Collaborative Research: CPS: Medium: Co-Designed Control and Scheduling Adaptation for Assured Cyber-Physical System Safety and Performance

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https://cps-vo.org/node/98020 and https://cps-vo.org/node/98165

Key Problems This Research is Addressing

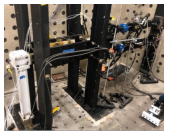
- Semantic integration of control and scheduling models in real-time hybrid simulations for mechanical and structural engineering
- Joint enforcement of safety constraints, objectives, and trade-offs spanning key control and scheduling parameters
- New platform abstractions, mechanisms, and policies for safe adaptive run-time management of constraints / tradeoffs

Scientific Impacts on CPS beyond Mechanical, Structural, and Natural Hazards Engineering

- Integrated mixed-criticality and elastic real-time scheduling for control-safe real-time adaptation as conditions or objectives change
- Quantitative examples and guidance towards co-designed safe real-time control and scheduling across CPS applications
- New benchmarks and open-source software to scale up parallel real-time computation and control atop heterogeneous hardware

New Multi-Axial Real-Time Hybrid Simulation (maRTHS) Benchmark Control Problem

We have developed a new benchmark control problem that is designed to (1) offer researchers a robust challenge, facilitating development and validation of innovative control techniques and (2) encourage the transition to multi-axial real-time hybrid simulation (maRTHS), and (3) investigate its challenges. It provides a MIMO control problem involving tracking of both translation and rotation degrees of freedom of an experimental substructure that consists of a steel frame, two hydraulic actuators and a steel coupler, and is accompanied by supporting models and software infrastructure.

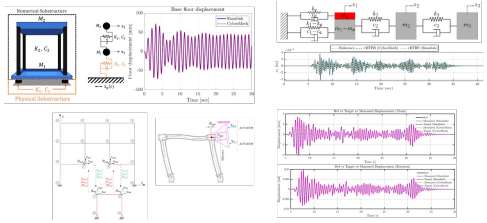


Updated CyberMech Codes for Conducting RTHS

- Interpolation of input signals to exploit the elasticity offered by variable-rate execution
- Discretizing continuous state-space models of the physical substructure using Zero-order hold (ZOH) and 4th-order Runge-Kutta (RK4) methods
- Incorporating measurement noise and uncertainty in virtual RTHS (vRTHS) by generating normally distributed random numbers and randomly perturbed models

Three benchmark virtual RTHS (vRTHS) experiments

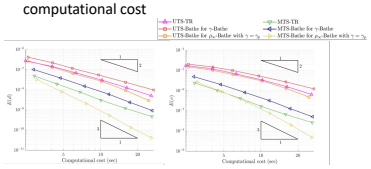
- vRTHS for a linear numerical substructure and nonlinear physical substructure without controller and transfer system
- Uniaxial vRTHS for three-story, two-bay building
- Multi-axial vRTHS for three-story, three-bay building



Improved Time Integrators

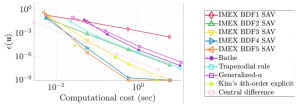
Multi-Time-Step (MTS) method (Bathe scheme)

- Allows different time-steps in different subdomains
- Provides unconditional stability, high accuracy, and low computational cost



A class of IMEX-BDF*k*-SAV schemes

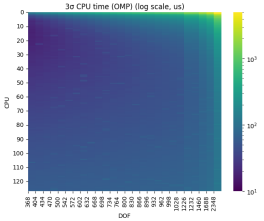
- Linear and nonlinear terms are treated implicitly and explicitly, respectively, thereby avoiding the need for iterations at each time-step
- Unconditional stability and accuracy up to 5th-order

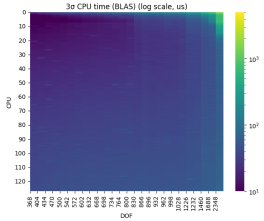


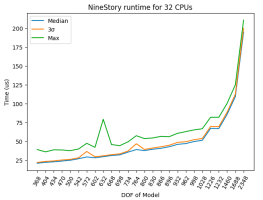
We exploit multicore/GPU parallelism for msec-scale RTHS and evaluate scalability w.r.t. model size

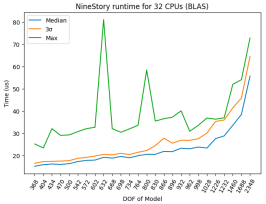
CPU Scalability

- We simulate the nine-story moment-resisting steel frame structure from [Aguilar2012]
- Parallel numerical simulation in CyberMech [Condori2020] using OMP and BLAS for matrix and vector operations at 1024Hz for 1 minute (61,440 iterations) on 128-core 3.1GHz AMD EPYC 9754 with 128GB of RAM: measured execution time of each iteration when executed on 1—127 cores for model sizes with increasing degrees of freedom



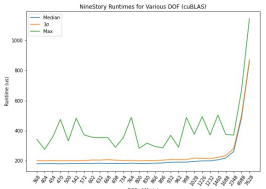






GPU Acceleration

- Offload numerical simulation to GPU kernel
- Avoid device-to-host memory copies
- Implement matrix operations with cuBLAS



Key Takeaways: CPU

- 3σ < 98 ms @ 1024Hz given enough cores
- We're working to address max time outliers to ensure tighter real-time safety guarantees
- BLAS (vector instructions) outperforms OMP
- Diminishing returns as CPUs increase due to thread synchronization overhead

Key Takeaways: GPU

- **Single RTX A5000 GPU capable of meeting deadlines** consistently for <7628 DOF
- BLAS version remains most performant
- cuBLAS performance may be improved if we can minimize kernel launch overhead

[Aguilar2012] Aguilar, N. E. C., 2012. Development and validation of a real-time computational framework for hybrid simulation of dynamically-excited steel frame structures. Ph.D. thesis, Purdue University.
[Condori2020] Condori, Maghareh, Orr, Li, Montoya, Dyke, Gill, Prakash, 2020. Exploiting parallel computing to control uncertain nonlinear systems in real-time. Experimental Techniques 44, pp. 735–749.

Broader Impacts on Society

- We are developing means to expand the kinds of high-performance operations can be achieved safely by cyber-physical systems
- Our scalability experiments indicate applicability of more complex RTHS to even wider ranges of problems, scenarios, and environments
- Both of these are broadening the potential of our research to impact other areas (e.g., astrophysics, environment, energy harvesting)

Broader Impacts in Education and Outreach

- Education and training of 8 PhD students (4 at Purdue and 4 at WUSTL) + 1 Masters Thesis student (at WUSTL)
- Planned involvement of undergraduate students in research experiences in Summer 2024
- Prompt publication of benchmark problem statements, software, platform specifications, and empirical results
- Regular publication of technical results in high quality conferences and journals relevant to the CPS community

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