EUROFUSION WPRM-CP(16) 15555

J Keep et al.

Remote handling of DEMO breeder blanket segments: Blanket transporter conceptual studies

Preprint of Paper to be submitted for publication in Proceedings of 29th Symposium on Fusion Technology (SOFT 2016)

Remote handling of DEMO breeder blanket segments: Blanket transporter conceptual studies

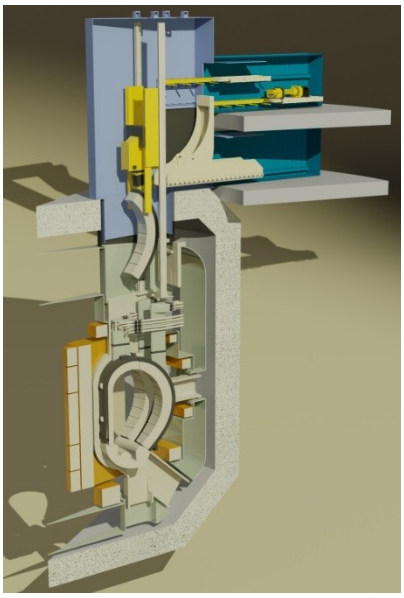
Jonathan Keep[a], Steve Wood[a], Neelam Gupta[a], Matti Coleman[b], Antony Loving[a]
[a]*RACE, UKAEA, Culham Science Centre, Oxfordshire, United Kingdom*
[b]*EUROfusion Consortium, Boltzmannstr.2, Garching 85748, Germany*

As part of the EURO*fusion* DEMO programme, RACE has been developing a set of concept designs for remote maintenance systems. The tritium breeding blankets will require periodic replacement via the upper vertical ports at the top of the vacuum vessel. This operation will be challenging due to the scale of the blankets (~10m tall, and presently assumed to weigh up to 80 tonnes). Concepts have been developed for the blanket replacement process. Analysis of this activity has identified the blanket transporter as a key system, carrying a high technical risk.

The blanket transporter will be required to manoeuvre the blanket segments between the mounts and fixations within the vacuum vessel, and a position that allows vertical lifting through the upper port.

This paper outlines a conceptual study to develop a feasible design for the blanket transporter. Requirements were obtained via functional analysis and CAD based kinematic analysis of the breeder blanket replacement. Concepts for the main kinematic mechanism were then developed. These concepts cover a range of different types of kinematic mechanism, from a conventional series arm to a fully parallel mechanisms and hybrids of these two types. Evaluation lead to down-selection of a concept for further development: A Hybrid Kinematic Mechanism with the first three of its degrees of freedom as a parallel mechanism. The proposed concept demonstrates potential for developing and integrating a number of technologies within the blanket transporter to produce an engineering design that can validate the blanket replacement strategy and hence viability of the DEMO concept.

Keywords: DEMO, Remote maintenance, Breeding blankets, Manipulator



---

author's email: jonathan.keep@ukaea.uk

1. Introduction

Working as part of the EURO*fusion* consortium, UKAEA's remote handling centre: RACE (Remote Applications in Challenging Environments) is currently involved in a project to develop a concept for Remote Maintenance (RM) of a Demonstration Fusion Power Plant (DEMO). DEMO is intended to demonstrate the production of several hundred MW of electricity to the grid and the operation of a closed tritium fuel cycle in the 2050s [1]. Remote Maintenance is one of the key technical challenges that ITER will not be addressing in a way that is relevant to the operation of future fusion power plants; as such, maintenance systems designed for DEMO should be power plant relevant, allowing DEMO to demonstrate suitable availability/reliability over a reasonable time span [1].

Along with enabling an informed, integrated DEMO design, that maximizes plant availability and minimizes downtime for maintenance, there is a need to develop and substantiate remote maintenance concepts to allow replacement of breeding blankets quickly and efficiently.

It is important to note that RM is not achieved solely by the design of suitable tooling, but requires all hardware to be designed to enable remote maintenance. RM design must be incorporated into the definition of maintenance requirements, interface designs and assembly/removal design. RM tooling design must inform system owners of RM capabilities to enable suitable requirements to be incorporated into the system design.

The RM project to date has developed concepts for blanket replacement via a vertical port (see fig 1.) [2-4] and identified several areas of high technical risk.

fig 1. Breeder blanket vertical port maintenance [4]

The Breeder Blanket (BB) segments are currently designed to be maintained via 16-18 vertical ports at the top of the Vacuum Vessel (VV). Each port accesses five blanket segments. The BB segments need to be assembled in the vessel with a small gap between them to minimise neutron streaming and maximise tritium breeding. A gap of 20 mm between segments is presently assumed. The largest segment is approximately 10m tall and is assumed to have a mass of 80 tonnes. At time of maintenance there is an expected gamma radiation dose (based on typical materials required for RM equipment) of around 2 kGy/hr inside the vessel and potentially 2-20 Gy/hr in the port [3]. The expected levels of radiation mean all operations must be remote, both planned and unplanned (i.e. recovery or rescue), and the radiation level constrains the technical solutions.

To achieve the replacement there are a number of activities that need to be completed: gaining access, removal and storage of old blanket, inspection and maintenance of vessel, installation of new blanket and restoring operational readiness of sector. A blanket transporter is required to install and remove the BB segments. This will manoeuvre the BB segments into and out of position in-vessel to a position in the port that enables them to be lifted using a conventional vertical lift.

A technical risk analysis of the DEMO RM [4] highlighted the risks associated with performing complex in-vessel operations. A substantiated design for the blanket transporter hardware is required to provide important requirements to the control system. The nature of the required movements and the scale of the load are far in excess of commercially available conventional manipulation devices [5, 6]. Therefore, a bespoke solution is required. The other systems defined as part of the blanket handling system (e.g. Vertical Transport System, transfer casks, etc.) do not carry the same level of technical risk, in that feasible solutions could be adapted from existing established technologies (for example the vertical lifts could be managed using a 4 rope crane solution). As a result, these systems will not require the same level of substantiation to validate the RM blanket handling concept. Several risks are associated with deflections and blanket transporter packaging size. A substantiated blanket transporter design will allow requirements and functional limits to be fed into the BB and VV design to enable a fully integrated DEMO concept to be developed.

This paper outlines the development of a concept for the blanket transporter, using requirements generated from the EU DEMO 2014 baseline configuration (A = 4, n_{TF} = 16).

The work presented demonstrates the initial systems engineering and research completed to enable a number of concepts to be quickly evaluated. The selected concept was then evaluated further and the paper shows the outcome of the design and analysis carried out to demonstrate feasibility of the mechanism.

2. Breeder blanket replacement

2.1. Design basis

The early stage of the DEMO project means a number of assumptions have been made to allow definition of requirements for the blanket transporter. The DEMO design is continually evolving, and maintaining parity with this compromises the ability to reach a solution for the blanket transporter. Regardless of the DEMO design point, a blanket transporter is likely to be required. This device will be novel due to its size and the nature of manipulation required. Understanding the limits of such a device can both validate the RM strategy and feed requirements into the DEMO design process. The decision was made to decouple from the current DEMO design and assume a fixed tokamak configuration. This enables requirements to be understood and a substantiated design providing proof of principle to be developed.

2.2. Assumptions

The DEMO baseline design that was chosen as the basis for the blanket transporter was initially developed during 2013 and presented in [7]. This tokamak design has an aspect ratio of 4 and incorporates 16 toroidal coils and five BB segments per vertical port. Fig 2. shows the basic layout of the BB segments in the port, and axis orientation. The design was modified to include some RM required changes that allow the BB segments to be removed. These included parallelization of the Centre OutBoard Segment (COBS) and straightening the interface between inboard and outboard BB segments.

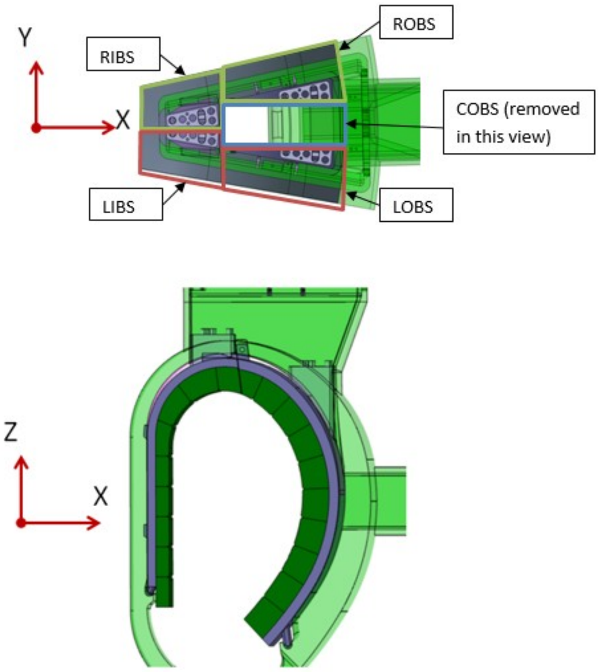


fig 2. Datum axes and BB segment definition

As there are a number of different BB designs currently being considered it was important to establish a fixed mass. Using the basic blanket mass (without coolant or breeding fluids) estimated from the four BB concepts and applying some reserve a conservative assumption for the mass of blankets was assumed: 80 tonnes for the outboard segments and 60 tonnes for the inboard [8]. The modular nature of the design means the distribution of mass is likely to be relatively homogenous so it is assumed that the centre of gravity is at the geometric centre of the BB segments.

Both the BB fixations and the interface for the blanket transporter have yet to be fully defined. The fixations are assumed to allow release and installation of the BB segments using a single transporter installed to the upper port. Similarly, it is assumed that the transporter interface design can be incorporated into the BB segments.

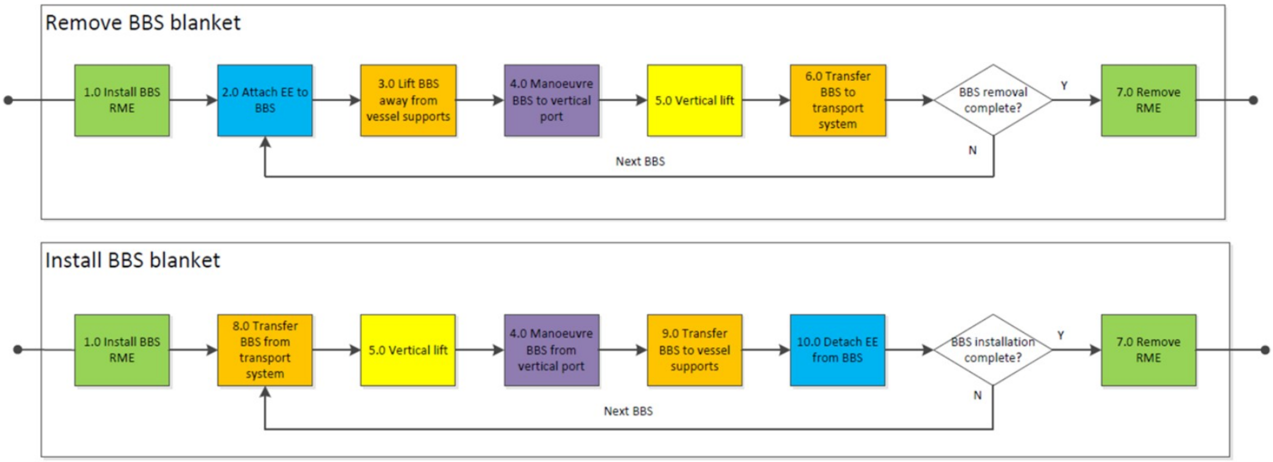


fig 3. Blanket replacement activity diagrams

The blanket transporter will only be used to manoeuvre the BB segments, all other required operations to allow access and release of BB segments will have been completed. Specifically: any upper port closures or doors have been removed; any other obstructing hardware has been removed; all service connections have been disconnected and hardware removed; and any fixations have been released.

2.3. Functional analysis

The basic purpose of the blanket transporter is to manoeuvre the BB segments between their installation blanket inside the VV and a position in the upper port that allows them to be lifted vertically. To fully define the problem and hence derive a thorough set of requirements it is important to understand the nature of the activities that need to be performed as part of the blanket removal and installation. Fig 3. shows the installation and removal activity diagrams that were used to allow functional analysis of the blanket replacement. These were further broken down into sub activities.

With an outline of the functions that have to be achieved it is then possible to define the key elements of the system. Figs 4. and 5. show system diagrams of the overall blanket handling system and blanket transporter, respectively. With the key systems defined it is possible to attribute functions to system elements, and hence derive the functional requirements for the system and sub-system items.

2.4. Breeder blanket kinematics

It is clear that the kinematic mechanism will be the design driving system within the blanket transporter. Many RM operations for JET were defined after the RM tooling already existed. a result, the kinematics for installation or removal of a component were based on the tool Degrees of Freedom (DoF) available, or extra extensions or modifications would need to be defined [9]. In this case, the kinematics will be designed to suit the manoeuvres required to extract and replace the blankets.

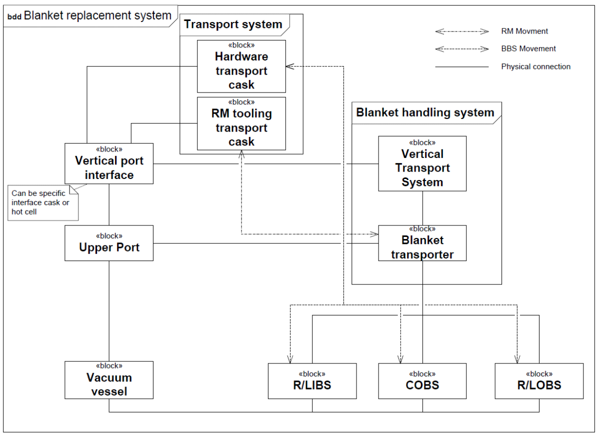


fig 4. Blanket handling system

A key requirement is to manoeuvre the blankets to a position that enables a simple vertical lift. The total range of motion of the blanket transporter will be defined by the kinematics so it is important to keep any complex kinematics as low in the VV or upper port as possible. This constraint minimizes the range of vertical motion required. An increase in vertical range increases the moment required by the transporter mechanism when it is reaching the extreme of its movement envelope to collect the BB.

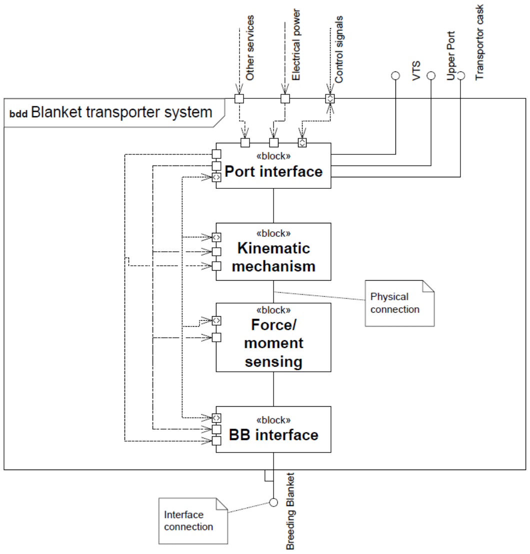


fig 5. Blanket transporter system

The kinematics for each segment were fully defined using CATIA, with a path generated and animated to enable evaluation of clearances during manoeuvres. Fig 6. shows the steps required to remove the LIBS. While the neighbouring IB segment is hidden for clarity, the challenge of the IB segment removal is negotiating around this neighbouring segment.

Further to the basic kinematics for the segments it is clear that there are a number of extra movements that must be considered for any transporter design. These are:

- Motion to release any stiction between BB and any fixations.
- Engagement of interface into BB.
- Corrective motion required both during manoeuvres and achieving installation location into VV.
- Motion to transfer BB to transport cask or equivalent to enable transfer to maintenance area.

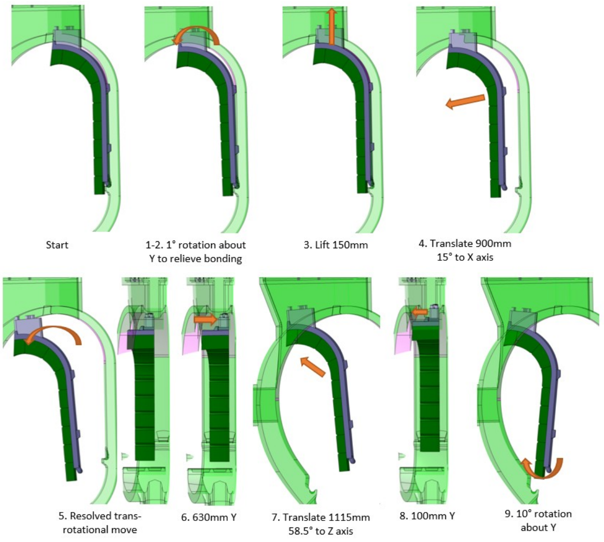


fig 6. Kinematic sequence to remove LIBS

3. Mechanism technologies

Manipulator mechanisms can be divided into two categories: serial and parallel mechanisms [10]. A serial manipulator's structure does not form a loop chain whereas a parallel manipulator does. Both have advantages and disadvantages associated with the motion and work area available against load capability. There is a further category – a hybrid kinematic manipulator. This combines both serial and parallel mechanisms, often providing a compromise between the two solutions.

Joint designs can also be divided into prismatic (i.e. linear sliding movements) and revolute (i.e. rotational) joints. A multi DoF manipulator will use a combination of several types of joints to produce the kinematics required.

Most commonly found manipulators tend to be Serial Kinematic Mechanisms (SKM). Manipulators such as those from Kuka [5] and ABB [6] combine a set of rotational joints to provide access to a very large working area. The JET articulating transporters are also SKM [9]. These can be used accurately with carefully designed control system, but ultimately increasing the numbers of degrees of freedom has a direct impact on the overall stiffness of the manipulator.

Parallel Kinematic Mechanisms (PKM) were originally conceived around the 1930s [11] and eventually found their use in hexapod based devices, including the Dunlop universal tyre test machine [12] and subsequently flight simulators [13,14] The hexapod design offers 6 DoF in a relatively short package space, but the size of the moving platform tends to be large relative to the working space. In the mid-1980s two key designs were patented: The Tricept [15] – see fig 7, and the delta [16]. Both designs saw development and implementation into industrial products. The delta robot is mostly used as a pick and place device and as the basis for 3D printers. This lightweight mechanism offers a good level of versatility within the operating range, but the working range can be compromised by the scale and orientation of the drive arms.

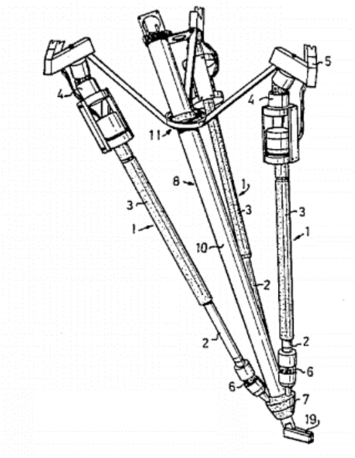


fig 7. Tricept mechanism [15]

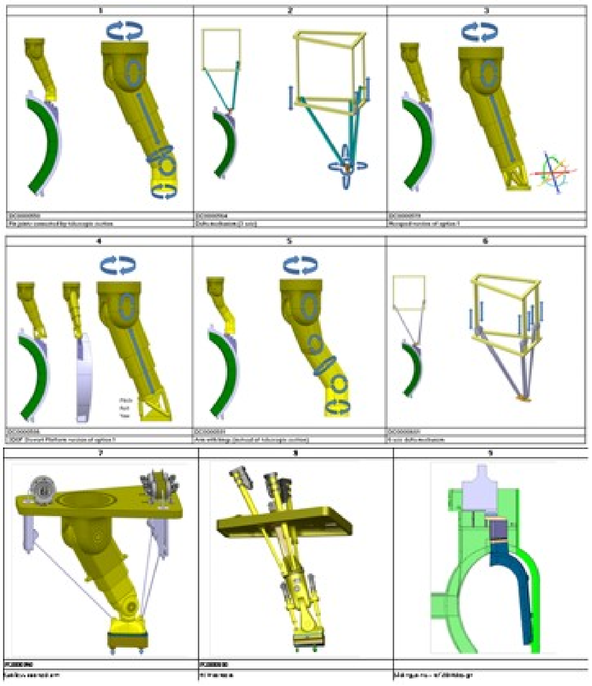
Tricept mechanisms have been developed into both manipulators and multi-axis machining centres that have been used in both aerospace and automotive production environments.

4. Concept studies

A number of mechanism concepts were studied, both SKM and PKM options, as shown in fig 8. These were modelled in CATIA and then, using the blanket kinematic models, the mechanism was evaluated through the ranges of motion required. This enabled a quick evaluation of the mechanisms and identification of limiting factors on each design. An analytic hierarchical process was used to evaluate the mechanism designs. The process scored each idea against a set of criteria. Weightings were applied to each criteria and the final score for each idea is shown in Table 1. The Hybrid Kinematic Mechanism was selected for further development.

4.1. Outline of mechanism

The blanket transporter mechanism design can be seen in fig 9. The HKM comprises of three linear actuators (T1-3) attached around a central prismatic column. The base of each of these has a gimbal arrangement built into the port interface plate that



Rank	Concept	Weighted total
1	HKM concept	4.5
2	SKM 6 DoF telescopic arm	3.3
3	6 DoF delta mechanism	3.2
4	Sliding joints - ref 2014 design	3.1
5	Cable supported arm	3.1
6	Telescopic arm with 3DOF Stewart Platform	3.0
7	Delta mechanism (3 DoF) with 3DoF end effector	3.0
8	6 DoF Arm with hinge	3.0
9	Telescopic arm with hexapod	2.6

fig 8. Kinematic mechanism concepts

Table 1. Mechanism evaluation

enables free x-y rotation, but prevents rotation about the axis of the actuator/slide. By increasing or decreasing the length of the three actuators the position of the HKM can be varied. The central column provides support against any torque resulting from any load away from the axis of the column.

Below the parallel section of the mechanism, three further joints in a series configuration create an extended ‘wrist’. Joint C is a revolute joint that rotates about the axis of the central column. Finally joints A and B provide x-y rotation via two perpendicular joints. This design is intentionally slender to ensure the mechanism can reach into the corners of the vertical port and access the BBs.

The port interface plate at the top of the mechanism is designed as a rigid frame that can transmit the reaction loads from BB manoeuvres directly to the port. This features an open frame design that can allow access for rescue or recovery purposes, with closing plates anticipated to allow some level of shielding for the mechanism.

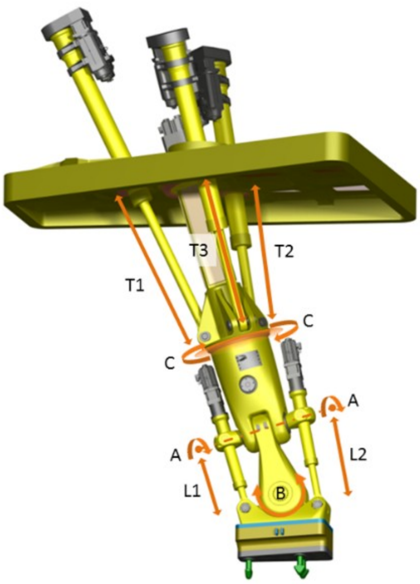


fig 9. Hybrid Kinematic Mechanism

4.2. Analysis

The initial analysis looked at the static load applied to the transporter, from the BB payload, at each position through the kinematic sequences for ROBS and LIBS. The positions that produced the peak load to the transporter were obtained and the final analysis work focused on these specific positions. In both cases the installed position is one of the peak load cases. The analysis model was positioned for each peak case and the assessment was carried out based on the static support of the blanket mass. Fig 10 shows the basic setup of the load conditions for the ROBS at the installed position.

Fig 10 Static analysis of ROBS at installed position

The structural assessment demonstrated maximum stresses within the structure of up to 124 MPa, well within the allowable limit for structural steel (stainless steel 316L) of 220 MPa. Furthermore, the model was setup to output the loads in each joint of the mechanism. This gives an initial set of load requirements both for supporting bearings and actuation of each joint. Bearings and actuator technologies were identified and further CAD based assembly engineering was carried out to ensure that these components would fit into the packaging space required, and a feasible assembly method existed.

An initial assessment of the impact of seismic events was carried out based on the ITER SL2 criteria [17]. The resultant behaviour showed significant movement in the blanket (up to 800 mm). The stress levels were high relative to normal operation (~200 MPa) but still below expected material limits. The biggest concern is that with up to 800 mm deformations seen, collisions of the blanket with in-vessel elements are very likely. Further work will need to be done to both validate these findings, assess potential collision scenarios, and investigate mitigating actions.

An initial modal analysis was performed as input to the seismic study and this highlighted one of the key expected problems for the transporter. The first five modes are all below 10 Hz. Avoiding exciting these would require a very slow movement speed. This problem was anticipated – the port size leads to a mechanism that is not as stiff as would be normally expected. Understanding the resulting dynamic problems and devising methods to predict and control these will be key reaching a working transporter

4.3. Concept Design Review

The mechanism has been reviewed both by representatives across the EURO*fusion* DEMO project team, featuring representatives from the RM team and interfacing work packages [18]. In parallel, the mechanism was also reviewed by Assystem UK ltd. Feedback has been used to identify further risks and work required to mitigate these.

5. Further work

As identified in section 4.2 the low stiffness and high payload will lead to dynamic problems. Understanding the nature of these problems will enable optimization the control, mechanisms, and kinematic path to allow the BB segments to be manoeuvred. There are three elements required to solve this problem: a model to simulate the dynamic behaviour; a control system capable of adapting its response based on both real and simulated feedback; a mechanism featuring actuators capable of providing the response required to mitigate the dynamic problem.

Full consideration will need to be given to the nuclear safety case for this device. Lifting the BB segment through the vertical port will lead to a large nuclear load being lifted over 30m above ground. This is clearly an unacceptably high risk and consideration needs to be made to mitigating this risk with suitable break fall devices.

Similarly rescue and recovery will require deeper analysis. The initial design features two motors for the drive of most of the actuators, to allow redundancy and all drives have been designed to enable either replacement or external input to allow for a recovery procedure using an external remote device. Further consideration of rescue and recovery scenarios is required to ensure that the possibility of an unrecoverable failure is acceptably minimised.

This design will need a substantial level of validation through physical testing. Complex manipulation of loads of this scale is novel. The work to understand, simulate and control the dynamic problems associated with this will be initially based on a number of assumptions associated with complex non-linear effects (e.g. bearing clearance and stiffness, assembly clearances, friction). This will require both sub system and proof or principle testing to validate the approach, and ultimately large scale mock up tests that properly represent the mass and stiffness (and hence dynamics) of the expected BB segments. Achieving nuclear safety requirements will require significant testing both for basic functionality and load capability but also accelerated life testing to validate the durability of the mechanism.

6. Conclusions

Manoeuvre of BB segments for replacement will be challenging. Many of the decisions both in previous studies [2-4] and within this work are driven by the effort to minimize modifications to the magnet configuration and vessel design whilst achieving quick and efficient BB exchange, demonstrating a powerplant relevant level of plant availability. Whilst this design has been based on an assumed BB and vessel design, it is clear from the requirements on port size and expected BB configuration that a blanket transporter mechanism that is capable of performing complex manoeuvres with large loads will be required.

A Hybrid Kinematic Mechanism has been presented that demonstrates basic mechanical feasibility with simple structural analysis. There is a significant level of further work required to reach an acceptable design and resolving the expected dynamic problems will be critical, and will require an integrated approach using novel simulation, control and hardware design.

Acknowledgments

This work has been carried out within the framework of the EURO*fusion* Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/I501045]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission. We would also like to thank Assystem UK ltd for their contribution to this work.

References

[1] G. Federici et. al., Overview of the design approach and prioritization of R&D activities towards an EU DEMO, Fusion Engineering and Design, 109-111, Part B (2016) 1464-1474.

[1] M. Coleman et. al., Concept for a vertical maintenance remote handling system for multi module blanket segments in DEMO, Fusion Engineering and Design 89 (2014) 2347-2351.

[2] A. Loving et al., Pre-conceptual design assessment of DEMO remote maintenance, Fusion Engineering and Design 89 (2014) 2246-2250.

[3] O. Crofts et al., Overview of progress on the European DEMO remote maintenance strategy, Fusion Engineering and Design 109-111 part B (2016) 1392-1398.

[4] Kuka Robotics 1000 Titan – 1000kg manipulators - http://www.kuka-robotics.com/united_kingdom/en/products/industrial_robots/heavy/kr1000_titan/start.htm

[5] ABB IRB 8700 – 1000kg manipulator - http://new.abb.com/products/robotics/industrial-robots/irb-8700

[6] G. Federici et. al., Overview of EU DEMO design and R&D activities, Fusion Engineering and Design 89 (2014) 882-889.

[7] D. Iglesias, Blanket handling assessment, EFDA_D_2HD4JD.

[8] B. Haist et al., Remote handling preparations for JET EP2 shutdown, Fusion Engineering and Design 84 (2009) 875-879.

[9] R.N. Jazar, Theory of applied robotics, 2nd ed 2010, Springer Science & Business media, p8.

[10] W.L.V. Pollard, Position controlling apparatus, Patent number US2286571.

[11] V.E. Gough and S.G. Whitehall, Universal tyre test machine, Proceedings of the FISTA Ninth international technical congress, p117-137.

[12] D. Stewart, A platform with six degrees of freedom, Proceedings IMechE Vol 180, Pt1 No 15.

[13] K. Cappel, Motion Simulator, Patent number US3295224.

[14] K. Neumann, Robot, Patent number US4732525.

[15] R. Clavel, Device of movement and positioning of an element in space, Patent number US4976582.

[16] G. Mazzone et al., Seismic design of the ITER main Tokamak components, Fusion Engineering and Design 86, issues 9-11 (2011) 1984-1988.

[17] S. Budden, Blanket transporter CDR, EFDA_D_2MVXC3.