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Modeling and vibration control of flexible mechanical systems for DEMO remote maintenance: Results from the FlexARM project

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ABSTRACT

The goal of this paper is to disseminate the main results achieved within the FlexARM project. The project deals with advanced modeling techniques and predictive control strategies for flexible mechanical systems intended to be used in remote tasks inside advanced nuclear fusion reactors. This article aims at underlying the main aspect of the FlexARM methodology and paves the way towards future research in the field.

1. Flexible mechanical systems in JET, ITER, EAST and DEMO

Several flexible mechanical systems have been developed during the years to perform remote tasks in nuclear fusion reactors. Illustrative examples include: the Telescopic Articulated Remote Mast in JET [1]; the Articulated Inspection Arm in ITER [2]; the EAST Articulated Maintenance Arm in EAST [3]. They have been designed to manipulate relatively small-scale payloads (up to 25–30 kg). Differently, for DEMO reactor, remote maintenance tasks involve handling of in-vessel components which are large-scale and very heavy (the current blanket modules weight up to 80 tonnes) [4]. Even if their robotic transporters are designed to be stiff, the large loads involved in their transportation induce nonlinear deflections and deformations, which need to be predicted in details to execute safe successful tasks. In this context, the FlexARM project aims at developing simulation tools to accurately predict the motion of DEMO flexible mechanical systems for analysis, planning and control purposes. This is important for reducing the need for full-scale mock-ups of remote operations. In the following, we describe the architecture of the FlexARM simulator as well as the modeling and control strategies pursued during the project.

2. FlexARM simulation architecture

The FlexARM simulation architecture is illustrated in Fig. 1 . It is composed by 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.

2.1. Input file

The FlexARM input file specifies the model data, features and parameters in a non-engine specific format. In particular, it specifies:

- Geometry of the mechanical system, in terms of nodes of the model.
- Mechanical system behavior, in terms of rigid and flexible bodies. A rigid body is defined by its inertia properties; a flexible body (one-dimensional element) 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. A joint is defined by setting the axes of allowed/non-allowed motions.
- Actuations, in terms of motion or forces laws on joints.
- Boundary conditions.
- Solving parameters.

2.2. Planner

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

2.3. Controller

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

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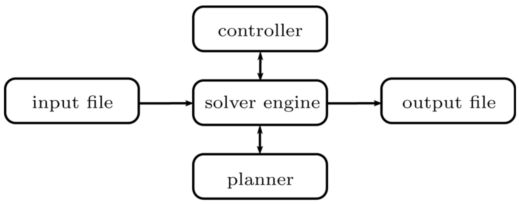

Fig. 1. FlexARM high-level architecture.

2.4. 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.

2.5. 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.

3. Mechanics modeling

A typical set-up in DEMO remote maintenance is represented by a large-scale robotic system handling an 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 behavior of such flexible mechanical systems are highly required [5]. Among the mathematical approaches to describe link flexibility, finite-element models involving nonlinear elasticity are the most appropriate in this context [6]. Their main problem is due to the computational complexity which makes difficult the use of finite elements in a control-oriented framework. In the following, a screw-theory finite element method is briefly described for accurate and computationally efficient simulation of flexible mechanical systems [7]

A generic flexible mechanical system is considered to be composed by rigid and/or flexible bodies connected through rigid and/or flexible joints, as illustrated in Fig. 2 . Due to the fact that robotic manipulators are usually constituted by mechanical links in which one dimension is predominant over the two others, we model the flexible bodies as *beams* with nonlinear geometric behavior. 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 as imposed by the joint. A single rigid body is described by the motion of one node in its center of gravity, to which a frame $\boldsymbol{H}_{CoG} \in SE(3)$ is attached; a flexible body is described by the motion of two extreme nodes, to which two frames $\boldsymbol{H}_A \in SE(3)$ and $\boldsymbol{H}_B \in SE(3)$ are attached and connected through an helical shape function [8,9]. Indeed, the relative motion between two nodes 1 and 2, belonging to two different bodies can be described by a relative frame $\boldsymbol{H}_{J,I} \in$ Lie subgroup of $SE(3)$ as $\boldsymbol{H}_2 = \boldsymbol{H}_1\boldsymbol{H}_{J,I}$ [10]. Collecting the motion variables in the matrix $\boldsymbol{H} = \mathrm{diag}(\boldsymbol{H}_1, \ldots, \boldsymbol{H}_n, \boldsymbol{H}_{J,1}, \ldots, \boldsymbol{H}_{J,k})$, with n the number of nodes and k the number of joints of the system, the strong form for the global dynamics equilibrium of the system take the form

$$\boldsymbol{M}(\boldsymbol{H})\dot{\boldsymbol{\eta}} - \boldsymbol{C}(\boldsymbol{H})\boldsymbol{\eta} + \boldsymbol{f}_{\mathrm{int}}(\boldsymbol{H}) + \boldsymbol{f}_{\varphi}(\boldsymbol{H}, \lambda) = \boldsymbol{f}_{\mathrm{ext}}(\boldsymbol{H}) \tag{1}$$

where $\boldsymbol{\eta}$ contains the absolute and relative velocities of the nodes and joints of the system, $\boldsymbol{M}$ and $\boldsymbol{C}$ are the global discretized mass and velocity matrices; $\boldsymbol{f}_{int}$ are the discretized global internal forces, including elastic forces of the beams and elastic and dissipative forces of the flexible joints; $\boldsymbol{f}_{\varphi}$ are the discretized constraint forces: using the Lagrange multiplier method, these forces take the form $\boldsymbol{f}_{\varphi} = \boldsymbol{A}^T\boldsymbol{\varphi}_q\boldsymbol{\lambda}$, being $\boldsymbol{A}$ a constant matrix accounting for joints, $\boldsymbol{\varphi}_q$ the gradient of the constraint and $\boldsymbol{\lambda}$ the Lagrange multiplier vector; $\boldsymbol{f}_{ext}$ are the discretized global external forces, including also gravity. An algebraic constraint equation $\boldsymbol{\varphi}(\boldsymbol{H}) = \boldsymbol{0}$ must be appended to the differential system (1) to define a differential-algebraic equation (DAE) system that must be solved for $(\boldsymbol{H}, \boldsymbol{\lambda})$. Finally, a geometric implicit integration scheme and a Newton-Raphson iterative method are used to numerically solve the DAE system [11].

The modeling approach shows an average accuracy below 5% with respect to benchmark from the literature. The method has been applied for dynamic modeling and simulation of two fusion related use cases: the Telescopic Articulated Remote Mast (TARM), an hyper-redundant spatial large manipulator representing the core of the JET remote maintenance system [12] (see, e.g. Fig. 3); the Hybrid Kinematic Mechanism (HKM), a serial-parallel large manipulator which is the current proposal for installation and replacement of breeder blanket segments for DEMO [13] (see, e.g. Fig. 4). A short speed-up video of the related simulations can be found here: https://youtu.be/yrlP-6W5x68.

4. Vibration control

Accurate motion of flexible mechanical systems is a challenging control problem, since it might results 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. This is the main idea of a control strategy referred to as command shaping [14].

Command shaping methods convolve the reference command of a FMS with a sequence of m impulses, whose timing locations t_i, $i = 1, \ldots, m$ and amplitude A_i, $i = 1, \ldots, m$ 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 $\sum_{i=1}^{n} A_i = 1$. The primary design constraint of a shaper is usually a limit on the amplitude

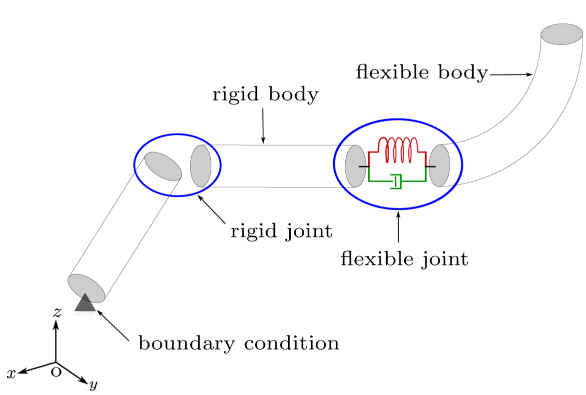

Fig. 2. A generic flexible mechanical system.

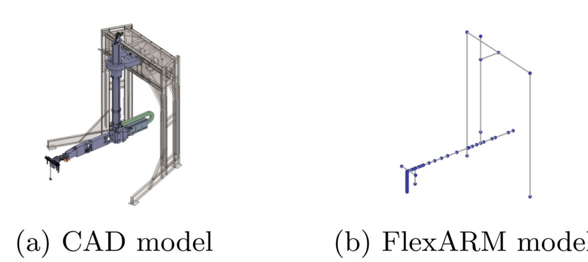

Fig. 3. TARM with flexible payload.

(a) CAD model (b) FlexARM model

Fig. 4. HKM.

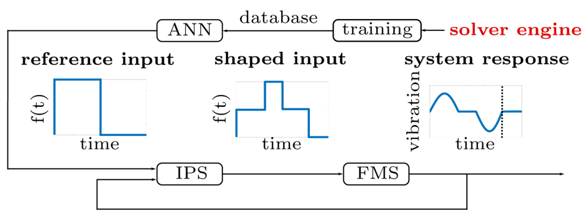

Fig. 5. Input predictive shaping process. ANN: Artificial Neural Network; IPS: Input Predictive Shaper; FMS: Flexible Mechanical System.

of vibration caused by the system. Whether an analytical expression of the vibrations induced by a train of impulses on a flexible mechanical system exists (or it can be learned from physical-based simulations), 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 [15]. Application of robust command shaping techniques to remote handling of large components in fusion reactors can be found in [16]. The disadvantages of the robust shapers are: (ii) increasing of rise time of the command; (ii) a-priori knowledge of the frequency range in which the mechanical system operates.

Since in remote handling of in-vessel components we deal with payloads with time-varying parameters (just think a flexible blanket module moving in space), an alternative approach should be pursued.

To this end, the FlexARM project proposes a predictive approach to input shaping, whose process is illustrated in Fig. 5 . The method foresees an offline and online phases. Offline, dynamic simulations of the FMS measures the induced vibrations at the payload side resulting from different motion commands. Based on this, a learned closed-loop controller generates a predictive train of pulses. This, anticipating the dynamics of the FMS, shapes the reference command such that the resulting system response has a tolerable value of vibrations.

To validate the method, we derive an input predictive shaping algorithm for fine motion control of an experimental overhead crane with a suspended payload [17]. A video of the related experiment can be found here: https://youtu.be/bDRSfERbbxI.

5. Discussion and future directions

FlexARM project results offer possible strategies to modeling 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.

Several issues need to be further investigated, in order to execute safe remote maintenance for advanced reactors as DEMO: (i) How to estimate the parameters of real manipulators in the nuclear vessel environments? (ii) How to consider all the causes of deformations (including thermal, electromagnetic and neutronic effects beyond structural ones) in the multibody solver? (iii) How to develop full online strategies to vibration control? (v) Will the full autonomous control be the best strategy for DEMO remote handling, or do shared control architectures deserve to be further investigated?

Since DEMO remote maintenance operations are extremely challenging, it is important to put a great effort in control system design. To this end, developing predictive and physical-based models which can be used for control purposes is essential. With this respect, we believe that geometric and port-Hamiltonian frameworks could offer unified and feedforward strategies for advanced modeling and control. However, the path towards the development of real-time controllers for DEMO remote maintenance will probably balance the accuracy and reliability of physical-based approaches and the computational advantages of artificial intelligence and deep learning techniques.

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