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ABSTRACT
To reduce the timescale of the JET Enhanced Performance 2 (EP2) shutdown, two multi-jointed Booms instead of one will be used for maintenance and upgrades inside the JET vessel. To fully utilize this new configuration, the control systems of the Booms have been modified at a high level to allow quick and safe interactions between them. This paper will discuss how the control systems of the Booms have been integrated to exploit the increased mechanical functionality of the Octant 1 Boom, and will demonstrate how this has improved safety, utility and efficiency for the remote handling operators during the EP2 shutdown. Other operational streamlining functions will be mentioned, as well as a look to the future of Remote Handling at JET.

1. INTRODUCTION
In preparation for the EP2 Shutdown of JET, the Remote handling (RH) systems have undergone a considerable mechanical upgrade [1]. Most notably the extension of the 'Short Boom' extending it into the Octant 1 Boom, a manipulator capable of reaching +/-125 degrees around the JET vessel (when constrained to the centre of the torus), see Fig 1.

With this increased reach, the efficiency of RH operations could be increased dramatically. By using this boom to supply tools and components to the Mascot at the workface, rather than continually running the Mascot telemanipulator to octant 1, to collect the equipment required for each task. Several challenges were presented by this increase in capability.

Limited ability of Boom Control hardware:

The hardware of the Octant 1 & 5 Boom controllers consists of industrial hardware from the 90's (with 33MHz Motorola 68040 microprocessors) and as such computationally expensive operations such as large or repeated matrix calculations are not viable at the lower levels of the control architecture.

Operation within common workspace of powerful machinery with potentially delicate components:

Both Octant 1 & 5 Booms will be operating simultaneously within the JET torus and any collision could damage wall tiles or the Booms or tooling. This scenario is at best expensive and at worst violates the As Low As Reasonably Possible hazardous exposure regime by forcing men to enter the vessel.

Efficiency of component transfer:

The purpose of the upgraded Boom is to transport components and tools to the Octant 5 Boom end effectors. This process will be carried out many times a day and so inefficiencies will mount up during the EP2 shut down.

Cognitive load on operators must be kept as low as possible:

Within the RH philosophy at JET the idea of the 'Man in the loop' is crucial. As the operator is responsible for the safe operation of the system the interface for any increased functionality of the systems should be as intuitive as possible [2].

2. OCTANT 1 BOOM AND RAIL CONSTRAINTS
The use of joint trajectory constraints, known as 'the Virtual Rail', to allow quick and safe access

around the torus, has been successful in the past and is a technique known and trusted by the JET RH operators. Therefore this system was replicated and applied to the Octant 1 Boom. This allows the operators to execute motion programs which constrain the positions of all the horizontally oriented joints of the Boom to the centre of the octant 1 port as the Boom enters the vessel then subsequently to the centre of the torus as it travels toroidally to a target angle. This keeps all joints of the Boom as far from the walls as possible until the Boom needs to be deployed to a working position.

The use of the Rail constraints also presented the opportunity to begin fulfilling one of the major functions of the Upgraded Boom; delivery of materials from the task module end effector. To carry out safe equipment transfer, the task module would need to be repeatedly placed in a position as close to perpendicular to the Mascot as possible. Radial constraints applied to the positioning of the tip of the Boom and preceding joint allow the task module to be deployed with the draws facing towards Octant 5 (pointing the task module towards the outer wall). With these constraints, a secondary set of solutions to the rail kinematic projections were introduced, allowing the Octant 1 Boom to assume a pose that would present the Task Module to the Mascot with the minimum angle relative to the vessel radius and maintain a guaranteed distance from the vessel walls. This kinematic solution can be used in the same way as the 'normal' rail, so the Boom can be driven between any 2 positions that satisfy the constraints, maintaining the desired toroidal positioning of the task module throughout.

As the position of the task module is fixed relative to the radius of the torus, it allows the Mascot telemanipulator to approach in a standardized way anywhere within the 193^{o} range that the Octant 1 Boom can assume this pose. There are also two poses at the octant 1 port where the Task module can be placed at a position relative to the torus' polar coordinate system, but with the task module facing the inner wall that allow a similar approach with Mascot.

3. RAIL AND INTERLOCKS

In order to prevent collisions between the Booms, the Human Machine Interfaces (HMIs) of the Booms were given the facility to connect via the existing Gigabit RH data transfer network. Both joint positions and tip positions (in polar world coordinates) are exchanged between the HMIs of each Boom, as well as configuration data regarding current end effectors. This allows the options presented to the operators to be modified dependent upon the condition of the other Boom, preventing a situation where the user constantly hits low level interlocks because the HMIs are not aware of hazards that are present.

As the Rail is the major method of access around the torus, it needs to be as safe to use as possible. Therefore the rail functionality was given a series of interlocks to prevent the generation of rail motions that would cause a collision with another Boom, blocking access to sections of the torus occupied by the other Boom. Where required the Octant 5 Boom was given 'right of way' to prevent instances of rail lock wherein neither Boom would allow motion upon the rail when in close proximity. The operators can choose to violate these constrains if needed, but they must acknowledge several warnings to do so.

Several other restrictions were applied to the motions of the Octant 1 Boom. The end effector lift/lower joint at the tip of the Boom (B6) has to be constrained above a certain height when moving on the rail, to ensure that the Boom always maintains a recoverable position. Also the Outer wall rail constraints do not allow the Octant 1 Boom access to octant 1 of the vessel so a switch to the normal rail is required to move between halves of the torus. A system that could aid the operator in navigating these constrains would prove invaluable.

4. AUTOMATIC MOVEMENT SEQUENCES

Improvements to the error correction system were desired for the EP2 shutdown. Previously, the Booms' control systems reported violations of any constraints (used primarily to manage the camera arms and rail on the Octant 5 Boom) to the HMI by presenting the operator with a series of corrected positions. A problem with this system was that the corrections could only be achieved by positioning joints directly to the suggested targets, leaving the operator to verify if this would cause a collision. Also if multiple interlocks were violated, then there could follow a frustrating process where the user commanded the same action repeatedly, correcting each individual error as they were highlighted.

Another challenge to overcome was how to approach the task of maneuvering the Octant 5 Boom into a docking position with the Octant 1 Boom's task module within the vessel. Positioning to the task module in the outer wall aligned position could possibly be achieved by Teach-Repeat files, but as this system uses fixed sets of joint positions the locations that the task module could be deployed to would be limited.

A solution to these problems was realized by additional functionality within the HMIs. A series of 'one step ahead' solutions to various problems & tasks were created, known as Automatic Movement Sequences (Auto-moves). When triggered, these Auto-moves observe the current state of the Boom, end effectors and, if relevant, the state of the other Boom then execute the next in a series of motions based upon these states to lead the Boom through complex series of actions. Each successful execution of the motion suggested by an Auto-move positions the system into the next state, so that the following action in the sequence will be executed when the next pass is made. The sequences are also stackable, so simple Auto-moves can be incorporated into more complex ones. For an example of Auto-move logic see Fig.3.

All of the actions executed by an Auto-move use almost identical functionality as a manual move by the operators (often so much so that the Auto-move function simply triggers a toolbar button in software), and to keep the operators informed as to the actions that the HMI is attempting, every Auto-move step is accompanied with a message detailing the final goal of the move, the current action and any special circumstances to be aware of. The operator can either accept the action or abort the Auto-move altogether. If they accept the action then the HMI prepares the next rail or joint move in the sequence. As this functionality is the same as that which the operators would execute when driving manually, they are immediately familiar with the consequences of executing a given motion type. As the moves are only prepared for the operator and not executed, they may also correct or trim the positions that are suggested, and then if the next iteration of the Auto-move finds them within safe bounds, the Auto-move sequence will continue with the joints in the updated state.

As these sequences are integrated at the HMI level they have access to all of the high level functionality that an operator has, but can also automatically apply offsets or quickly calculate and drive to useful positions within the workspace, based upon the positions and end effector configurations of both Booms. Complex kinematic functions that would be too computationally expensive to run upon the Boom controllers can also be carried out with ease within the HMI.

The key application of this is to solve the second issue presented at the beginning of this section; aligning the Mascot to the deployed task module. This can be achieved by driving the Octant 5 Boom to a preset angle away from the task module on the rail, placing the cameras and Mascot in a pose that is safe to approach the task module and then running upon a slightly modified rail to another pre-determined angular offset from the task module position. The reverse can also be carried out with ease, adding automation to the potentially hazardous task of bringing the two Booms into and out of close proximity, yet still allowing the operator full control of the actions of the Boom.

The Auto-moves have been in use continually during the EP2 shut down and are used constantly for collision prevention in almost all instances of the two Booms being brought into proximity. Some of the currently implemented Auto-move types are:

Rail alignment:

Auto-moves to allow the safest return to the rail possible in a given scenario.

Rail Management:

Auto-moves which manage some of the repetitious aspects of the use of the Virtual rail such as the need to stop to ensure Mascot arms are folded before crossing octant 5, or bridging the gap in the outer wall aligned rail between vessel halves.

Mascot-Task Module Approach/Disengage/Stand off:

Auto-moves which manage the alignment of the Octant 5 Boom to and from an outer wall aligned Task Module. See Fig 4.

Winch Alignment:

Auto-moves which drive the Octant 5 Boom over the Octant 1 Booms' Tine end effectors, placing the winch hook directly over components to be lifted from the Tine.

5. RECORD & PLAYBACK

A system to allow the operators to record the motions of the Booms as they operate has been introduced. This system differs from the Teach-Repeat system in that it does not require the operator to manually trigger the recording of each individual desired way-point in the path of the Booms motion. Instead this system tracks the relative velocities of the joints over time and looks for changes in the ratios of joint speeds. The positions of the Boom at these moments are logged in the Teach-Repeat file format, and a second reversed copy of the motions made in the same file. This allows the operators to run back and forth through a sequence of Auto-moves, and joint positionings repeatedly. This is particularly useful for transporting many smaller components from the vessel wall to the Task module.

6. HMI CONNECTION TO TASK PLANNING & EXECUTION SOFTWARE

Integration between the Boom control systems and the operational control and management software have also begun during the EP2 shutdown. The Boom HMIs now include limited access to the

Operations Documentation System (ODS) [3] that is used to plan, direct, and record execution of the tasks carried out with the remote handling systems.

Currently the system allows the operator in charge of the Active process map software to place either one, or list of teach files associated with a task into a buffer within the database, which is then retrieved for use by the Boom driver through the relevant Boom HMI. This has expedited operations by reducing the time spent directing the Boom driver to the correct directory for the relevant teach file for a task. This also allows the Boom driver access to the ODS' ability to procedurally generate the correct name for a repeat file during repeated operations.

7. FUTURE WORK AT JET

There are still many plans to improve RH operations at JET.

The Auto-move functionality may be extended to allow moves to be specified in an XML like format and then loaded during operations. This would allow the sequences to be developed by operators, instead of by the software development team. If such a system could be built into existing systems such as the active process map, this would be ideal.

The Mascot control system is still not integrated with the rest of the JET Remote handling equipment. Doing so could improve operational safety and efficiency in several ways: by allowing safety checks to ensure that the Mascot arms were within acceptable bounds before executing Boom motions, integrating Mascot data into the Booms Auto-move sequences allowing the Boom to position the Mascot grip or tools precisely, or tracking the actions of the Mascot with the Boom camera arms and thus reducing the operators need to continually position cameras for the best views of Mascot's workspace. The link between the ODS and the Control systems of the Booms could also be extended to the Mascot to allow rapid selection of move files used to position the Mascot arms.

JET remote handling could benefit from the inclusion of an on-line collision detection / prevention system. Although the risk of collisions is minimized by preparation & verification of the Booms motions, additional verification would be desirable where circumstances present unaccounted for hazards, or cause modifications to the execution of tasks.

8. RELEVANCE TO ITER & OTHER RH ENVIRONMENTS

The implementation of interconnections between multiple control systems as discussed in this paper should prove useful in any application of multiple non-autonomous robots to simultaneous tasks in an environment. These connections can be used to adapt any user generated motion programs to suit the states of other systems in the workspace and for the provision of access to relevant information generated by any high level task planning for the operation of robotic systems. The use of systems akin to the Automatic movement sequences discussed may also be of interest to engineers in remote handling as they allow the addition of a level of automation to a system whilst ensuring that the 'man in the loop' aspect of successful remote handling operations is maintained.

The aspects of ITER closest to the operations at JET are the use of the Multi Purpose Deployer (MPD) and operations within the hot cells, as these tasks will involve multiple Boom like devices operating in the same environment. Remote handling operations at JET have shown that rigorous task planning and preparation are the key to success. However the inclusion of an intelligent system for positioning the manipulators within the workspace ready for deployment can drastically increase safety and productivity. This system should be intuitive to operators and easily subject to interlocks to prevent collisions with other items or devices within the workspace.

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References

[1]. B. Haist et al, Fusion Engineering and Design, Volume **84**, Issues 2-6, June 2009, Pages 875-879, Remote handling preparations for JET EP2 shutdown Karoliina Salminen., et al, Fusion Engineering and Design, Volume 84, Issues 7-11, June 2009, Pages 1697-1701, Observations on human–technology interaction aspects in remote handling for fusion

[2]. Edward Robbins et al, Fusion Engineering and Design Volume **84**, Issues 7-11, June 2009, Pages 1628-1632, The use of virtual reality and intelligent database systems for procedure planning, visualisation, and real-time component tracking in remote handling operations

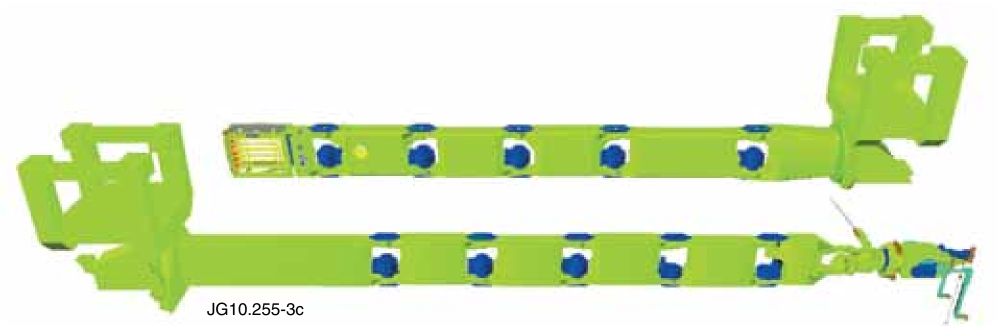

Figure 1: Comparison of Octant 1 & Octant 5 Booms

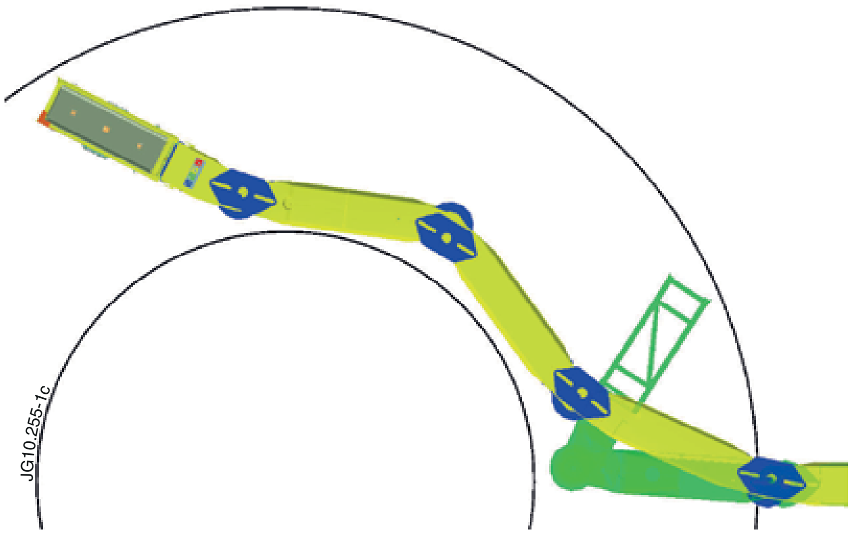

Figure 2: Limits of Octant 1 Boom Outer wall Rail motion in North half of JET Torus, with safe Min/Max Radii

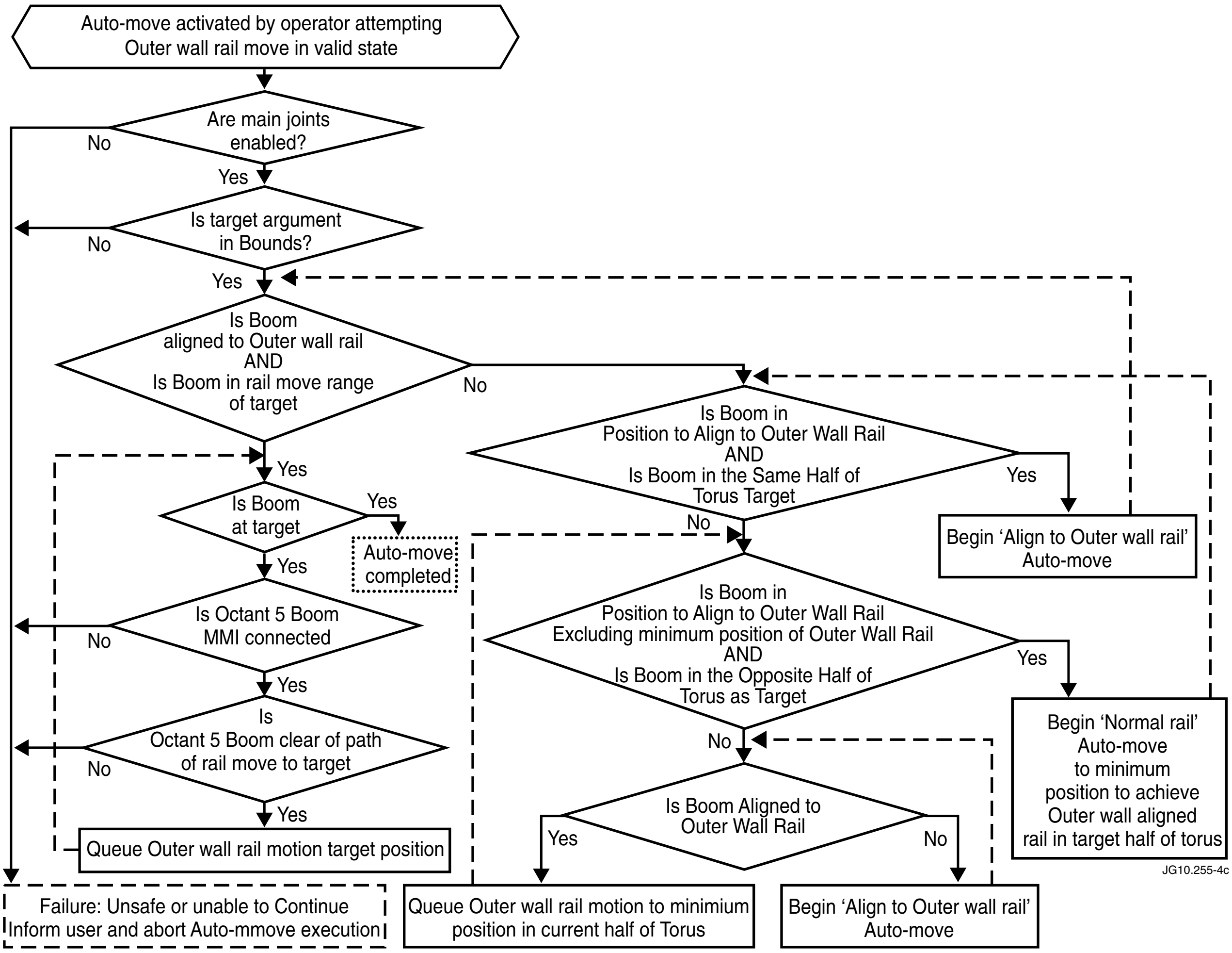

Figure 3: Flow diagram for 'Drive on Outer wall rail' Auto-move, dashed arrows denote where decision outcome will be changed after action completion

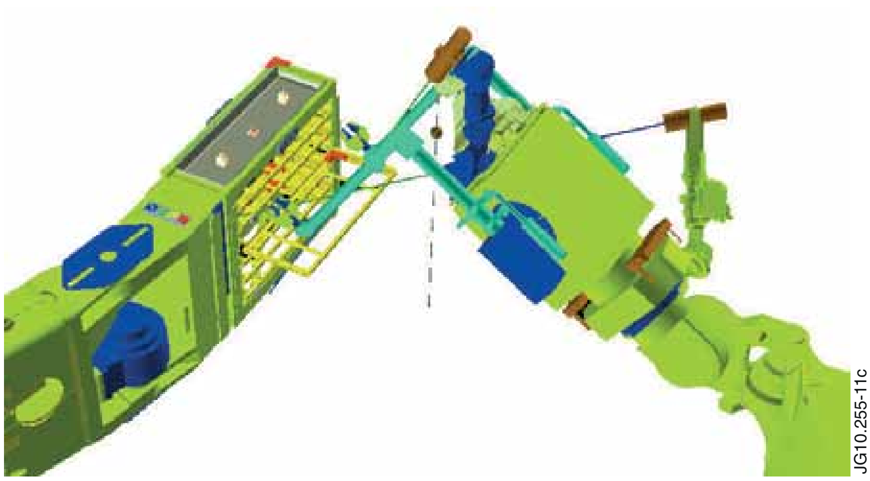

Figure 4: Octant 1 & 5 Booms in component exchange position