Robotic machining and applications:

Performance and efficiency of co-simulation for milling operations in robotic machining

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Abstract

In robotic machining, tool/workpiece interaction generates forces that affect the robotic arm's performance, leading to deflections due to its lower stiffness compared to milling machines, especially at the joints. These deflections can degrade machining quality, making trajectory and orientation optimization crucial. Optimization requires knowledge of the transient force field and a robot model. Currently, simulations use two in-house frameworks: EasyDyn for multibody dynamics and Dystamill for cutting force modeling. To improve modularity, a co-simulation approach is proposed, coupling the multibody system (MBS) of the robot with the workpiece using a displacement-force interaction. This method allows better integration of different robots and machining models, but comes at the cost of reduced accuracy compared to monolithic models. This research aims to evaluate the impact of this accuracy loss on a simplified model.

Introduction

Recently, Industrial Robots (IR) have been widely used in the industry because of their relatively low cost and their wide range of application. However, for machining, as their stiffness is 50 times lower than that of specific machining machines, they deform when cutting forces are applied to their end effector. These deformations lead to a lower quality of the machined pieces. Furthermore, their lack of stiffness induce vibrations and chatter. Different methods are used to compensate for these issues [1]. From these methods, it can be highlighted that there are 2 main parts in the robot/tool/workpiece models (Figure 1) : the robot itself, and the workpiece, with their interface, the tip of the tool. Research in the literature has shown that modelling these parts can be done with different methods (examples for the workpiece : FEM, dexels, etc.) depending on the software used by the teams and the precision needed [1, 2, 3]. Being able to change one of the sub-models (robot or workpiece) without affecting the other ones is then interesting. Co-simulation, which is a numerical simulation approach in which a whole system is divided into different subsystems that are modelled and simulated separately and communicate at discrete times, separated by a time step (figure 2), offers this modularity [4]. However, there are drawbacks to co-simulation as it decreases the accuracy of the results due to discrete data exchange between subsystems (sometimes due to violation of the conservation of energy principle, for example). The information exchange is shown at figure 2. It is composed of the cutting forces at the interface (F_c) as well as the positions $q(t)$ and velocities $\dot{q}(t)$ of the bodies.

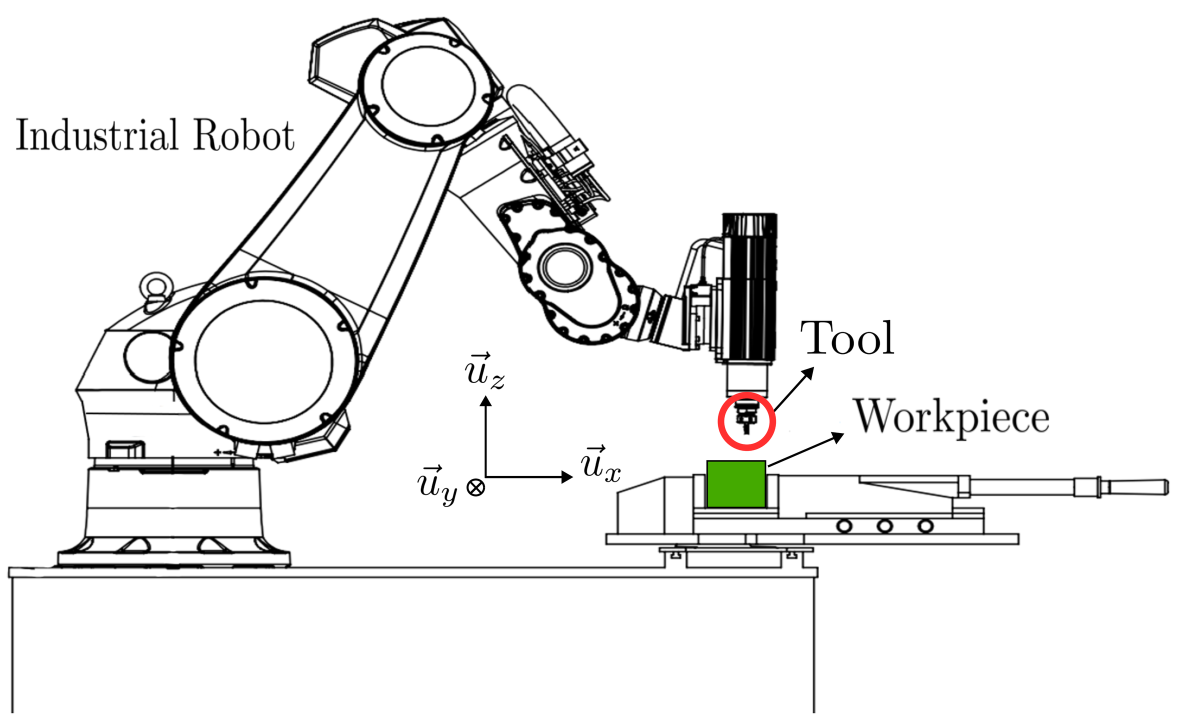

Figure 1: Robot/tool/workpiece

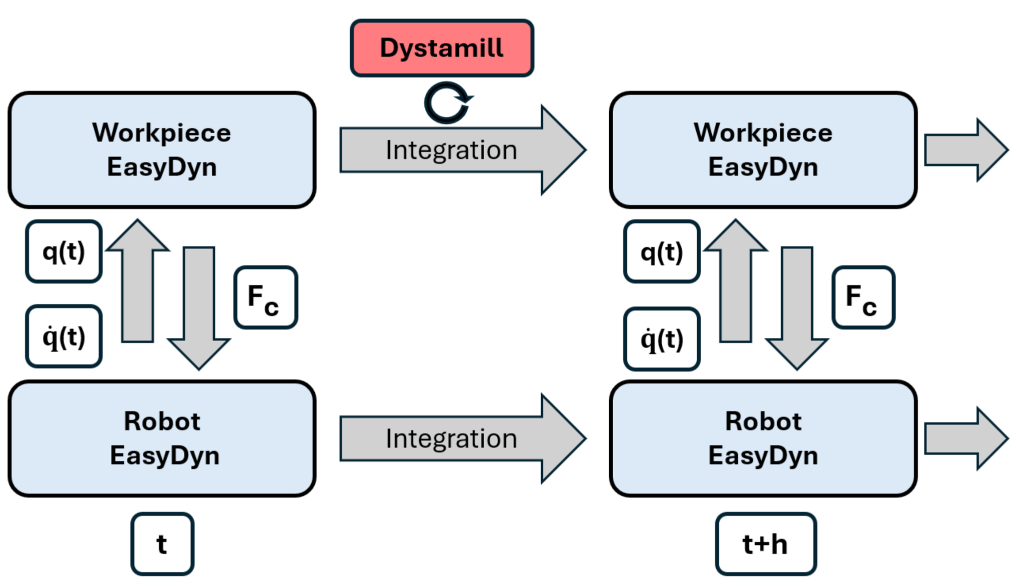

Figure 2: Co-simulation methodology

Model

A simplified bi-mass model is used to compare monolithic and co-simulated approaches for robotic machining (figure 3). The robot mass (m_1) and workpiece (m_2) are connected by a spring (k_c) and damper (d_c), representing the tool. The dynamic parameters of the robot (k_1, d_1) are simplified as constants. The same is done for the workpiece (k_2, d_2), which is fixed in space. The co-simulation interface is placed at the tool level, allowing specialized software for machining (Dystamill) and robotic dynamics (Easydyn) to interact. In the monolithic model, all components are integrated within a single code, reducing numerical errors and serving as a reference for simulations. Cutting forces are computed in Dystamill layer by layer using Altintas' model and sent to the robot subsystem at each macro time step. This framework enables modular, specialized simulations while maintaining accuracy.

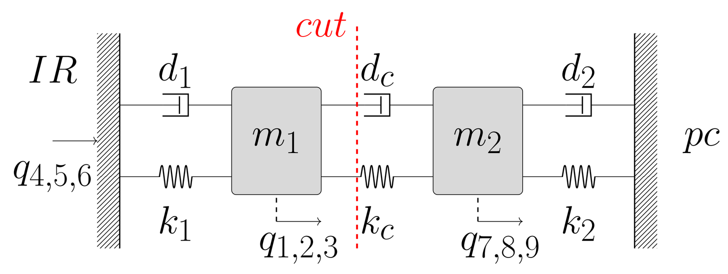

Figure 3: Double mass-spring-damper system

Simulation tests

Simulations were performed to evaluate the error introduced by co-simulation compared to a monolithic model. Figure 4 illustrates the workpiece displacements in the x and y directions, showing that both models produce nearly identical results, indicating minimal error. However, during transient states (entering and exiting the workpiece), the errors are substantially bigger as displacements are larger than when the tool is fully engaged.

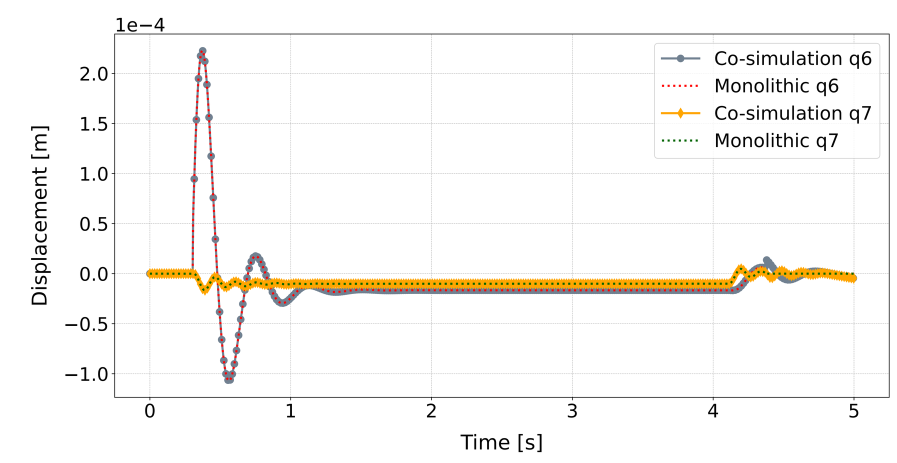

Figure 4: Comparison of the x and y (q6 and q7) displacements of the workpiece for both models

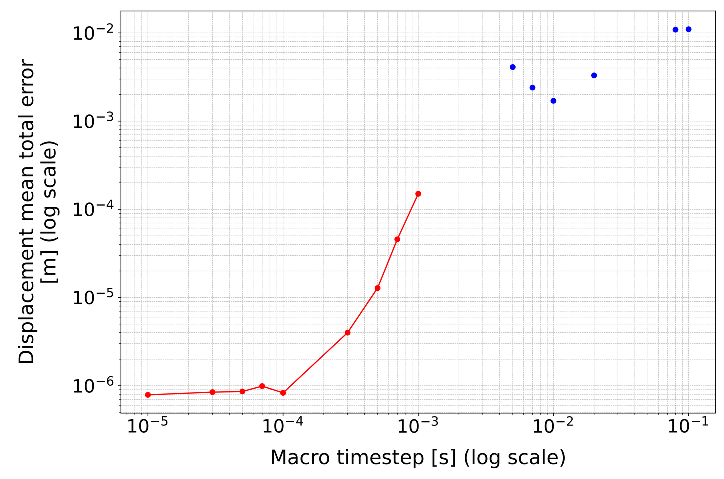

Figure 5: Evolution of the displacement mean total error with macro time step

Figure 5 shows that increasing the macro time step (h) in co-simulation increases displacement errors due to fewer data exchanges. For $h > 10^{-3}$ s, errors become erratic, and some simulations fail. Larger h also reduces Dystamill's accuracy, affecting displacement values, while for $h < 10^{-4}$ s, errors remain stable.

Conclusion and outlook

This study validates the potential use of co-simulation for robotic machining, showing that with a sufficiently small time step, errors remain negligible compared to subsystem deflections. Several simplifications were made, but this is not a limitation in the context of this work, which aims to introduce the concept of co-simulation in robotic machining. The key advantage of this approach is its modularity, allowing the integration of specialized software for different model components. Future work will focus on refining robot flexibility modelling, incorporating workpiece dynamics in the z-axis, and comparing simulations with experimental data to further assess co-simulation's accuracy and relevance in robotic machining.

References

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