WPRM-CPR(17) 17291

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Towards controlling flexible deforming manipulators/structures with limited available sensing in DEMO

Preprint of Paper to be submitted for publication in Proceeding of 13th International Symposium on Fusion Nuclear Technology (ISFNT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Controlling flexible deforming remote manipulators and structures in DEMO with limited sensors

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EU DEMO's scale pushes remote handling technologies to their extremes. In particular, remote manipulation in DEMO requires extraordinary precision requirements for under-actuated, degrading, flexible manipulators with highly-flexible, deforming payloads/structures, where flexibility leads to significant deformation at higher modes of vibration that will need to be controlled. This is further complicated by the limitations on sensors that will work DEMO's extreme environment, which precludes the more traditional control techniques for a problem of this type. This paper will outline the remarkable peculiarities in the scenarios that DEMO poses. A short survey into the currently available techniques for control of flexible manipulators and payloads, summarizing the current field in this area will follow. Finally, the proposed methods for control shall be presented, with the aim to discuss the feasibility of controlling such remote handling equipment in a timely and cost effective fashion. This includes investigation and comparison of intelligent and cutting edge control techniques applied in simulations, and a novel control technique which uses an online learning neural network control method for slow dynamics and an adapted prescribed performance control for vibration reduction.

Keywords: Flexible Manipulator, Remote Handling, DEMO, Intelligent Control.

1. Introduction

The DEMO Remote Maintenance System (RMS) functional requirements and working conditions are extremely demanding [1]. The operational complexity, very high payloads, elevated temperatures and gamma radiation, limited feedback and sensing, along with very tight working clearances, produce a mix that no present robotic technology can solve simultaneously.

In the current design of the in-vessel RMS, blanket segment maintenance represents one of the most challenging tasks overall. The weight of the segments can be as high as 80 ton[1] [2, 3] with temperatures over 100 ^{o}C [4], contact dose levels up to 2kGy/h [4], and some level of magnetization of the Eurofer steel. The in-vessel handling of those massive components shall be achieved with clearances of just 20mm [2], with very limited feedback.

Within each torus segment, the blanket layer is split into five multi module segments (MMS): two in-board segments (IBS); and three out-board segments (OBS) (*Error: Reference source not found*), based on the original Vertical maintenance system layout [2]. This segmentation was designed to allow all MMS to be extracted for a minimal vertical port size. The number of MMS was minimised, in order to minimise maintenance time and the number of service connections to be made in-vessel. It is important to note that: 1) the available space on the vertically accessible surface of the MMS for service connections, support features and RH interfaces is severely limited; 2) the centre of gravities (CoGs) of the MMS are generally not located within the bounds of the vertical port. The latter issue precludes the use of a simple cable lift arrangement due to a large overturning moment from the off-centre CoG and small clearances.

Each MMS is extracted and replaced through the upper port, requiring it to be manipulated in-vessel and positioned below the port such that it may be lifted vertically. Given the layout of the MMS within the port, this results in the need for them to be extracted and replaced in a specific order; starting with the out-board MMS (central, then left and right), then the in-board MMS, one after the other. The most complex manipulation is for the first in-board segment extracted, as it must clear the remaining in-board segment as well as be translated outwards and downwards. The kinematic operations for each segment differ. A 40mm toroidal gap was left between the OB MMS, and 25 mm for the IB MMS, to facilitate extraction [4].

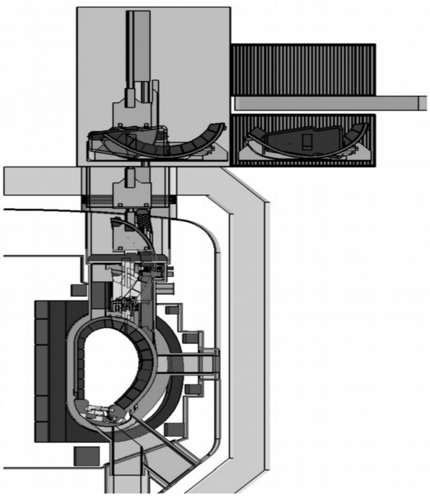

Figure **1***: COBS* removal *and storage.*

All of these blankets must be removed using the same manipulator and control system. What follows is a short introduction into the control problem, a short survey into the currently available techniques for control of flexible manipulators and payloads, summarizing the current field in this area will then follow; followed by the proposed methods for control shall be presented, with the aim to discuss the feasibility of controlling such a remote handling equipment in a timely and cost effective fashion; finally, a short conclusion is drawn.

2. Control Problem

[1] *Ignoring any residual liquid lithium-lead, which would significantly increase the weight and complexity of handling.*

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The environment and other factors will be highly challenging from a maintenance perspective, the main points of issue are as follows:

- **Radiation**

The cool down period for maintenance on DEMOs reactor blankets is one month. At one month, the predicted radiation levels in the upper port are 3.5Gy/h and in the lower port about 80Gy/h [28].

- **Temperatures**

The temperature in the pipes will be connected to the decay heating temperature of the blanket. The blanket is expected to be about 200°C after a month of cool down and the inside of the pipes through convection and radiation will also be at a similar temperature. Firm data must still be obtained regarding this, but assuming temperatures of 200°C for the cutting process the tool will require active cooling for deployment

- **Magnetic Field**

There is predicted residual magnetic field of up to 0.1 Tesla from the plasma containment coils. It is also predicted that these shall not static magnetic fields.

- **Access Restriction**

In the current maintenance scenario, there are many pipes built into the port closure flange and therefore once the flange is in place and the port is sealed the exterior of these pipes will be inaccessible. This results in most pipe operations during maintenance and repair in the ports being done in-bore. The clearance allowed for blanket module removal is 20mm. It is notable, that the blanket is held at the top point, and the blanket modules are approximately 15m tall. Thus, a 0.0764° deflection would result in a collision, assuming that the payload is rigid (which they are not).

- **Payload deformation**

The static payloads deformation under gravity is currently predicted to be up to 22mm. However, this deformation shall be inevitably affected by the state of the deterioration of the payload, variations in the manufacturing, the current varying temperature, and the localised temperature extrema. It also doesn't consider the manipulator linkage and joint deflection. It may be affected by moving through the magnetic fields present in the vessel. Additionally, a factor in the deflection of payloads is moving CoG during the exit motion. Furthermore, the Payload will suffer deformation from vibrations. These vibrations will exist with several modes, under such extreme requirements the payload could experience payload vibrations such that higher-order modes (7th mode) and all the lower modes could cause amplitudes that extend beyond the clearance window. However, the exact nature of this issue is currently unknown.

A simplified 2-dimensional version of an MMS blanket segment can be modelled using Euler-Bernoulli equations applied to a curvilinear shape, inspired by the work of [26]. The results demonstrate the chaotic behaviours of the DEMO-like blanket section, particularly demonstrating its sensitivity to initial conditions, and the rapid change in oscillation frequency, even in a simplified 2D model. These characteristics make it hard to model the system with high accuracy for long periods of time. Although detailed hypotheses of motions could be made and used for control, such a method would be novel and would require adequate testing. It is worth noting that on the translations of these mathematical models to 3D, the complexity will only increase. For the outer OBS, twist will be a major constituent in the oscillations of the blankets. This added complexity may damp the strange behaviour demonstrated in the supplementary study; or it might accentuate it, whilst adding its own peculiarities. However, it is highly probable the traditional (adequately computationally efficient) methods for model based control would be implausible. Therefore, non-model-based control of a blanket should be investigated.

- **Manipulator deformation**

Although, the exact type of manipulator that will be used for the task is unknown; what is known, the manipulator must operate in extreme conditions, acting on different payloads of extreme mass. Moreover, the space constraints on the manipulator will require the arm to be highly compact, possibly to the point of under-actuation. This will cause deformation of the link and joint of the manipulator. It shall also cause complex vibrational behaviour in the manipulator during motion [29,30].

- **Deterioration**

During the course of DEMO operations, the Payload and Manipulator will deteriorate due to the extreme environment factor such as neutron exposure and extreme temperature variations. This shall affect the dynamics of it deformation and vibrations. The nature of the deterioration will be hard to predict and will seriously effect physical parameters (e.g. stiffness).

- **Sensor limitations**

The vessel is extremely unfriendly to sensors. In particular, the radiation and temperature is extremely deleterious to the sensors. The sensor shall inevitably deteriorate over time. This shall lead to an increase in the measurement uncertainty. There also exists the possibility that sensors shall fail entirely or enter fault states. Moreover, there shall be limited access for sensors; i.e. sensors may not be attachable to the payload and sensors may not be insert-able into the hollow of the vessel. Furthermore, the sensors that are usable in this environment may be limited; i.e. LIDAR may not usable in the environment. However, the available sensors are subject to change over the development cycle of DEMO [27].

- **Safety Requirements**

Being a nuclear facility there are some very strict safety requirements for the control system. Primarily, there can be no situation where the Payload is dropped, or can be no longer retrieved. To extend this issue, there exists the requirement to survive a seismic event. In particular, a seismic event that would cause 3g's of lateral force on the payload during free-motion transit.

- **Other limitations**

The development cycle for DEMO is in the scale of decades; therefore, hardware specification probably will evolve. Therefore, the control system should be somewhat hardware agnostic. The complexity of model required to model the system, may be prohibitively complex to run in

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real-time. Even reduced model may prove prohibitive complex. For example, the current estimates for a front-running predictive model candidate, the Structural Simulator expect an update rate of approximately 2Hz [3]. Finally, possibly the most important consideration is speed, as for DEMO to be cost effective its down time must be as short as possible. This means that the blanket must be removed quickly.

3. Flexible Manipulators

Flexible robots have been of research interests across many engineering disciplines, and the study of flexible manipulators are of on-going research interest for researchers worldwide since the 1970's. Although this research area has received reduced attentions now due to many satisfactory results obtained, but newer applications and latest technological advancements made researchers to attend to those remaining open problems which were too complex to solve. Generally, research is focused on for flexible manipulators for the interesting properties such as higher bandwidths; whereas the DEMO problem is restricted to Flexible manipulators out of necessity. As with most control strategies, flexible control algorithms can be categorized into Model-based and non-model-based. Only Non-model-based control techniques shall be investigated as they can deal with the complexities such as degradation, unknown manipulator type and design, and the possible complexity of the model, which are particular to the DEMO problem. A brief survey of Non-model-based Control techniques which are outlined in Table 1.

Table **1**: *Non-model-based Control techniques.*

Non-model-based Control techniques	***Example***
Positive/Negative Position Feedback	[5,6]
End-point acceleration	[7]
Linear velocity feedback	[8]
PID	[9]
Repetitive	[10]
Direct Strain Feedback	[11]
Fractional order	[12]
Singular perturbations	[13]
Generalised proportional integrator	[14]
Integral resonant control	[15]
inner/outer loop	[16]
two-time scales	[17]
sliding mode	[18]
robust	[19]
adaptive	[20]
Neural networks	[21]
Fuzzy logic	[22]
Prescribed performance	[23]

The methods that are being proposed for application in blanket removal in ITER the preliminary plant being developed before DEMO are discussed. In [24], a proposed method for vibration control with the proposed application of ITER blanket removal. Presented is a robust vibration control for a flexible inspection arm moving in an unknown environment. Its particularity is to entail a vibration estimator that reconstructs the vibrations from visual data without any a priori knowledge of the surroundings. To that purpose, a robust tracker based on the KLT algorithm feeds a two-time-scale Kalman filter in which a part of the measurements is delayed. Moreover, the issue of Image Jacobian on-line estimation has been assessed and an adaptive method is proposed to ensure both stability and sensibility of the estimation whatever the camera velocity may be. Similarly, in [25], a Vision-based online vibration estimation of the in-vessel inspection flexible robot for application in ITER. This paper proposed a vision-based method for online vibration estimation of a flexible manipulator, which is achieved by utilizing the environment image information from the end-effector camera to estimate its vibration. Short-time Fourier Transformation with adaptive window length method is used to estimate vibration parameters of non-stationary vibration signals. Both methods manage stable and estimation error quickly, but suffer from high error in the first oscillation.

4. Proposed Solution

To continue development without being limited unnecessary over-complication in this early concept phase, a simplified scenario is required. For this purpose, a two-link flexible manipulator is used. A two-link flexible manipulator is a two-link manipulator with flexible joints, which is a more complex version of the traditional Double Pendulum. The added complexity makes the model sufficiently detailed to act as representative control problem. Controlling flexible link manipulators is difficult because discretization of the partial differential equations describing the coupled rigid and flexible motions gives rise to dynamical systems of high order. In addition, the system is underactuated because the number of available control inputs is less than the number of degrees of freedom. This difficulty is accentuated in the case where both the links and joints are flexible since the actuating torque for each link then must control the flexure of both the link and its corresponding joint.

Non-model-based control techniques have been investigated to deal with the complexities such as degradation, unknown manipulator type and design, and the possible complexity of the model, which are particular to the DEMO problem.

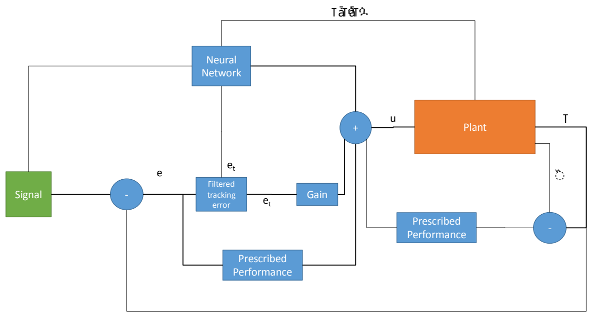

Figure 2: NN+PP Control with PP oscillation reduction control.

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For this purpose, we investigate a linear combination of: Prescribed performance (Cascaded and otherwise) [23], Adaptive neural networks [21], and PD controllers.

In the case of a manipulator with many flexible links and joints, the dynamic equations involve a set of highly nonlinear and coupled partial differential equations, thus posing a difficult control problem compared to a simple single flexible arm. A neural network based controller is likely to perform better than an inverse dynamics scheme in controlling the slow dynamics since it does not require exact knowledge of either the system dynamics or the inverse dynamic model evaluation. Furthermore, it guarantees boundedness in the tracking errors and control signals [21].

The Prescribed Performance augments the control scheme with the aim of reducing the steady state error and backlash. Prescribed Performance whilst offering hyper-stability has unrealistic expectation when it comes to practical control. Namely, infinite allowable torque and bandwidth, if smoothness is required to guarantee stability. It also does not cope with saturation or discretized time steps. To mitigate these issue, we propose using Prescribed Performance to only augment existing control techniques, thus getting most of the benefits whilst be practically usable. The Prescribed Performance enhances the control scheme with the aim of reducing oscillations that occur between the motor and link because of the flexibility. It worth noting that the Neural net has been set to run at 50Hz, the first prescribed performance has been set to run at 100Hz, and the final prescribed performance has been set to run at 200Hz.

5. Testing & Results

The testing has been implemented in Simulink using the standard toolboxes. This allowed rapid development and detailed simulations. The implementation has been designed to fit the large mass and scale problem that DEMO poses. For this reason, the simulated manipulator is 5m at full extension, and weighs 2000kg. This clearly leads to very large momentum values that is analogous to the DEMO problem. The high stiffness is considered as 200GPa (steel), and low stiffness as 4GPa (Nylon). Damping is considered at a low range of 10. White noise is added at 5%

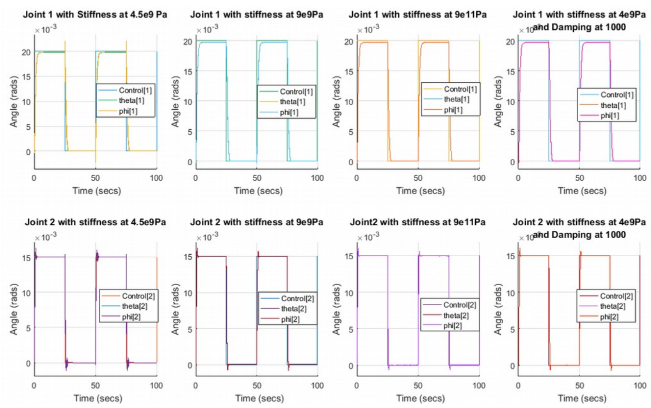

Figure 3: Flexible Joint Neural Network and Prescribed Performance Control with Prescribed Performance Joint-Motor error rectification, on a large range of stiffnesses without retuning.

Table 2: Joint 2 results to a step wave of 15 and 20 mrads respectively.

Joint2 Stiffness and damping	***4.5GPa / 10***	***9GPa / 10***	***900GPa / 10***	***4GPa / 1000***
Rise time (s)	1.2	3.1	1.1	2.5
Overshoot (%)	4.3	2.9	2.8	3.0

As can be seen in Figure 3, the algorithm with no additional parameter tuning is both resilient to vastly changing stiffness and damping values, whilst also keeping response time in a period <5seconds. Without the secondary motor rectification, prescribed performance loop, the primary prescribed performance works with the impractical assumption of infinite bandwidth on the motor. This results in a 3% output variation at ~30Hz as the motor attempts to stabilize the system. This for the payload size is unmanageable and wear the system would far greater than desired. If this noise is removed directly, the system becomes unstable within the first second. However, the secondary prescribed performance serves to stabilize and smooth the more eccentric behaviors in the first, as can be seen Figure 3.

6. Discussion & Conclusion

Figure 4 shows that the Neural Network and Prescribed Performance Control with Prescribed Performance Joint-Motor error rectification is resilient to change in parameters (such as stiffness and damping) for a large range of values, without retuning. This maps well to being resilient degradation of hardware. This is achieved by having the highly adaptive, non-model-based prescribed performance control methods integrated with a run-time learning Neural Network, this leads to a control scheme that is resilient to degradation, noise, flexibility, and change of manipulator. The fact that the control scheme is also joint-based means that is very applicable to more complex manipulators.

The largest issue for control in the DEMO RMS is the flexibility, degradation, and evolving manipulator designs, this requires a non-model-based highly flexible manipulator controller that is resilient degradation and agnostic to arm design (as much as possible). In the above work, a control method (Neural Network and Prescribed Performance Control with Prescribed Performance Joint-Motor error rectification control algorithm) has been proposed that fulfils these criteria on a simulation analogous to the possible DEMO RMS. However, it would need to be tested to see if it would perform well with more degrees of freedom, although is not linked to the number of joints it merits investigation. It also needs validation as to whether the control method would work on hardware. It is worth noting that consideration of practicability has been demonstrated throughout the simulated results.

Future work will focus on: Neural network and deep reinforcement learning techniques as these can model complex non-linear control problems generically; Off-manipulator visual servoing; and sensor fusion for fusion RMS.

Acknowledgments

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This work has been carried out within the framework of the EUROfusion 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]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Joints for Use in DEMO. Presented at SOFE 2017. To be published in IEEE Transactions on Plasma Science

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