Towards a Remote Handling Toolkit for Fusion: Lessons Learnt and Future Challenges – 17360

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ABSTRACT

It is increasingly recognised within the fusion research community that the next generation of remote maintenance solutions will be a 'device defining driver' for a future fusion power plant.

The unique Remote Handling Systems that operates at JET, EUROfusion's research reactor that is operated by the UKAEA at Culham, Oxfordshire, remains the archetype for future designs.

At ITER, the international fusion research experiment being constructed in the South of France, many $100's millions will be invested in supplying and then operating remote handling solutions.

This paper will provide a brief history of the JET Remote Handling System in recent campaigns and will present initial results of the ITER remote operated cutting and welding trials.

Finally, the paper will comment on reasons for establishing RACE, the UKAEA's centre for Remote Applications in Challenging Environments and the task of integrating new robotics including autonomous vehicles, snake-like manipulators and autonomous remote maintenance systems into the design of a future fusion reactor.

INTRODUCTION

New and improved remote handling solutions will be needed if we are to achieve viable fusion reactors [1]. For magnetic confinement fusion (e.g. JET, ITER) the deuterium/tritium fuel mix will reach 200millionK under ultra high vacuum contained within a magnetic field. The fusion reaction generates 14 MeV neutrons and 3.6 MeV alpha particles that degrade and activate local materials. In a fusion power plant concept, beyond ITER, the equivalent of the fission fuel rod will be a tritium 'breeding blanket'. Current concepts suggest that ~100 breeding blanket sections weighing ~80 tonnes each will need to be replaced periodically during the reactor's life. These blankets also contain the primary coolant, which may be a lithium-lead eutectic, hence when removing these component, it will be necessary to cut and remake a series of pipe welds: all to nuclear codes. In-vessel remote handling systems will need to operate in kGy/hour radiation fields with zero possibility of human intervention.

RACE has been established as the UK Atomic Energy Authority's centre for Remote Applications in Challenging Environments. This comes at a time when robotics and autonomous systems are being recognised as a key component of the emerging digital economy. RACE's long term technology roadmap acknowledges the potential to learn from other sectors: driverless cars, drones, household robotics and of course machine learning. There is an expectation that these new technologies will accelerate the availability of mature hardware and change acceptance of new technologies. A challenge for the nuclear sector is to keep up with these developments so that these tools are useful at all stages of the nuclear lifecycle: research strategy, plant design, build, operation, decommissioning and waste management.

Whilst there is much that the nuclear sector can learn from others, there are areas in which we must lead because of the specific end use requirements. Operation in high levels of radiation imposes significant extra constraints. Two areas in which the nuclear sector should lead are key components of a re-usable remote handling toolkit: snake-like robot arms, and, remotely operated cutting, welding and inspection technologies.

The extremely high heat loads and vacuum necessitate cutting and welding of cooling systems as part of routine maintenance of all in-vessel components. First trials in 2015 of the prototype solution for cutting and welding 200mm OD stainless steel pipe using remotely delivered and operated tools show that achieving high quality welds is possible within the space constraints. Many challenges remain.

JET REMOTE HANDLING SYSTEM

JET has two snake-like robot arms to conduct work inside the toroidal reactor vessel. Both are horizontal planar 7 jointed booms approximately 12m in length [2]. One carries the slave of a force feedback master-slave system called Mascot that is used to conduct most of the dexterous work within the vacuum vessel. The other carries a tool chest which increases operational productivity [3]. This system has more than 35,000 hours of operational use and in a two shift 18-month campaign was used to replace the complete plasma-facing wall comprising more than 3,000 components [4].

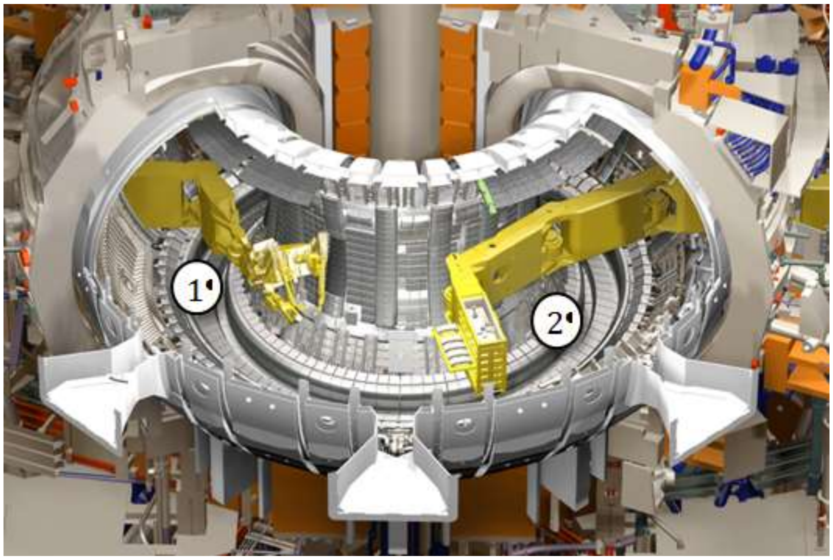

Figure 1 Remote handling systems used to service the JET tokamak through equatorial ports. 1. Articulated transporter and servo manipulator; 2. Articulated transporter and component/tooling delivery system.

The Mascot manipulator is the basic workhorse of the remote handling system. It consists of two force reflecting, master-slave, servo-manipulators with load a capacity of 20 kilogram and with a force sensitivity of 100 gram per arm. The units are linked by computer, not mechanically, so that the slave unit can be operated at any distance from the master. Mascot is used by the operator to undertake a wide range of tasks including welding, cutting, bolting, handling and inspection. Engineering design and development of Mascot v6 is a major enhancement to the Remote Handling System, improving reliability, availability, maintainability, and inspect-ability and addressing the obsolescence issues of the current v4.5. The upgrade includes: replacing obsolete induction motors, new actuator design, modular components with improved interconnections and complete replacement of the control system including electronics and software. Software upgrades include a generic, robot-independent communications protocol, Cartesian bilateral control which calculates forces and torques inside 1kHz loop allowing use of dissimilar master/slave devices, static and dynamic balancing, inertia dynamics and torque ripple compensation, VR simulation and active collision avoidance and an new HMI with real time performance monitoring. Having software that is future-proofed in order to be able to accept advances that are arriving is vital.

Figure 2 - Mascot

Performing tasks with a manipulator is difficult: there is no depth perception and no peripheral vision. Most of the feedback we take for granted and use without thinking are not available to the remote handling operator. Improved virtual reality and augmented reality techniques are breakthrough technologies but are no replacement for good design. The basic remote handling design principle is to make the task as foolproof as possible by reducing uncertainty. At a very basic level this means knowing that the component being handled will locate exactly every time and will fasten into place every time with minimal risk of wedging. To achieve this certain remote handling design principles have been developed [9].

Locating: Location features help with the remote positioning of components and prevent problems such as wedging. A wedging condition is hard to recover from because the magnitude of the wedging load is a priori unknown and difficult to quantify. Location features minimise wedging by accurately positioning a component through successive simple steps that progressively remove degrees of freedom. A long ball-ended dowel paired with a second short dowel is one of the most common location features used in remote handling, Figure 3. Figure 4 shows how electrical connections can be designed around such a feature to ensure that fragile components mate reliably.

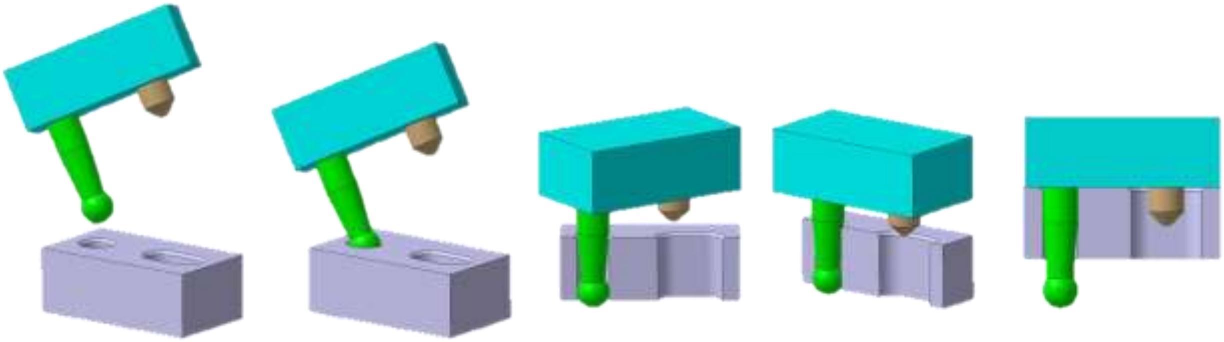

Figure 3 - Kinematic mating features

Figure 4 - An RH electrical connector and a tool with multiple handling interfaces

Fastening: Fasteners need to be designed to include features that facilitate robotic fastening and unfastening. Bolts can be designed to prevent cross-threading using a lead-in on the end of the bolt, an unthreaded portion at the start of the bolt and feathered threads to start the thread mating. Captivated bolts (already attached to the part) avoid having to carrying the bolt separately to the component, stop the bolt falling into undesirable or inaccessible places. Pop-up bolts make it obvious when the bolt is undone and lift the bolt out of the support structure. Even so bolts do become immovable and as a last resort must be drilled out, remotely. This has been achieved at JET but will be a challenge for ITER which uses M64 stainless steel bolts.

Handling: the primary environment interface for a master-slave manipulator is a gripper. Figure 4 also shows a typical tool which three identical grip interfaces which include pin features so the item cannot be knocked out of grip. Angled edges and gripping surfaces aid alignment of grip fingers.

Such simple design features will become increasingly important in ITER where operations will be performed over months and equipment must not fail.

ITER CUTTING AND WELDING

The challenge of conducting working within the ITER vacuum vessel is far greater than in JET because of the spatial reach requirements, payloads and more hostile conditions. Many remote maintenance tasks required at ITER will require modular components first be disconnected from their services; services such as power, instrumentation and control, and cooling.

ITER will be the first nuclear installation where remote welding and cutting of pipes is performed routinely. This presents some unique challenges, key amongst these are producing and inspecting welds to international codes and standards, operation in high radiation and UHV clean environments, working within confined spaces, with limited viewing to high precision.

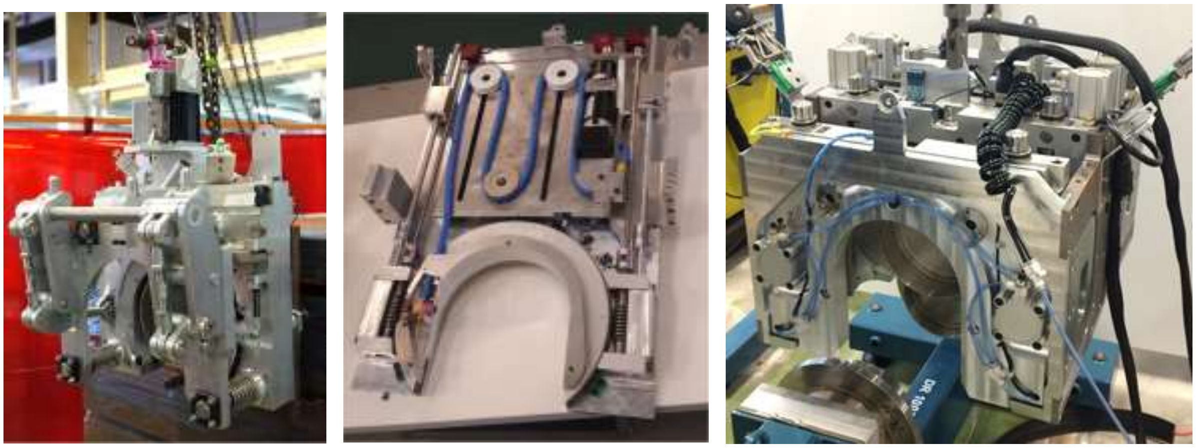

Figure 5 - Cutting tool (left), welding tools (centre) and alignment tool (right)

The basic scheme proposed in the concept design [5] was to have a removable bellows section to allow the flexibility to the pipe to the rigid component. The tolerance of this is around 40mm, more than a practical bellows would allow. Metrology of the final component position, and a matched removable bellows assembly has been proposed for each joint, with the bellows taking up only manufacturing and metrology tolerances. A datum flange located on either side of each cut location would allow for accurate positioning of the tools and manipulation of the bellows. Three tools were developed starting with a systematic process of gathering requirements including ITER NBRHS Generic Tooling Design [6], Codes and Standards for ITER Mechanical Components [7] and the ITER Vacuum Handbook [8]. A wide range of tool and operational requirements also were captured, these came from relevant European directives, the ITER Remote Handling

Code of Practice [9], and the professional experience of the JET remote handling operations team [4].

A lathe based cutting method, Figure 5 (left), was selected due to its low power requirements, good resulting finish and geometry, ease of application, and its proven record both at JET and wide use in commercial equipment [10]. The defined deployment volume allowed for the tool was extremely limited, and for this reason a U-shaped rotor was selected as the most practical configuration.

The weld tool, Figure 5 (centre) was based on a TIG arc welding process [11]. When compared to the other most promising technique identified, laser welding, TIG was chosen due the arc's ability to follow the charge concentrator that is the joint edge. Laser weld heads compact enough to fit in the available space are also not currently available although this is likely to be addressed over coming years.

The alignment tool, Figure 5 (right), was required to bring and hold the joints to sufficient alignment for coded welding, support and to position the weld tool and tension the bellows.

In order not to damage the faces ahead of welding, a 7.5mm joint gap was planned. Two mating options were considered: compress the bellows during fitting, or stretch the bellows to bring pipe ends into contact. The latter option was selected as it would fail safe, not allowing the bellows to jam. It was found that the tensioning mechanism could be incorporated into the joint closing feature, removing the requirement for any mechanism between the bellows assembly flanges. This design also offered the added benefit of the ability to accommodate any offset.

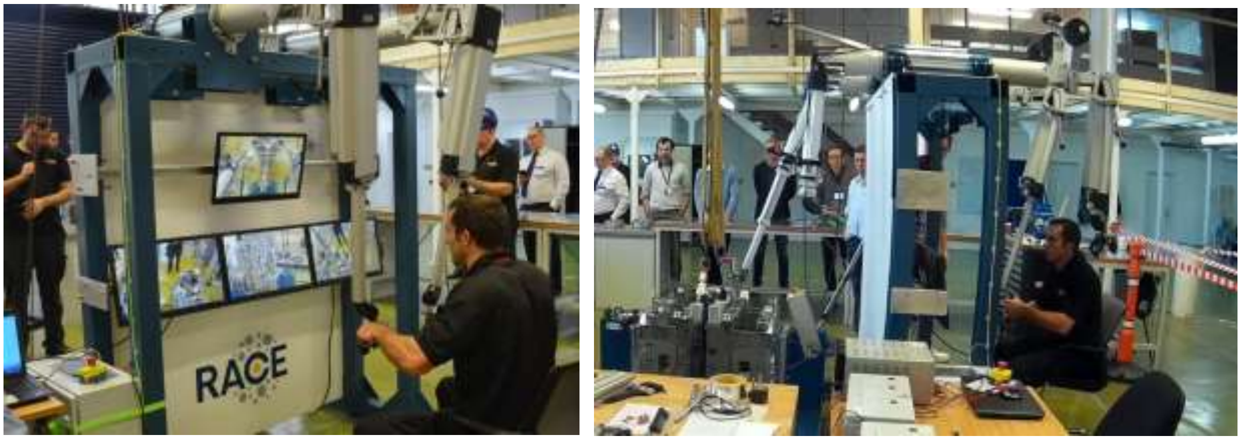

Figure 6 - Prototype demonstration using manual remote handling

The work culminated in a demonstration of a fully remotely deployed align, Figure 6, weld and cut process on a full size joint [12]. Tools were deployed by crane and manipulator onto a mock up joint; the operator viewed this task remotely using cameras to mimic the final deployment.

DEMO CONCEPT DESIGN

Remote handling in future fusion power plants will be yet more challenging because of increased radiation, increased size and the need to replace tritium breeding blankets which are the equivalent of fission fuel rods [1].

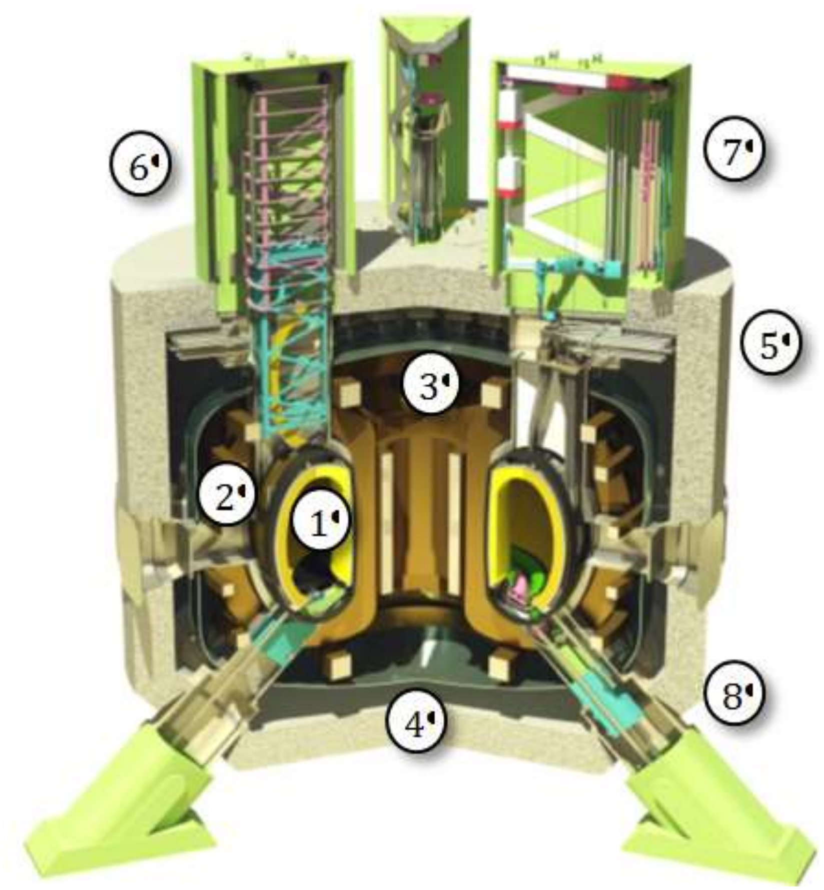

Figure 7 - Primary demonstration power plant component confinement structures:1. First wall blanket segments and divertor cassettes; 2. Vacuum vessel; 3. Magnetic coils; 4. Cryostat; 5. Concrete bio-shield. In-vessel remote maintenance systems: 6. Blanket segment transporter cask; 7. Blanket service connection remote handling systems; 8. Divertor cassette handling system.

In one current concept ~100 curved breeding blanket segments, each ~15m long and weighing ~ 80 tonnes, will be contained within the main vacuum vessel [13]. As well as slowing the neutrons and channeling away the fusion energy through heat exchangers, these blankets also breed tritium for the main fuel cycle as the neutrons bombard the lithium. Replacing the blankets once the lithium has been used up entails them being removed/inserted through vertical ports in the vessel between the confinement magnets [14]. As they are actively internally cooled, as part of the primary cooling circuit, cooling pipes must be disconnected when a blanket segment is removed. Similarly, when inserting a new blanket, the coolant pipes must be re-welded to strict nuclear standards. These blanket segments have to be accurately positioned (±10 mm) to avoid neutron leakage that would otherwise cause damage to the reactor vessel and external components, most notably the superconducting magnets. A complication is that neutron-damaged steel is difficult to weld because the voids created within the steel are filled by hydrogen atoms.

RESEARCH PROGRAM

RACE's remote operations research is now being driven by issues that will be relevant to fusion reactor architecture. These include:

- Combining into a single analysis tool the many causes of material deformation including static and dynamic loads, radiation, decay heat, neutron deformation, magnetic loads and heat flow. Such analysis is relevant to the design of both the in-vessel components and the large manipulators that will be required to maneuver the components. Neither can be made rigid enough that such deformations can be ignored. Reliance on computer modelling requires validation using near full scale mockups.
- Developing remote techniques for joining services including welding long non-straight pipes. Laser welding is the strongest candidate, with the main challenges being size reduction of the tool head and delivering the tools to and from the weld site whilst guaranteeing recovery of any temporarily installed equipment.
- Calculations show that replacement of all in-vessel plasma-facing components will take many months of continuous operations. This is a key parameter that affects plant utilisation, and hence the cost of electricity. Ex-vessel logistics of delivering tools, removing radioactive components into storage and then introducing clean or refurbished components is also a considerable challenge.
- Safety and recovery systems that must be designed to meet the relevant nuclear standards. Ex-vessel remote handling equipment are likely to become semi-autonomous, using sensors to modify actions including changing the trajectory of moving elements. Recovery from a failure of the remote handling systems is a particularly challenging issue.
- Fusion codes of practice and standards. It is likely that processes and standards developed for other remote handling activities will not be appropriate for fusion. Therefore it will be necessary to revisit these and solve safety issues in the most cost-effective manner.

Clearly, many challenges remain to be overcome, which is why the UKAEA's Remote Applications in Challenging Environments (RACE) facility was created. In time RACE will provide state-of-the-art large-scale, long-term testing facilities, remote-handling equipment and design expertise for developing the design of fusion reactor remote-handling systems. Beyond fusion, robotics in all its forms is an emerging market. Fusion will benefit greatly from developments in sectors as diverse as autonomous cars to remote inspection of oil refineries. It is envisaged that RACE expertise will be useful for many different industries with an interest in robotics and autonomous systems. Two recent non-fusion developments, **Error! Reference source not found.**Figure 8, are examples of progress being made. Oxbotica, a spin out from Oxford University, is using RACE to test driverless cars [15]. The LaserSnake trials led by OC Robotics at Sellafield also show the way forward combining dexterous snake-arm manipulators with a compact laser cutting head [16]. The common technology being developed for location, navigation, user interfaces and safety are all directly relevant to nuclear robotics.

Figure 8 - Driverless car testing at RACE and OC Robotics vehicle mounted snake-arm

CONCLUSIONS

Delivering fusion power is a grand challenge and will take an exceptional, determined team of physicists and engineers to find a winning solution. We will need to draw on developments made across industries from construction, where precision placement of large components is routine, to rocket and aero-engines that use materials that function at extreme temperatures. Human creativity and need will continue to drive the progress of remote-handling technologies over the coming years. This, coupled with a symbiotic relationship with fusion physicists and reactor designers, provides the best route to achieving viable fusion electricity.

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