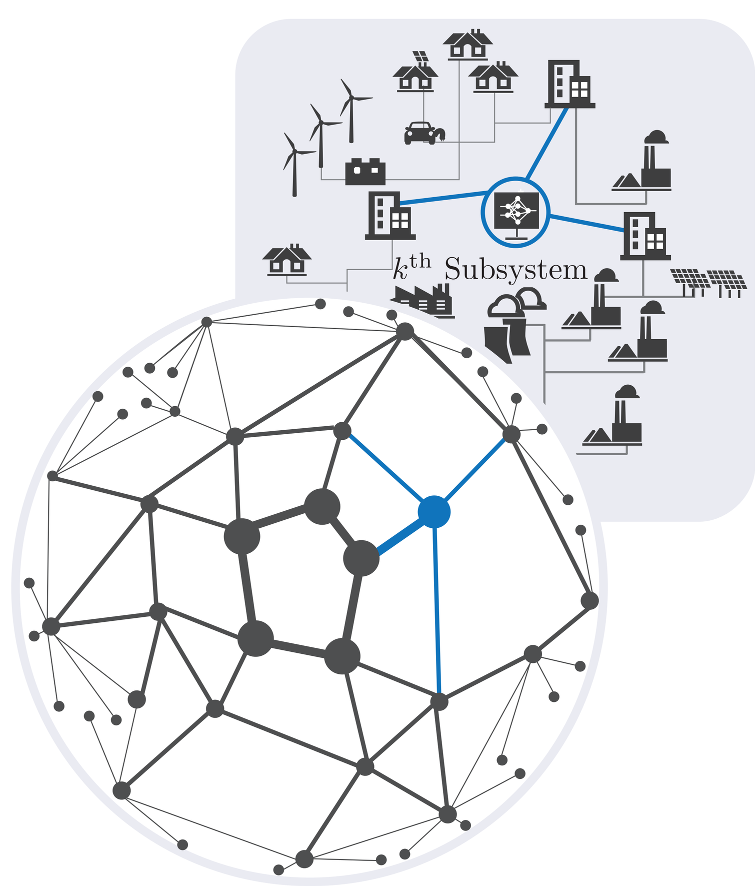
CPS: Medium
Compositional Learning and Control of Networked Cyber-Physical Systems

David Fridovich-Keil, Brian Johnson, and Ufuk Topcu (UT Austin)

TEXAS
The University of Texas at Austin



Preliminary work
- Port-Hamiltonian neural networks
- Enforcing physical invariants in neural network models of dynamical systems
- Neural stochastic differential equations for dynamical system modeling

Thrust 2: Uncertainty-Aware Learning
- Learn stochastic differential equation models of port-Hamiltonian systems
- Design risk-aware algorithms for subsystem control that exploit the computational structure of the learned models

Thrust 1: Data-Driven Port-Hamiltonian Subsystem Modeling
- Exploit physical invariants and component interface topology to learn with limited data
- Real-time data-driven control with robust tracking guarantees

Thrust 3: Network-Level Guarantees and Subsystem Model Refinement
- Derive system-level guarantees from learned subsystem models and controllers
- Targeted data collection for refinement of learned subsystem models and controllers

Key Challenges

1. Data-driven models often generalize poorly, especially when trained on limited data
   (e.g., renewable energy generation and storage system dynamics are poorly modeled)
2. Large-scale networked systems demand modular, compositional designs which scale gracefully while preserving performance guarantees
   (e.g., power systems can include millions of thousands to millions of endpoints)

Scientific Impact

1. Develop data-driven models of subsystem dynamics which leverage physical invariants and connection topology to generalize and adapt to new circumstances with minimal training data.
2. Derive system-level guarantees based upon learned subsystem models and connection topology, and use the structure of these guarantees to guide targeted data collection for subsystem model refinement.

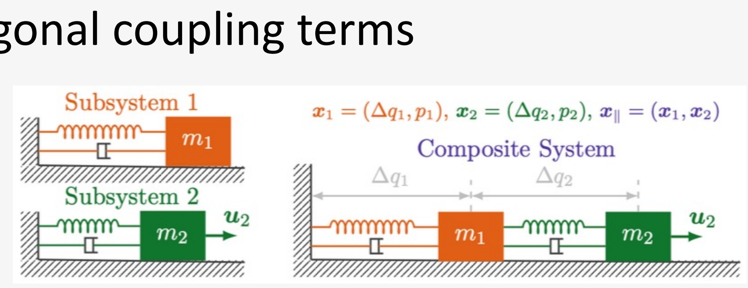
Background

A *port-Hamiltonian* dynamical system is expressed via:

$$\dot{\boldsymbol{x}} = [\boldsymbol{J}(\boldsymbol{x}) - \boldsymbol{R}(\boldsymbol{x})]\nabla_{\boldsymbol{x}} H(\boldsymbol{x}) + \boldsymbol{G}(\boldsymbol{x})\boldsymbol{u}$$

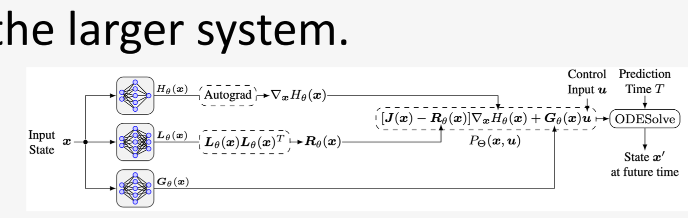
energy-conserving interactions; energy dissipation; total energy; input; state

To compose two port-Hamiltonian subsystems:
- Dissipation and control input matrices stack diagonally
- Interconnection matrices stack diagonally, and include additional off-diagonal coupling terms
- Hamiltonians add

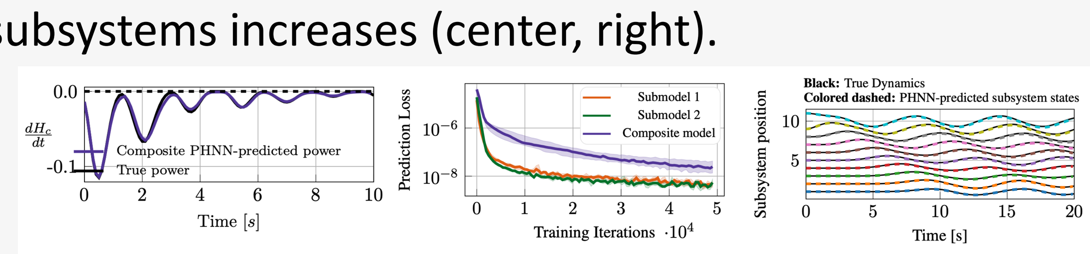


Enabling Result

We can train separate port-Hamiltonian neural networks on data from each subsystem, and compose learned models via *known* interconnection matrix *J(x)* to model the larger system.

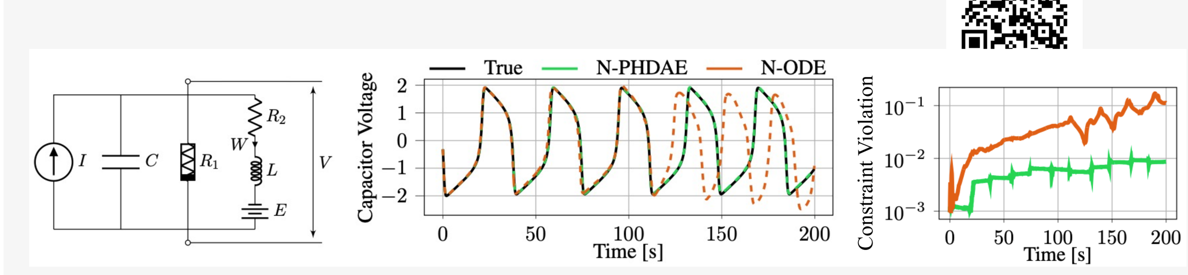


These models enforce cyclo-passivity (left) and strong prediction accuracy even as the number of connected subsystems increases (center, right).



Recent Progress

We have extended the framework of port-Hamiltonian neural networks to account for algebraic constraints on state variables that can arise in power systems. The resulting neural port-Hamiltonian DAEs achieve order-of-magnitude improvements in prediction accuracy and constraint satisfaction when simulating the dynamics of nonlinear circuits.



Broader Impacts

- Proposed techniques can integrate modularly with legacy power system designs, presenting a low barrier to entry which will enable utilities and regulators to insert and test these tools in larger networks without a substantial overhaul.
- Ultimately, the proposed research will generate more accurate subsystem models than exist today, and controllers which exploit these models to save energy while improving reliability in the face of environmental and other shocks.

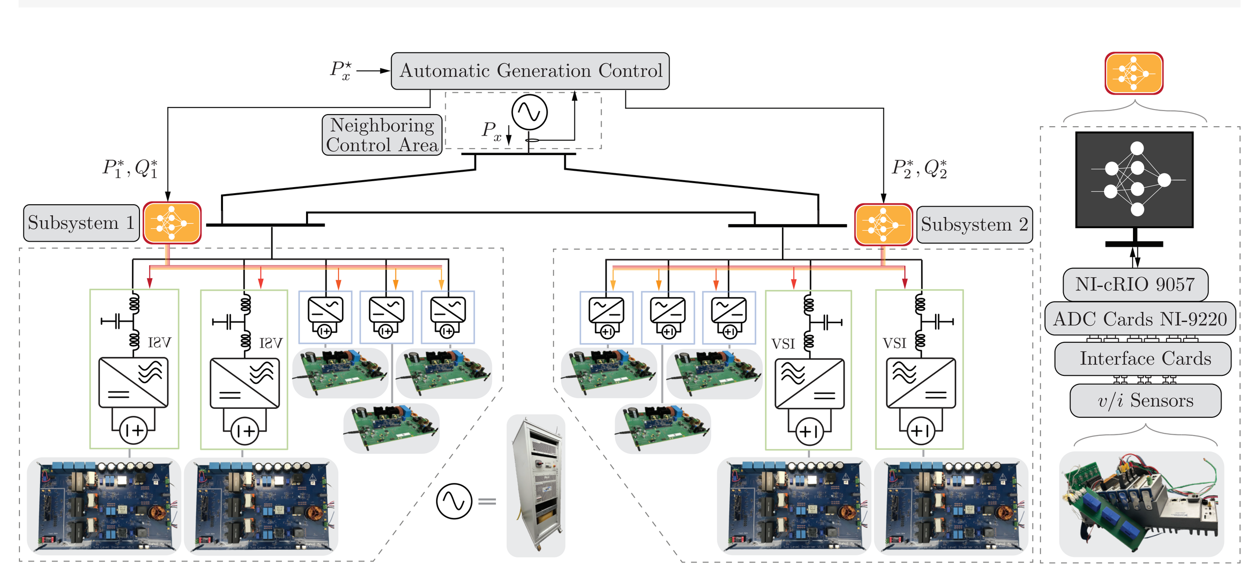


Diagram of hardware testbed with programmable inverters hardware that will act as grid assets. The testbed will contain two subsystems controlled by the proposed learning-based methods embedded within NI modules. A neighboring control area is mimicked with a programmable grid simulator.

Education and Outreach

- Integration with existing graduate classes in *Verification and Synthesis in Cyberphysical Systems* (Topcu) and *Advanced Power Electronics* (Johnson)
- Mentoring undergraduate researchers, e.g. through REU programs and course projects
- Exposing local high schoolers to ongoing research via the Career and Technical Education program in unmanned aerial systems at the Del Valle Independent School District (Del Valle, TX)