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Offline Learning Control to Improve the Accuracy of Real-time Explicit Co-simulation

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EXTENDED ABSTRACT

1 Introduction

Co-simulation has become a cornerstone method for model-based system development. The latest developments on this subject have combined it with physical systems in applications such as hybrid substructuring, hybrid simulation and hardware-in-the-loop testing. It constitutes an intuitive approach to model large and complex systems by dividing them into subsystems that are easier and faster to integrate. The simulation of these interconnected subsystems requires discrete-time communication, i.e., the exchange of the inputs and outputs of the subsystems (the coupling variables) at specific time instants. This exchange is the task of the co-simulation manager, which not only handles the communication between subsystems, but also compensates for any inaccuracies. In most cases, this manager contains an extrapolation algorithm. When the outputs of a subsystem directly depend on its inputs, direct feedthrough is present, resulting in an algebraic loop. This algebraic loop can be resolved by the co-simulation manager either iteratively or by extrapolating the unknown inputs. However, the latter can cause accuracy loss and stability issues. This has led researchers to investigate methods to monitor and correct co-simulation errors, e.g., by using indicators or adapting the communication step size of the problem [1, 2]. In the case of hybrid physical-virtual applications, where physical systems are connected to virtual systems, adapting the step size is not possible and one has to resort to explicit fixed time step correction methods. In this context, the term 'explicit' signifies that rollback is not allowed: a time step cannot be solved iteratively. If some or all subsystems are so-called 'black boxes', i.e., their internal states are not accessible, the information exposed by the subsystems becomes the only data that can be used by the correction methods. The coupling variables have to be modified during real-time execution based on this limited information, e.g., the force correction in [3]. Alternatively, control algorithms using the available coupling data can compensate for the chosen extrapolation methods, such as the H_∞ solution presented in [4].

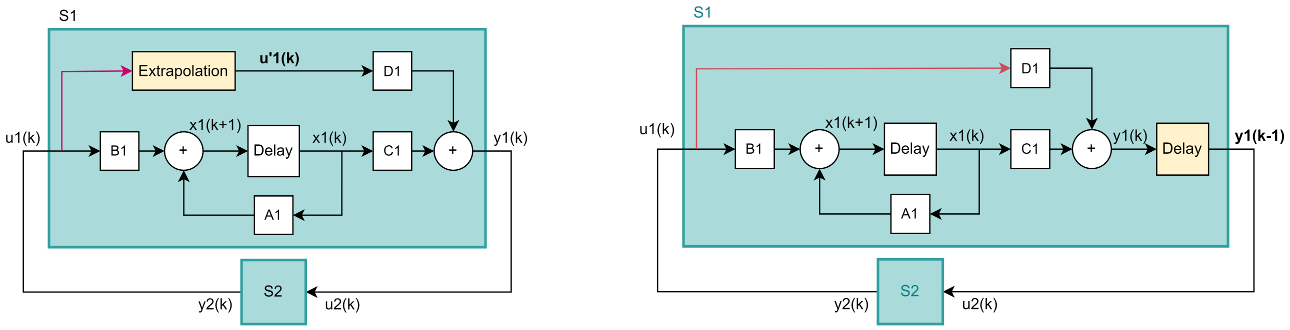
2 Methodology

In this paper we propose a novel, twofold approach to correct coupling errors in single-rate explicit co-simulation. We formulate the co-simulation as a control problem, where the manager, containing the extrapolation method, is the system to be controlled. Firstly, we propose an iterative method, consisting in performing a sequence of consecutive co-simulation runs. A correction is added to the co-simulation after every run, based on the information collected during the run. This yields a correction approach that does not require using implicit methods, adapting the communication step size, or modifying interface variables during runtime, which makes this approach compatible with real-time execution. This iterative control method, referred to as Iterative Learning Control (ILC) [5], is well known in control engineering. The goal of ILC is to iteratively learn a control input from previous test runs to improve the tracking of a specified reference. The tracking error and control inputs of the entire test are memorized and fed back offline into the ILC algorithm to improve the control input for the next test run. In the case of co-simulation, however, a reference is not available, because the analytic and the monolithic (numerical) solutions, which could be used to determine the correctness of co-simulation results, are not available in most applications of interest. As a consequence, appropriate assumptions have to be made to provide a valid reference for the ILC in co-simulation experiments.

This is the second part of the approach: instead of using an extrapolation method as shown in Figure 1a, the co-simulation manager delays the output of the subsystem with direct feedthrough with one time step, as shown in Figure 1b. This delay leads to a larger error in the uncorrected co-simulation, but the resulting system is easier to correct with ILC. When an output is time-delayed, its desired value, which will become the ILC reference, is the output without this delay. This means that we need a time prediction of one time step, in other words, we need a non-causal controller. It is precisely in this type of situation where we can fully exploit the strengths of ILC. Since the ILC algorithm memorizes control inputs and outputs from the previous run, these can be shifted ahead in time, giving insight into future time steps. This way, the ILC can accurately compensate the addition of a delay to a subsystem during the next run. If instead the co-simulation is using an extrapolation method, for example zero-order-hold (ZOH) extrapolation, the exact subsystem output is not available anymore as a reference signal for the ILC scheme. The ILC sequence of co-simulations can still converge to zero tracking error but with an incorrect reference. Calculating another ILC reference that exactly compensates for the ZOH error is generally not possible, since the subsystems' internals are not accessible.

3 Results

To demonstrate our novel twofold approach, we use a popular benchmark problem [3]: a linear oscillator composed of two masses connected to each other and to the ground with ideal springs and dampers, without external excitation inputs. We study

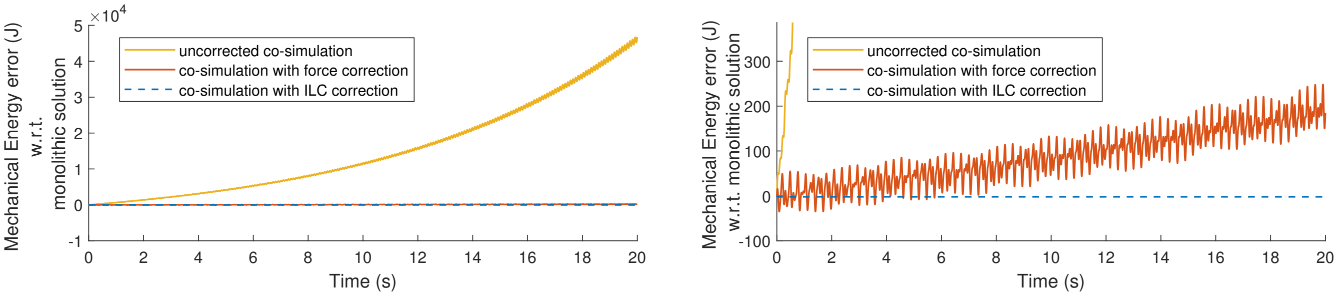


(a) Using extrapolation.

(b) Using a time delay.

Figure 1: Control loops used to represent a co-simulation environment with an algebraic loop.

the ILC performance for two different scenarios: (a) When co-simulation uses a time delay to eliminate the algebraic loop (the time delay assumption holds), and (b) when the co-simulation uses ZOH extrapolation (the time delay assumption does not hold). We investigate how the same control algorithm behaves in both situations, and how it compares to the energy method in [3] and to the uncorrected co-simulation. To verify the accuracy of the results, the co-simulated solution is verified against its monolithic numerical counterpart using the mechanical energy of the system as a metric. It must be noted that neither the monolithic solution nor the mechanical energy are usually available in applications of practical interest, so they are only used to verify the results, but not as sources of information for the ILC. Figure 2 confirms that, with the presented approach, the mechanical energy of the co-simulation compensated by ILC is exactly the same as the energy of the monolithic solution. When the time delay assumption is not satisfied, in contrast, a perfect correction is not possible. The force correction from [3] yields stable results with a satisfactory accuracy, although the simulation error is still not exactly compensated. The uncorrected co-simulation has an unstable response, since the mechanical energy error grows indefinitely over time.



(a) Mechanical energy error.

(b) Close up of the mechanical energy error.

Figure 2: Errors in the co-simulation of the linear oscillator benchmark with respect to the monolithic solution.

4 Conclusion

To conclude, our novel approach has delivered accurate results when the co-simulation model complies with the standing time delay assumption. For cases that rely on different approximation schemes or without direct feedthrough, the performance of the developed approach has not been evaluated yet. Next to that, future work will revolve around the development of strategies to determine the existence of direct feedthrough in the subsystems, which is necessary to apply the method satisfactorily.

References

[1] S. Sadjina, E. Pedersen. Energy conservation and coupling error reduction in non-iterative co-simulations. Engineering with Computers, 36:1579–1587, 2019.

[2] M. Benedikt, D. Watzenig, J. Zehetner, A. Hofer. NEPCE - A nearly energy-preserving coupling element for weak-coupled problems and co-simulation. In NAFEMS World Congress, Salzburg, Austria, 2013.

[3] B. Rodríguez, A. J. Rodríguez, B. Sputh, R. Pastorino, M. Á. Naya, F. González. Energy-based monitoring and correction to enhance the accuracy and stability of explicit co-simulation. Multibody System Dynamics, 55(1-2):103-136, 2022.

[4] W. Chen, S. Ran, C. Wu, B. Jacobson. Explicit parallel co-simulation approach: analysis and improved coupling method based on H-infinity synthesis. Multibody System Dynamics, 52(3):255–279, 2021.

[5] D. A. Bristow, M. Tharayil, A. G. Alleyne. A survey of iterative learning control. IEEE Control Systems Magazine, 26(3):96–114, 2006.