Data-Driven Model Order Reduction for real-time multibody simulations

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Currently, multibody models are the state of the art to describe the dynamics of complex mechanical systems. However, due to the nonlinear characteristics and the relatively large number of Degrees of Freedom (DoFs), multibody simulations typically cannot be run in real-time. In this work, a novel data-driven local Model Order Reduction (MOR) approach is proposed, in order to perform most of the computations offline and obtain online real-time capabilities. Using displacement data either from experiments or simulations, a local Principal Component Analysis (PCA) is performed. The obtained Reduced Order Bases (ROBs) permit to locally reduce the system to a linear model and to constrain its motion without the necessity of additional equations. Thus, the dynamics can be linearly approximated with a reduced number of DoFs in a system of Ordinary Differential Equations (ODEs) that can be solved in real-time. An application example of the technique shows its increased velocity with respect to the solution of a full multibody simulation while maintaining results accuracy.

In order to perform real-time dynamics simulations, a local MOR technique is developed. Firstly, displacement data from experiments or simulations are collected. Then, it is necessary to separate the displacement space in linear subdomains. In this case, the K-Means clustering technique [1] based on Euclidean distance between the displacements is applied. At this point, PCA [2] can be performed in each separate cluster. Each group of local ROBs is obtained through the Singular Value Decomposition (SVD) of the displacements belonging to a certain cluster. By means of the obtained ROBs, the full multibody model can be locally reduced and its number of DoFs considerably decreased. All these operations can be pre-executed offline, thus they do not impact on the online computational load.
During the simulation, at each time step, the cluster that has minimum distance between its centroid and the current simulated displacement state is found. For the initial time step, it is assumed that the initial conditions of the system are known. Then, the Reduced Order Model (ROM) associated with the located cluster is recalled. Since the motion of the model is allowed only along the obtained principal components of the ROBs, additional constraint equations are not necessary and the ROM dynamics can be linearly approximated and described through simple ODEs:

$$\mathbf{M}^{red}\,\ddot{\mathbf{q}} + \mathbf{K}^{red}\,\mathbf{q} = \mathbf{F}_{\text{ext}}^{red} \qquad (1)$$

Where $\mathbf{q}$ is the vector of the reduced-order DoFs and the double-dot accent indicates its double derivative with respect to time. $\mathbf{M}$, $\mathbf{K}$, $\mathbf{F}_{\text{ext}}$ are the mass matrix, stiffness matrix and external forces vector, respectively. The superscript *red* indicates their reduced order version. Here, a simple Forward-Euler integrator is used to solve such dynamics equation.

In order to show its potential, the proposed methodology is applied to a rigid pendulum model trained with a translational motion along the x axis due to a force F and a rotational motion along the yz plane due to a torque T, as shown in Fig. 1. The procedure described above is followed. Initially, the clustering and PCA of the displacement data are applied. Then, the reduced order simulation is performed recalling in each cluster the associated locally linear ROM, as shown in Fig. 2. Finally, in Fig. 3, the reduced order simulation is compared with a classical multibody simulation, for example according to the procedure described in [3]. The simulation time with the proposed MOR technique is in the order of milliseconds, while a standard multibody simulation has taken some minutes. Hence, it can be noticed that, while maintaining sufficient accuracy, the methodology substantially increases the simulation speed achieving real-time requirements.

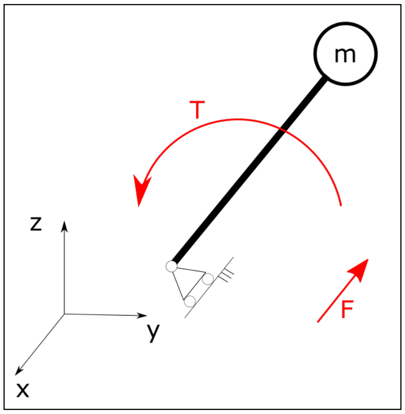

Fig. 1: The example pendulum model.

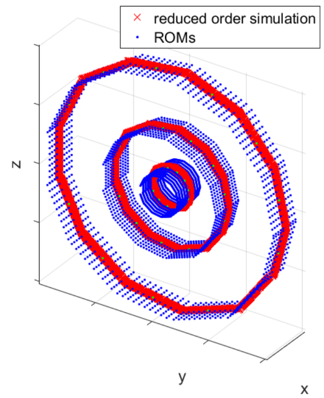

Fig. 2: Simulated displacement using the linear ROMs.

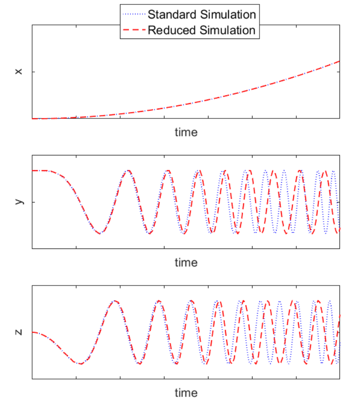

Fig. 3: Centre of Gravity displacement, comparison between the reduced order simulation and the standard simulation.

A novel data-driven local MOR technique for real-time multibody simulations has been proposed. The results of a simple application example show that real-time simulation velocity is achieved while maintaining sufficient accuracy of the results. Further research is under development in order to increase the robustness of the technique and extend it to flexible models.

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