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

Washington University (Lead): Chris Gill (PI), Sanjoy Baruah (co-PI); Purdue University: Shirley Dyke (PI), Arun Prakash (co-PI)
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

New Real-Time Hybrid Simulation (RTHS) Setup for Nonlinear MIMO Experiment

- The system comprises a nonlinear multi-actuator assembly with two vertical actuators operating in force control, a horizontal actuator functioning in displacement control, and a small-scale specimen, all connected through a coupling beam
- The objective of this setup is focused on investigating the mechanical behavior of complex specimens utilizing RTHS and developing the control system for this purpose
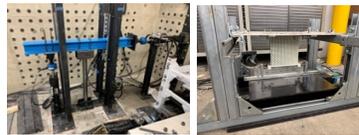
New RTHS Setup for Characterizing Seismic Metamaterials

- Experimental setup for testing architected seismic metamaterials under dynamic loads was designed
- Seismic metamaterials are architected materials with extraordinary properties that have the potential to drastically mitigate the impact of seismic events
- To characterize the dynamic performance of seismic metamaterials, RTHS can be carried out using the CyberMech platform

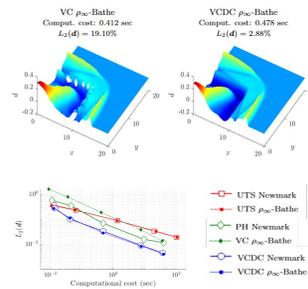## Updated CyberMech Codes for Conducting RTHS

- virtual RTHS (vRTHS) for an isolator supported two-story frame which is separated into linear numerical substructure using the CyberMech platform, which are connected to Matlab-Simulink served as nonlinear physical substructure
- Uniaxial vRTHS for a benchmark control problem of a three-story two-bay earthquake-excited building was conducted
- Multi-axial vRTHS for a benchmark control problem of a three-story three-bay earthquake-excited building was also conducted
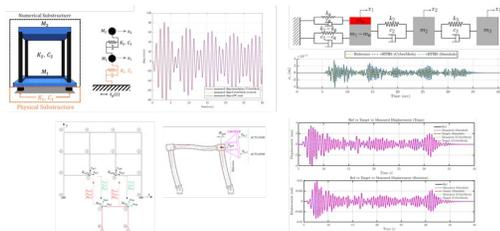
Improved Time Integrators

Unified Multi-Time-Step (MTS) framework

- Allows multiple time-steps in multiple subdomains with multiple continuity conditions
- New MTS methods that simultaneously impose velocity and displacement continuity
- Eliminates drifts in displacement
- More accurate and lower computational cost compared to existing MTS methods, achieving unconditional stability

VC ρ_∞-Bathe
Comput. cost: 0.412 sec
$L_2(d) = 19.10\%$

VCDC ρ_∞-Bathe
Comput. cost: 0.478 sec
$L_2(d) = 2.88\%$

- □ UTS Newmark
- ■ UTS ρ_∞-Bathe
- ◆ PH Newmark
- ◆ VC ρ_∞-Bathe
- ○ VCDC Newmark
- ● VCDC ρ_∞-Bathe

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

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

3σ GPU time (log scale, us)

RTX A5000 DOF 2348

Latency of GEMV on U250 and A5000
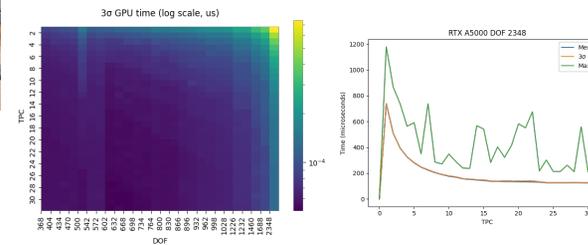
GPU Analysis

- Multiple individual cuBLAS kernels
  - Transforming kernels into a single CUDA graph greatly reduces execution time
- CUDA Green Contexts allow device partitioning
  - TPC units can be partitioned with each containing 2 compute processors
  - Multiple models could be executed concurrently if device is partitioned
- Some model sizes cause large regressions in running time
- Small models constrained by device response time
- Large but rare spikes in response time still present due to communication on graph launch

Hardware Comparison

- CPU – parallelism with OMP or BLAS
- Test scalability with nine-story moment resisting frame structure from [Aguilar2012]
- BLAS outperforms OMP
- Diminishing returns and then receding benefits as more cores added
- GPU – implement matrix operations with cuBLAS
- Outperformed by CPU blas implementation due to kernel launch overhead
- FPGA – custom BLAS implementation
  - GPUs better at large linear operations, eg GEMV (left)
  - FPGAs likely better at nonlinear operations, eg parametric functions in nonlinear state estimators

Scheduling of Linear vs Nonlinear State Estimators

- Tradeoff of the computational efficiency of linear estimators vs the accuracy of nonlinear estimators
- Dynamic switching of state estimator may be required, creating two questions:
  - What metrics decide when such a handoff is necessary?
  - How many timesteps are needed to complete the handoff?
- Simulink testbench made to examine these questions
  - Tests open loop – measures error of state estimation given disturbance
  - Tests closed loop – measures energy consumed to stabilize system

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
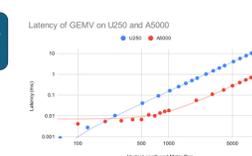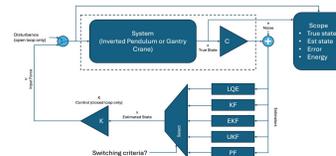
Broader Impacts on Society

- 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)

[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.

Washington University in St. Louis

PURDUE UNIVERSITY