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High level integration of remote handling control systems at JET

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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 mechanical upgrade [1]. Mainly the extension of the 'Short Boom' extending it into the Octant 1 Boom, a manipulator capable of reaching ±125° around the JET vessel (when constrained to the centre of the torus). The Mascot (a 2-arm Master-slave telemanipulator and primary end effector used at JET) and the Octant 5 Boom (the multi link boom used to position Mascot and other end effectors with a reach of ±190° around the JET torus) remain largely mechanically unchanged, 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 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 and 5 Boom controllers consists of industrial hardware from the 90s (with 33 MHz 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 and 5 Booms will be operating simultaneously within the JET torus and any collision could damage wall tiles, 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.

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[1] See the Appendix of F. Romanelli et al., Proceedings of the 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland.

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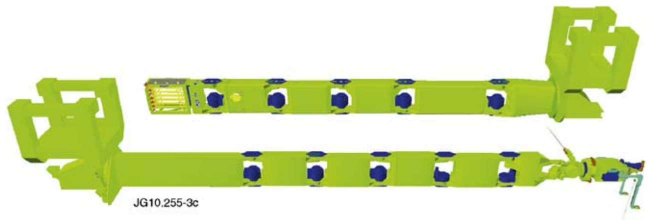

Fig. 1. Comparison of Octant 1 and Octant 5 Booms, with task module and Mascot end effectors, respectively.

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 (Fig. 2).

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° 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.

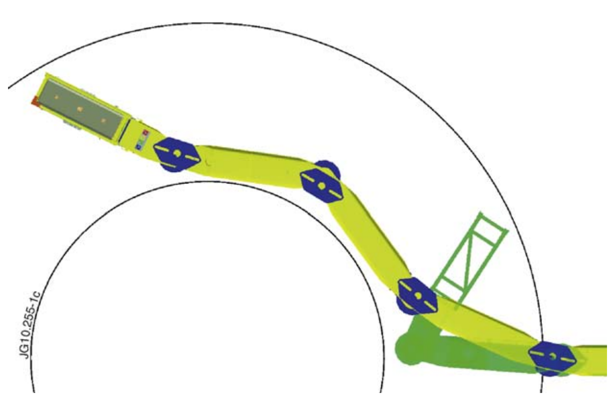

Fig. 2. Limits of Octant 1 Boom outer wall rail motion in north half of Jet Torus, with safe min/max radii.

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 and 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 in some cases, 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