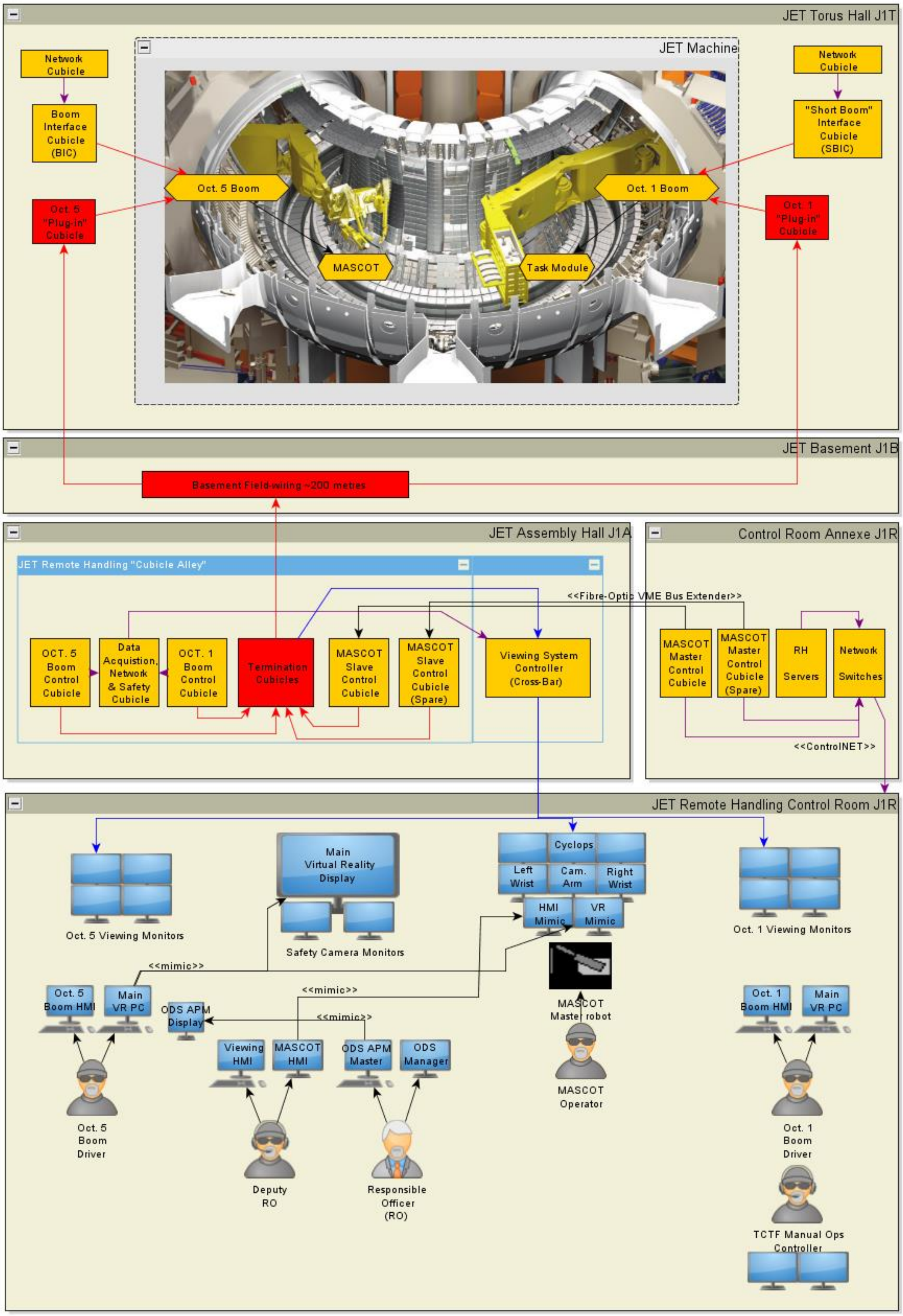

Figure 1: JET RH System Overview

4.1 Control Room

The JET RH control room requires at least four operators to use Oct. 5 Boom and MASCOT, but usually has six operators, with Oct. 5 Boom and MASCOT working in tandem with the Oct. 1 Boom and the TCTF (see section 4.4).

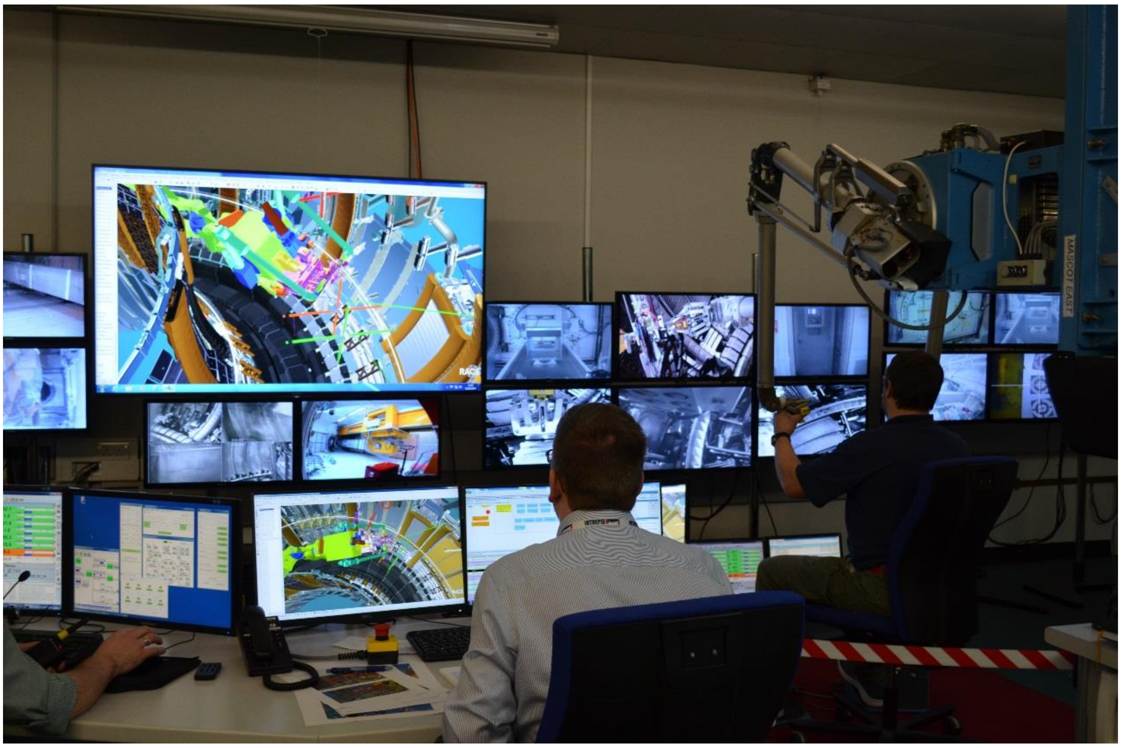

Figure 2: JET RH Control Room

4.2 Dexterous Manipulator

The dexterous telemanipulator robot, known as MASCOT [3] [4] [5], is a two-armed machine with back-drivable actuators and a large dexterous workspace in which each arm can operate within the full 6 degrees of freedom. The manipulator is remotely operated from a control room, where a kinematically similar master manipulator is used to control motions, and provide high-fidelity force feedback.

Teleoperation has been employed for many decades in the Nuclear sector. Traditionally, this means a purely mechanical arm, a 'Master-Slave Manipulator' or MSM, constructed of mechanical linkages so that the slave arm mimics the movements of the master arm, but forces are transferred between the two arms in both directions so that the operator can feel the objects that the slave arm is touching.
Although electronically actuated telemanipulators have been in development since the 1950s, mechanical MSMs are still very much the norm in the nuclear sector, because of their passive safety and extremely high radiation resistance.
JET, however, cannot use mechanical MSMs, because of the large distance between the operator and site of work, as well as the variety of deployment positions and complexity of mechanical transmission. These constraints are also present in other specific areas within the nuclear sector, for example very large hot-cells such as those under construction at the European Spallation Source [6], and to nuclear decommissioning projects where it is preferable to exclude humans from a large area.

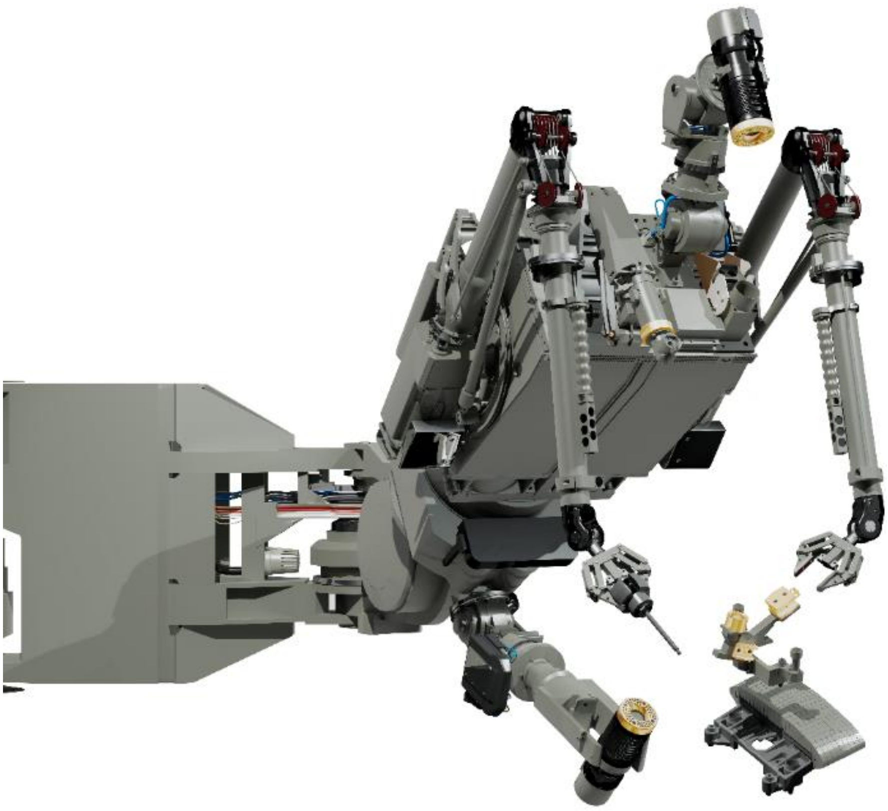

Figure 3: MASCOT system mounted to Oct. 5 Boom

Each motor on the Slave arm produces a torque proportional to the difference in position between its position and the position of the same motor on the Master arm, and the motors on the master arm produce the opposite torque, scaled by a factor selected by the operator. This is illustrated in Figure 4 below. This principle, known as a bi-lateral or "force-reflecting" servomechanism was developed in 1952 for the original MASCOT system [7].

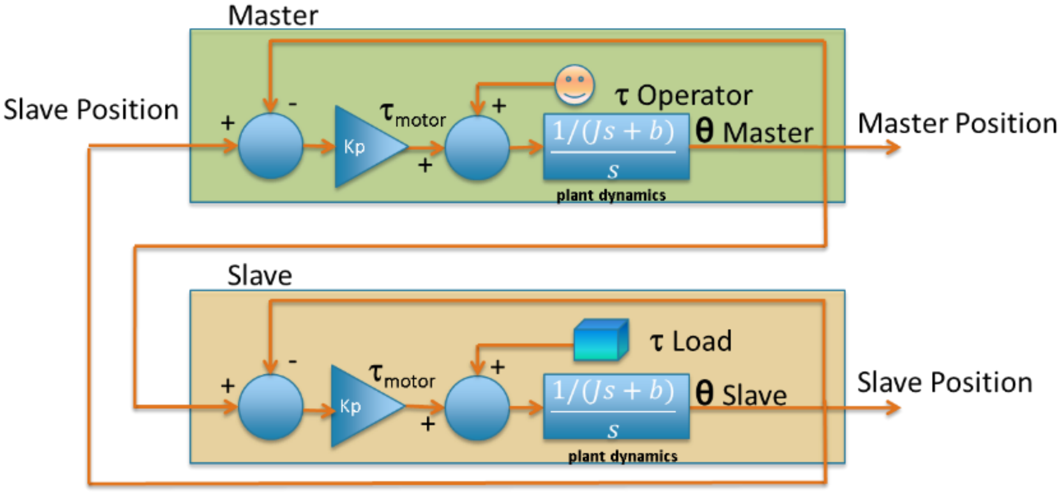

Figure 4: Simplified illustration of joint-space bi-lateral control scheme

A torque proportional to the difference in *velocity* between the two motors (not shown above) is additionally produced, so the MASCOT system can be said to implement a bi-lateral proportional-differential (PD) controller for each joint in the system.
The successor to this system, MASCOT 6, changes this for a much more modern and flexible control scheme, and is discussed in section 6.1.

With flexibility in mind, MASCOT is designed to support a large number of possible tools, developed for each planned task as required.
A special tool exists for MASCOT to handle each type of tile or component in the JET machine. There is zero possibility of dropping the item, provided the instructions given by the ODS Active Process Map (see section 5.1) are followed, thanks to special gripping features on each of the tools, which interlock with MASCOT's grippers.

MASCOT supports various attachments to its front "chest" plate in addition to "cyclops", its permanently-installed HD remote-viewing camera. The remote handling connector supports inspection cameras, power tools, welding equipment including gas supply, scientific instrumentation, and any future device that needs to be handled by MASCOT.
The left hand side of the chest plate can support either a 200kg winch, or the '3rd arm', an extendable holster on which MASCOT can stow tools and other small equipment during operations. The holster is twist-locked so again there is no possibility to drop items, even when MASCOT is working upside-down on the ceiling of the JET vessel.

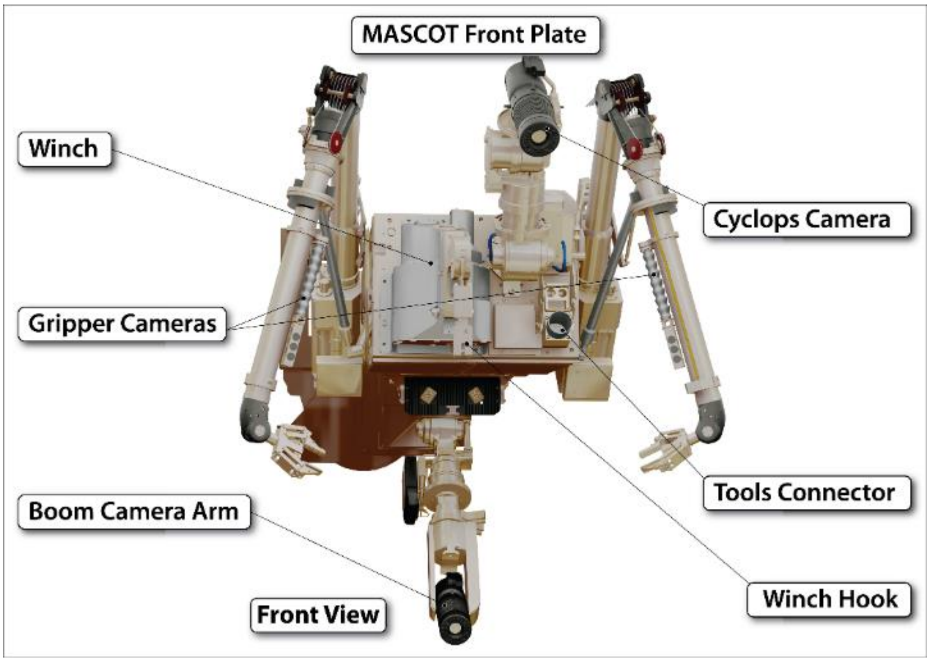

Figure 5: Illustration of MASCOT with front-plate attachments

4.3 Octant 5 Boom

The Octant 5 Boom, named after the segment of the vacuum vessel which it enters from is primarily designed to carry MASCOT, but can also carry other end-effectors, for inserting and removing large components of JET.
Figure 6 below shows the boom's nine main axes, including one prismatic joint (A0), six revolute joints on the horizontal (yaw) plane, and two more revolute joints on the pitch and roll axes behind MASCOT. The Boom includes a high-definition camera which can be rotated to orbit the end-effector (usually MASCOT).

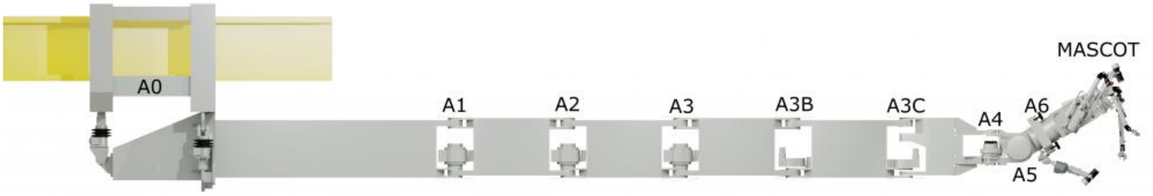

Figure 6: Octant 5 Boom joints

With six joints in the same plane, the Boom has a high-level of kinematic redundancy. However, a 'Virtual Rail' inverse-kinematic system constrains the joints A1-A3C to a predefined path that follows the curve of the torus. This system can position Mascot on a continuum around the JET vessel, as if it were on a rail.

Each of the Oct. 5 Boom's joints, except for A4, A5 and A6 are driven by two identical brushed DC motors, mechanically connected to the same input shaft of a harmonic-drive gearbox. Electrically they are independently wired back to the control cubicle, where they are connected in series or parallel, depending on the joint. For fault diagnosis it is possible to isolate one motor and check its electrical resistance compared to the other, which would highlight any electrical connection problems in the 200 metres of cabling back to its control cubicle in the adjacent hall.

The JET booms are designed for recoverability. In the event of a wiring failure or a failed motor, the motors are sized to be able to drive with only one motor active. Together (when current limits are raised) the Boom motors can overpower their own brake in the event the brake has failed to release.
For last-resort emergencies, special 'remote disconnect' actuators can mechanically de-couple the boom actuators, so that the whole boom could be dragged out of the JET vessel if necessary.

4.4 Octant 1 Boom

The Octant 1 Boom is used to transport tools and components to and from MASCOT, via a manned area known as the Tile-Carrier Transfer Facility (TCTF). Groups of tiles and/or tooling are loaded into tile carriers, known as Task Modules.
The Oct. 1 Boom is designed in the same way as Oct. 5. The boom and its joints are illustrated in Figure 3 below.

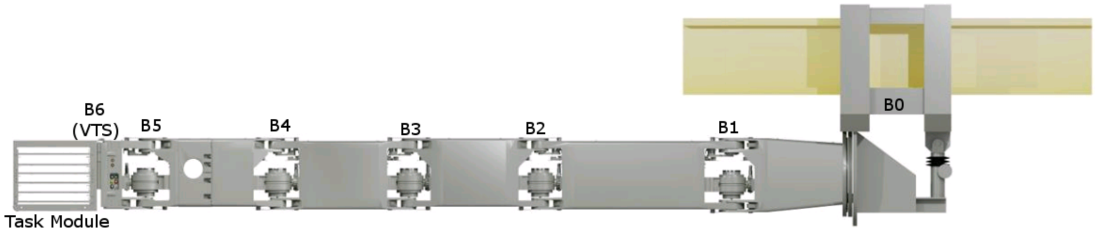

Figure 7: Octant 1 Boom Joints

Figure 8 illustrates the TCTF installed in JET. A shipping container can be docked to the side of this facility to enable bulk transport of task modules from storage. The Octant 1 boom automatically moves to the position required to pick up the next task module, and then back into vessel to meet the MASCOT using the Virtual Rail. To achieve this, the two booms communicate their positions on the rail so that they can automatically pick the best position for MASCOT to be able to access the task module.
Before each move is started, a human operator checks the path using the Virtual Reality system to make sure that no collisions can occur.

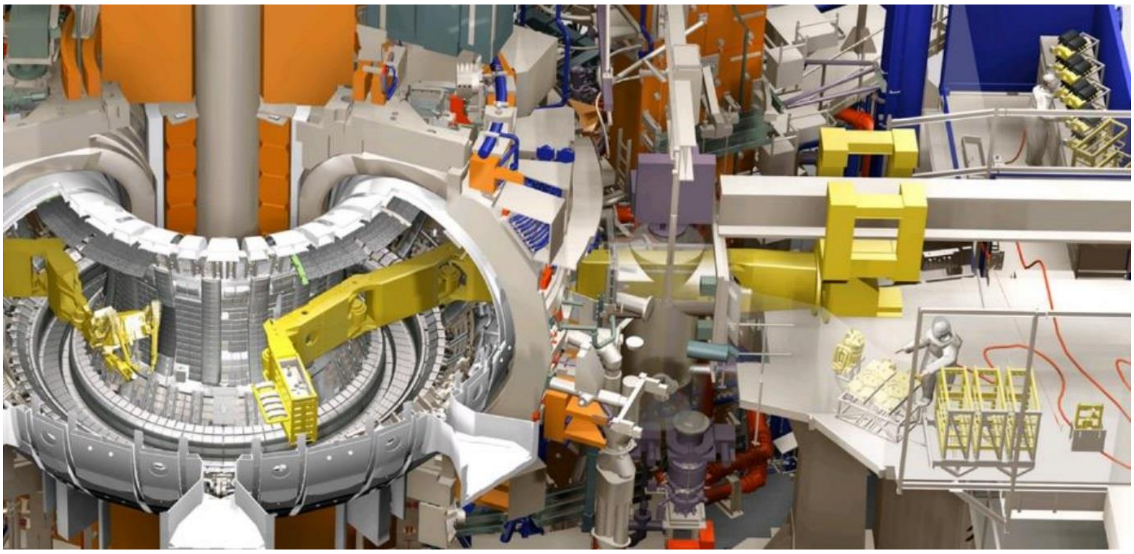

Figure 8: Octant 1 boom being used to deliver components from the TCTF

5 SYSTEM INTEGRATION AND VIRTUAL REALITY

In addition to a comprehensive, low-latency CCTV viewing system, operations at JET utilise synthetic views created by a virtual reality system which is constantly updated in real-time with position data relating to the robotic systems.

The virtual reality system incorporates a live 3D model of the environment, with each of the serviceable components, as well as all of the special tools which can be deployed, existing as separate meshes in the VR scene-graph. This model is continuously updated throughout operations to represent the precise configuration of JET and the RH systems. The positions of MASCOT and the Booms are automatically displayed based on the position sensor data from their respective control systems, while any planned automatic moves are illustrated as semi-transparent green indicators ‘ghosts’ of the target configuration.
The VR display is central to the JET control room, and allows the operators to clearly see the state of the RH systems and the JET machine itself, providing views that cannot be obtained by cameras.

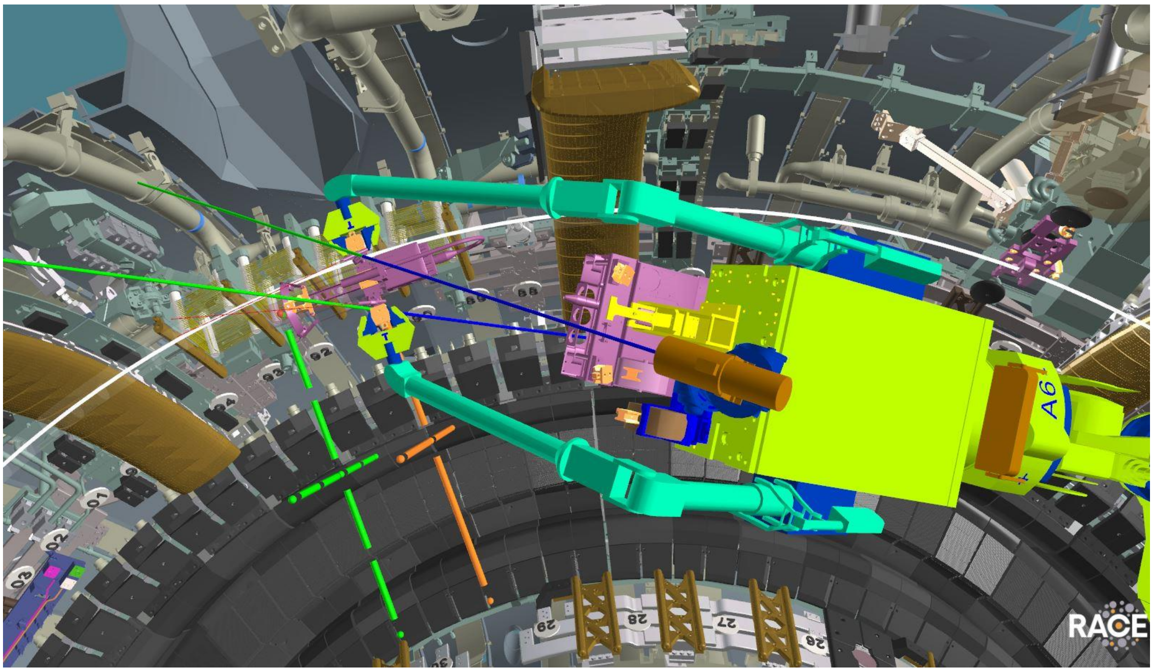

Figure 9: JET VR Display showing MASCOT positioning a tool in the JET vessel

Components are coloured and textured in a manner to allow for clear distinction and identification of components, which may otherwise be difficult due to the highly uniform visual appearance of the various parts.

In addition to supporting live operations in real-time, the virtual reality tools can be used in combination with simulated robotic control systems to allow operation planners to design and trial-run remote handling tasks offline in their own office, without access to the real systems. Motion path plans can be generated in this offline environment, and these are used to conduct validation mock-ups in virtual reality which are independently reviewed prior to approval for live operations. Once complete, the procedures and relevant teach-files can be entered into the ODS system, a database driven planning tool. [8]

5.1 Operations Document System (ODS)

The ODS is the central JET remote handling operations support tool. It is a database tool with a variety of graphical user interfaces used for a variety of tasks.

The primary function of the ODS is to enable and provide a set of controlled digital operations procedures, which guide the human operators through each task sequence. An online flow-chart is produced, called ODS Active Process Map (APM), with strictly controlled syntax and semantics preventing ambiguity in definition of tasks, and enforcing the use of standardised language and terminology. The system is used to develop procedures, as well as supporting the live execution of a remote task, providing a description the current operation, and ensuring that the operators check each condition and performing each sub-task before proceeding. APM is invaluable in ensuring that each operation is repeatable, controlled, and recorded.

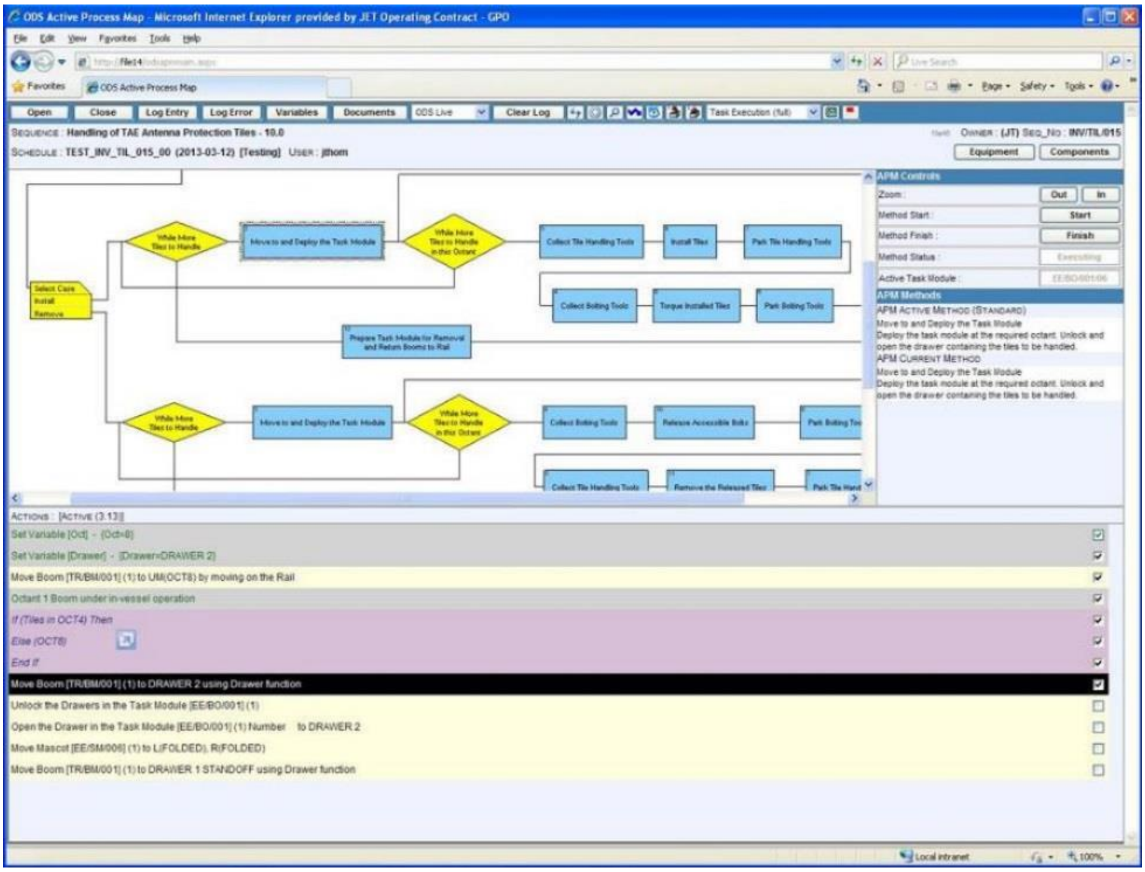

Figure 10: An example of an ODS APM flow-chart.

The ODS plays another key role in JET remote operations in that it provides an equipment management system, tracking the location, configuration, status, and history of all tools and components involved in a remote handling campaign. A number of interfaces are provided for equipment related tasks such as moving/storing of components, loading operations, maintenance procedures, and health-physics history tracking. This is a vital component in the logistical support necessary for efficient execution of such complex remote operations.

6 JET RH UPGRADES

The JET RH system is under constant modification due to the need to address obsolescence issues with the ageing equipment, and the need to meet constantly changing experimental requirements of the JET machine. This section describes a few of the major upgrades that are currently being undertaken by RACE for JET.

6.1 MASCOT 6

MASCOT 6 [9] is the biggest project in the JET RH upgrade. The project scope includes a complete redesign of the MASCOT control system, plus design of new actuators in both master and slave robots. Some of the key changes in MASCOT 6 are:

- Permanent-Magnet Synchronous Motors (PMSMs) will be used for all motion axes, replacing the obsolete 2-phase induction motors
- EtherCAT servo drives supporting CANopen-over-EtherCAT (CoE) and the CiA DS402 standard for interfacing to servo drives. These off-the-shelf drives replace an obsolete 2-phase servo system built in the 1990s based on the original 1952 design.
- PC-based control system incorporating RACE's "CorteX" distributed control software and a software EtherCAT master, to replace the obsolete VME-bus based system.
- Functional Safety – The MASCOT 6 Master station will include functionally safe speed monitoring on its major axes of motion, using safety rated encoders and a safety PLC to immediately stop the system if it ever exceeds a set speed limit, according to guidance set by ISO TS-15066 (collaborative robots) and ISO 13849-1.

6.2 Immersive VR interfaces

While the VR in use on JET does not include head-mounted displays, RACE is making use of the latest video game engines to develop immersive interfaces, which will allow operators to interact much more closely with the VR environment, as well as enabling remote participation in a virtual control room. This kind of VR is being considered at the European Spallation Source [8].

Figure 11: RACE Immersive VR using Haptic Glove

6.3 OMS

RACE Operations Management System (OMS) is a complete re-design of the JET ODS discussed in section 5.1 earlier. While the ODS has evolved over many years to meet JET's specific requirements, OMS is designed to meet the requirements of ODS while being flexible enough to meet the requirements of ITER, DEMO, and perhaps also non-fusion remote handling systems such as the Active Cells at ESS.

6.4 CMS

The RACE Condition Monitoring System (CMS) expands on JET's existing Data Acquisition System, and provides an extensible framework for monitoring signals from within the JET RH system. CMS will allow data analysis modules to be developed as plugins, with access to all of the data gathered from the JET RH plant in one place, including real-time high-resolution signals such as motor current, voltage, velocity, position, controller following error, as well as other data streams from sensors such as strain-gauges. CMS plugins can make use of JET's HPC and GPU clusters to predict failures before they happen, using modern machine learning algorithms.

7 CONCLUSIONS & WIDER APPLICATIONS

JET has a highly integrated remote-handling system, which has been developed over many decades. While maintaining and upgrading this system, RACE are developing replacement systems that have their place not only in JET, but are applicable to a wide variety of robotic, autonomous and human-supervised remote operations around the globe.

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