# A multi-physics-based methodology for electro-magneto-mechanical co-simulation in dynamic applications: A case study

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**EXTENDED ABSTRACT**

## 1 Introduction

Multibody dynamics methodologies represent an indispensable tool for the kinematic and dynamic description of mechanical interaction among rigid and flexible bodies. However, when such interactions come from events of a different physical nature, the estimation of the whole phenomena can be extremely complicated. In this study, we propose a novel Matlab/Simulink-based architecture for the integration, under general multibody codes, of the multi-physics analysis devoting particular emphasis to the interaction between the mechanical, magnetic, and analog electronic domains, tacking efforts from two novel implemented bi-directional co-simulation routines based onto Spice® and ESRF Radia® engine. A common approach toward these arising aspects is to narrow the complexity of the numerical modeling through the isolation of the main macro-domains, and thus solving the different phenomena through dedicated languages, tools, and algorithms [1]. However, in applications where the strict interdependence between the different physical domains and scales cannot be decoupled the introduction of a complete multidomain co-simulation architecture is required necessary [2], [3]. Matlab/Simulink® certainly represents the most advanced graphical programming environment for the simulation of dynamic systems, being developed for the analysis of multipurpose and general nature problems, the proposed co-simulation algorithm exploits the capabilities of a system-level environment in order to integrate under a single dynamic model, whose core is designed into the multibody ambient, several device-level simulators implemented respectively for the electronic and magnetostatic analysis through the equivalent circuit methodology (ECM) and the 3D finite volume modeling (3DFVM). To test and validate the proposed methodology, a micro-electromagnetic actuator is taken under analysis, the numerical results obtained by the multi-physics model are compared with the experimental relatives reported by Kim et al. in [4].

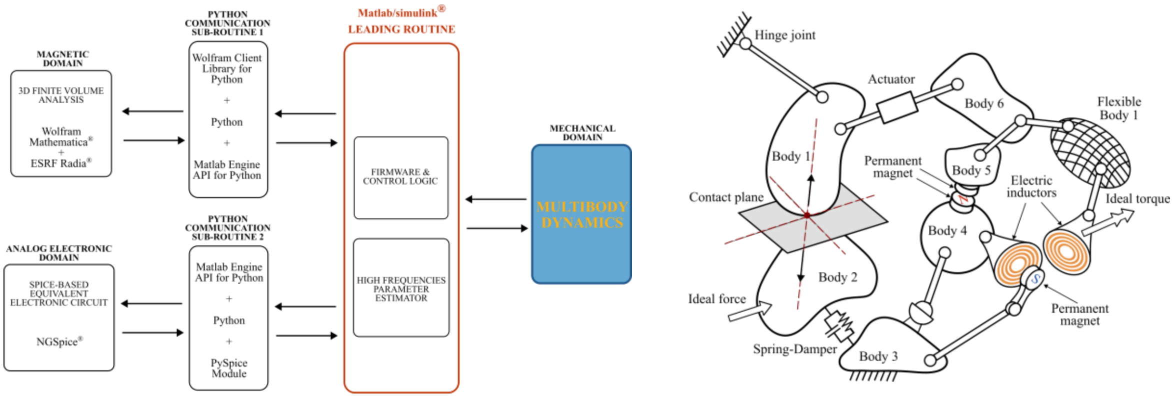


Figure 1: (a) Proposed multi-domain co-simulation architecture; (b) General representation of a multibody model.

## 2 The multibody dynamics formulation

The equation of motion (EOM) characteristic of a general multibody system as depicted in Ficure 1.b, is given by:

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{\Phi}_q^T \boldsymbol{\lambda} = \boldsymbol{f} \tag{1}$$

Where $\boldsymbol{M}$ is the global mass matrix of the system, $\ddot{\boldsymbol{q}}$ the vector of natural accelerations, $\boldsymbol{\Phi}_q^T$ the constraint vector of the kinematic topology, $\boldsymbol{\lambda}$ the vector of Lagrange multipliers and finally $\boldsymbol{f}$ is the generalized force vector. The main target of the proposed architecture is to integrate, on the bases of the reached configuration enclosed in the generalized coordinates vector $\boldsymbol{q}$, a classic force element, which does not introduce state variables and algebraic constraints, that comes from the interaction of the analog electronics and the magneto-static fields. This approach essentially integrates the generalized force vector $\boldsymbol{f}$ according to Equation (2).

$$\boldsymbol{f} = \left\{\boldsymbol{f_{mech}}, F_{mag1}, F_{el_{mag2}}, F_{el3}, \dots\right\}^T \tag{2}$$

Where $\boldsymbol{f_{mech}}$ is the purely mechanic generalized force vector, instead $F_{mag1}, F_{el_{mag2}}, F_{el3}$ represent the general force elements coming from the electro-magneto-mechanic interactions.

## 3 The proposed multi-domain architecture & the Matlab/Python-based co-simulation routines

Figure 1.a depicts with a block diagram representation the proposed implementation logic behind the co-simulation multi-scale and multi-physics modeling technique. The core of the model developed in Matlab\Simulink, discretizes the time of the simulation interfacing the different physical domains. The kinematic and dynamic aspects are studied through a complete Multibody model of the full device assembly, the Mathematica open-source package: ESRF Radia solves the static and dynamic electro-magnetic fields through a 3D FVM algorithm, and finally the equivalent circuit properties are integrated and solved through the Spice engine. The core of the proposed multi-domain algorithm is constituted by the two novel Matlab/Python-based co-simulation routines. In detail the analog electronic domain is integrated through the Matlab Engine API for Python that through the PySpice module executes the NGSpice engine and solves the continuously updated circuit Netlist and allows the extraction of all the voltages and currents at every nodes and branches of the circuit. The magneto-static domain instead, is integrated through the Wolfram Client Library for Python that interpretate the 3D FVM magnetic model implemented via Wolfram language and embedded into a Python module that calls through the Matlab Engine API for Python the ESRF Radia solver and allows the extraction of all the magnetic fields intensity, magnetic forces and torques in every position of space.

## 5 A case study

The mechanical dynamics of the micro electromagnetic actuator (Figure 2.a) is studied as a validation test and implemented via Multibody analysis. In detail the device is constituted by three main micro-coils that are embedded in parylene layers, the circulating current induces in each coil an electromagnetic field that interacts with the field generated by the relative NdFeB permanent magnet and actuate the coil itself. The frame composed of a Fe core and a silicon substrate guides the field lines and improve the performances. Figure 2.b shows the capabilities of the proposed methodology and depicts onto two different graphs the laser-based displacement measure obtained at different level of applied current (on the top-right corner) and the obtained numerical trends of the estimated deflection amplitude due to a 1Hz square wave excitation in the amplitude range of [10; 190] mA with a step of 20 mA (bottom-right corner). Further and in-depth dynamical analysis will be presented in the related paper.

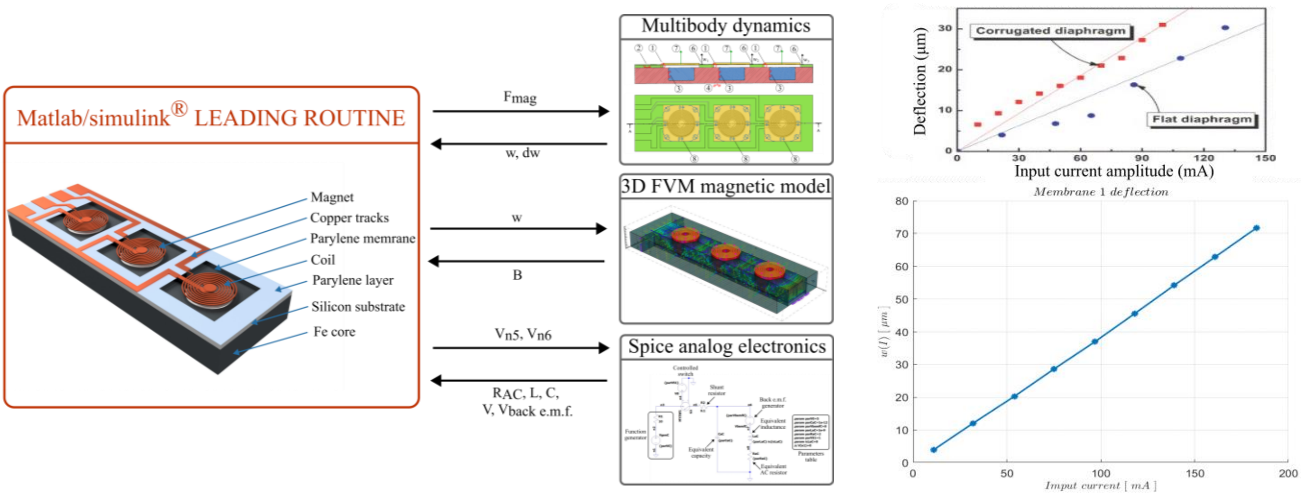


Figure 2: (a) Multi-domain architecture applied to the micro actuator; (b) Experimental and numerical results comparisons.

## 6 Conclusions

Multi-physics analysis represents a promising solution for those applications whose design and comprehension require the co-simulation among strongly coupled physical domains. The main strengths of the proposed methodology are represented by the Python and Matlab/Simulink-based bi-directional co-simulation routines. The work introduces an improvement in the simulation capabilities of complex and strongly coupled devices, with particular emphasis on the coupled analysis between Multibody dynamics, analog electronics, and magneto static/dynamic phenomena.

## References


[1] F. Cremona, M. Lohstroh, D. Broman, E. A. Lee, M. Masin, and S. Tripakis, "Hybrid co-simulation: it's about time," *Softw. Syst. Model.*, vol. 18, no. 3, pp. 1655–1679, Jun. 2019, doi: 10.1007/s10270-017-0633-6.

[2] W. Wang, W. Yang, and V. Dinavahi, "Co-Simulation Interfacing Capabilities in Device-Level Power Electronic Circuit Simulation Tools: An Overview," *Int. J. Power Electron. Drive Syst. IJPEDS*, vol. 6, pp. 665–682, Dec. 2015, doi: 10.11591/ijpeds.v6.i4.pp665-682.

[3] X. Zhao *et al.*, "Co-Simulation Platform for Modeling and Evaluating Connected and Automated Vehicles and Human Behavior in Mixed Traffic," *SAE Int. J. Connect. Autom. Veh.*, vol. 5, Apr. 2022, doi: 10.4271/12-05-04-0025.

[4] K. H. Kim, H. J. Yoon, O. C. Jeong, and S. S. Yang, "Fabrication and test of a micro electromagnetic actuator," *Sens. Actuators Phys.*, vol. 117, no. 1, pp. 8–16, Jan. 2005, doi: 10.1016/j.sna.2003.10.079.