EUROfusion
TECHNOLOGY TRANSFER PROGRAMME

Modelling and vibration control of flexible mechanical systems for remote maintenance

Remote handling of heavy in-vessel components inside nuclear fusion reactors requires the use of large robotic systems that are subject to large deformation, either induced by the geometric configuration of their mechanical structure or by the heavy payloads they usually transport. In this context, the modelling and vibration control of flexible mechanical systems aims at developing simulation tools to accurately predict the motion of flexible mechanical systems for analysis, planning and control purpose, crucial for reducing the need for full-scale mock-ups of remote operations. The approach already validated in the fusion sector can be extended to other application domains outside fusion where accurate modelling or remote handling systems is required.

Description of the technology

A typical set-up in DEMO remote maintenance is represented by a large-scale robotic system handling a heavy mechanical in-vessel component. In this scenario, flexibility arises from both sides, the manipulator, and the payload. In order to plan safe and collision-free remote autonomous operations, methods to accurately predict the nonlinear behaviour of such flexible mechanical systems are highly required.
To simulate the dynamics of large flexible manipulators, many mathematical models have been introduced and adopted such as: limped parameters models, assumed mode models, transfer matrix models. All of them assume linear elasticity, small deflections, light damping, and rotational motion of modest angular rate and are usually suited only for serial manipulators with revolute joints. Their main problem is due to the computational complexity which makes difficult the use of finite elements in a control-oriented framework.
A screw-theory finite element method is the alternative solution for accurate and computationally efficient simulation of flexible mechanical systems. The screw-based dynamic model could be numerically solved by using geometric time integrators, which might significantly speed up the numerical computation of the equations of motion.

A generic flexible mechanical system is considered to be composed by rigid and/or flexible bodies connected through rigid and/or flexible joints. Due to the fact that robotic manipulators are usually constituted by mechanical links in which one dimension is predominant over the two others, the flexible bodies are modelled as beams with nonlinear geometric behaviour. The effects of the joints connecting the bodies could be taken into account by imposing a set of algebraic constraints, which prevent the non-allowed motion.

The modelling approach shows an average accuracy below 5% with respect to benchmark from the literature. The method has been applied for dynamic modelling and simulation of the fusion related use case: the Hybrid Kinematic Mechanism (HKM), a serial-parallel large manipulator which is the proposal for installation and replacement of breeder blanket segments for DEMO.
The HKM allows the installation and replacement of the inboard and outboard blanket segments through the vertical upper port of the vessel. Its topology is hybrid, and it includes a parallel and a serial kinematic structure.

The simulation method predicts the dynamics of the HKM while performing the sequence of manoeuvres which have been planned for the removal of the outboard blanket segment (OBS) and inboard blanket segment (IBS). The two sequences of manoeuvres translate into two sequences of point-to-point motions. Each joint of the manipulator moves from an initial to a final configuration through a sequence of points so as to guarantee a correct blanket removal. In particular, for the OBS removal, six manoeuvres have been planned; for the IBS removal, nine manoeuvres have been planned. The solution selected a test joint trajectory algorithm and simulated the displacements of the manipulator tip as well as the reaction forces at the boundaries, as resulted from the simulations using two modelling assumptions.

Regarding the vibration control, in these field of activities, an accurate motion of flexible mechanical systems is a challenging control problem, since it might result in high levels of vibrations. In the context of DEMO remote maintenance, generating motion profiles for the flexible mechanical systems wherein the motion cancels the incipient oscillation that had been created by earlier motions would be highly desirable.

Command shaping methods convolve the reference command of a FMS with a sequence of m impulses, whose timing locations t_i, i = 1, ..., m and amplitude A_i, i = 1, ..., m are computed by solving a set of constraint equations. In order to ensure that the shaped command produces the same motion of the unshaped command, it must be guaranteed that the impulse amplitudes sum to one as $\sum_{i=1}^{n} A_i = 1$.

Modelling and vibration control of flexible mechanical systems for remote maintenance

Remote handling of heavy in-vessel components inside nuclear fusion reactors requires the use of large robotic systems that are subject to large deformation, either induced by the geometric configuration of their mechanical structure or by the heavy payloads they usually transport. In this context, the modelling and vibration control of flexible mechanical systems aims at developing simulation tools to accurately predict the motion of flexible mechanical systems for analysis, planning and control purpose, crucial for reducing the need for full-scale mock-ups of remote operations. The approach already validated in the fusion sector can be extended to other application domains outside fusion where accurate modelling or remote handling systems is required.

Whether an analytical expression of the vibrations induced by a train of impulses on a flexible mechanical system exists one can force this expression to be less than or equal to a certain tolerable value, in the frequency range in which the system operates. When multiple output impulses are added in the shaping process, the robustness of the method is enhanced.
The simulation architecture is composed in three main modules: planner, controller and solver engine. An input file is used for the pre-processing phase, while an output file post-processes the results of the simulation.

Input file

The simulation input file specifies the model data, features and parameters in a non-engine format. It specifies:

- Geometry of the mechanical system in terms of nodes of the model
- Mechanical system behaviour, in terms of rigid and flexible bodies. A rigid body is defined by its inertia properties; a flexible body is defined by its initial and final node, as well as the mass and stiffness matrices of its cross-section
- Kinematic joints: rigid constraint, revolute, prismatic, screw, cylindrical, planar, universal, and spherical joints
- Actuations, in terms of motion of forces laws on joints
- Boundary conditions
- Solving parameters

Planner

The planning module contains a set of trajectory primitives to generate motion through sequences of path points.

Controller

The control system module provides a set of algorithms for accurate vibration control of flexible systems. It contains the implementation of classic and advanced command shaping techniques.

Solver engine

The solver engine is responsible of computing the equations of motion of the model given in the Input file, along the trajectories defined in the Planner and using the control algorithms defined by the Controller module. It provides both rigid and flexible multibody dynamics capabilities. A geometric finite element approach involving helicoidal shape functions is used to discretize the flexible bodies as one-dimensional elements. The material model is the isotropic elastic Hooke model. Static and implicit-dynamics integrators are provided.

Output File

The Output file contains kinematic data as positions, velocities and accelerations of the nodes of the model, as well as stresses and strains of the flexible elements, reaction forces at the boundaries.

Dynamic models could play an important role in providing information for the mechanical and control design. Further, they allow simulating the motion of mechanical systems during remote tasks. In challenging domains as fusion reactors vessels, where remote handling procedures involve the manipulation/ transportation of large payloads in tiny spaces, it is crucial to have realistic virtual models based on computational mechanics strategies, which can help in planning safe operations, in combination to full-scale physical mock up. FlexARM project results offer possible strategies to modelling and simulation of high-complex FMS for DEMO remote maintenance, as well as possible vibration control strategies to remote handling of DEMO in-vessel components.

EUROfusion
TECHNOLOGY TRANSFER PROGRAMME

Modelling and vibration control of flexible mechanical systems for remote maintenance

Remote handling of heavy in-vessel components inside nuclear fusion reactors requires the use of large robotic systems that are subject to large deformation, either induced by the geometric configuration of their mechanical structure or by the heavy payloads they usually transport. In this context, the modelling and vibration control of flexible mechanical systems aims at developing simulation tools to accurately predict the motion of flexible mechanical systems for analysis, planning and control purpose, crucial for reducing the need for full-scale mock-ups of remote operations. The approach already validated in the fusion sector can be extended to other application domains outside fusion where accurate modelling or remote handling systems is required.

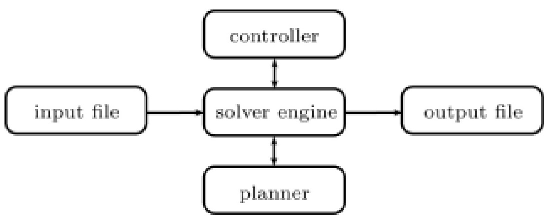


Fig. 1. FlexARM high-level architecture.

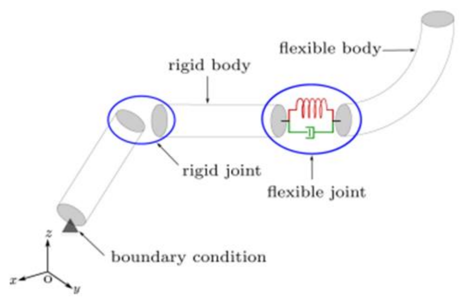


Fig. 2. A generic flexible mechanical system.

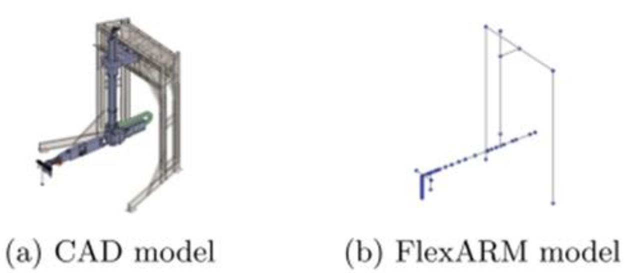


Fig. 3. TARM with flexible payload.

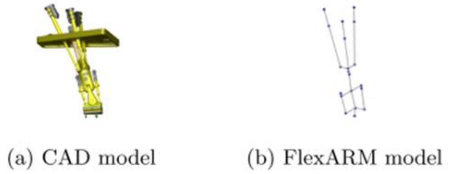
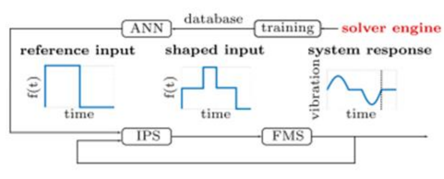


Fig. 4. HKM.



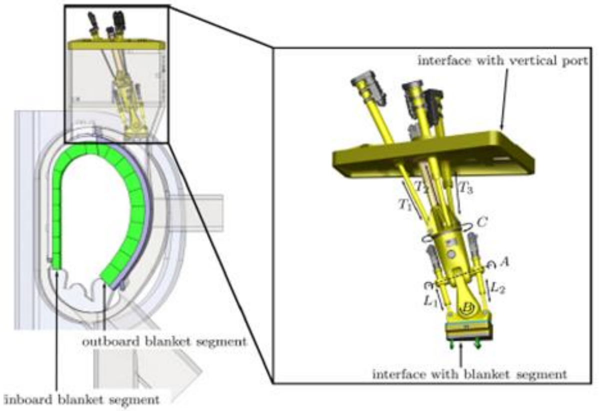


Fig. 1. Hybrid kinematic mechanism for EU DEMO blanket remote handling.

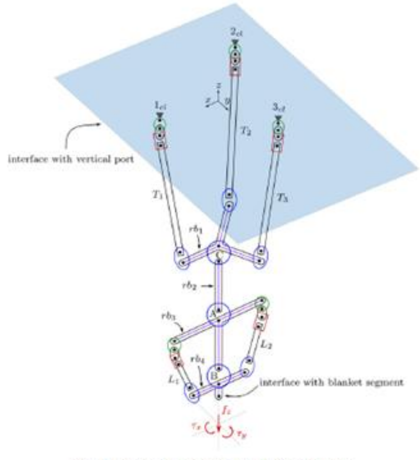


Fig. 2. Model of the hybrid kinematic mechanism.

EUROfusion
TECHNOLOGY TRANSFER PROGRAMME

Modelling and vibration control of flexible mechanical systems for remote maintenance

Remote handling of heavy in-vessel components inside nuclear fusion reactors requires the use of large robotic systems that are subject to large deformation, either induced by the geometric configuration of their mechanical structure or by the heavy payloads they usually transport. In this context, the modelling and vibration control of flexible mechanical systems aims at developing simulation tools to accurately predict the motion of flexible mechanical systems for analysis, planning and control purpose, crucial for reducing the need for full-scale mock-ups of remote operations. The approach already validated in the fusion sector can be extended to other application domains outside fusion where accurate modelling or remote handling systems is required.

Innovation and advantages of the offer

Over the past years, many mathematical models have been introduced to simulate the dynamics of large flexible manipulators. Currently, the most adopted approaches in the robotics research include lumped parameters models, assumed mode models, transfer matrix models. They assume linear elasticity, small deflections, light damping and rotational motion of modest angular rate. Furthermore, they are usually suited only for serial manipulators with revolute joints. Even if these are reasonable assumptions for most robotic devices, the nature of the movements for in-vessel operations, the mechanical complexity of the mechanisms involved, as well as the scale of the loads in a fusion scenario, push towards an alternative approach.

The solution has tackled this problem by using a screw–based nonlinear finite element approach for flexible manipulators that can be numerically solved by using geometric time integrators which might significantly speed up the numerical computation of the equations of motions, maintaining an extreme simulating accuracy at the same time. Dynamic models are essential for mechanical design, analysis of manipulator structures, design of model-based control algorithms and simulation of motion. The simulation tools can accurately predict the motion of flexible mechanical systems for analysis, planning and control purposes. This is important for reducing the need for full-scale mock-ups of remote operations

Non-fusion Applications

The model can be used for the implementation of simulation software tools for flexible manipulators, deformable elements and soft robots with articulated and/or continuum structure. It can be used to simulate or predict movements of the tools (such as soft robots) applied in the field of remote handling and maintenance in harsh and tight environments. Some examples of potential domains applications where remote handling is applied include nuclear industry, space and deep-sea exploration, hazardous environments (e.g. mining, oil and gas extraction, chemical plants), the medical field, manufacturing and industry (e.g. robots are often used for assembly, welding, and painting operations), just to name few.

EUROfusion Heritage

This solution has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014-2018. In particular, this solution was developed during the the FlexARM project, which has received funding under the EUROfusion Engineering "Design of Control Systems for Remote Handling of Large Components".

Visit our website to learn how fusion can help your business
www.tech-transfer.eurofusion.eu

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.