Cyber-Physical Energy System Modeling

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Goal

- Codify and define the cyber-physical modeling approach developed at Hyper to create an extensible industry-facing cyber-physical modeling approach to complex energy system development,
- identify and develop academic, national lab, and industry partners who can participate in the development of this approach,
- work with these partners to identify needed cyber-physical models of energy systems, and
- start to develop an initial open source software base to support the integration of cyber-physical systems.
What is the purpose of models?

“In modern engineering practice, scarcely any new type of structure or machine, whether it be a long-span bridge, a canal, a jet engine, or a supersonic speed airplane, is constructed until a model of it has been built, tested, redesigned, and retested, often several times.”

... 

The observations may be made on models, or entities which are usually smaller, less expensive, and more easily altered than the one for which the characteristics are to be established.”

Glenn Murphy, *Similitude in Engineering*, 1950
Cyber-physical systems

- Engineered systems that are built from, and depend upon, the seamless integration of computation and physical\(^1\)

- Physical and engineered systems whose operations are monitored, coordinated, controlled, and integrated by a computing and communication core\(^2\)

- The integration of computation with physical processes whose behavior is defined by both cyber and physical parts of the system\(^3\)

- Networks of tightly integrated physical processes with computation components designed to monitor and control the physical world intelligently\(^4\)

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\(^1\)National Science Foundation, “National Science Foundation Cyber-Physical Systems Solicitation.” (2021)


Cyber-physical models

- Intelligent models whose behavior is driven by cyber and physical parts that are seamlessly integrated by a computing and communication core.

- These models can be less expensive than the engineered system tested and can be quickly and easily altered, tested, redesigned, and retested, multiple times to enable co-design of complex or entangled systems.

*Models constructed using cyber-physical systems to accurately predict the performance of a specific detail or aspect of an engineered system or component.*
Today, much of physical modeling has been replaced by computational modeling with the benefits of cost, flexibility, and time; however, the “ground truth” of physical modeling is now provided by an extensive (time consuming and expensive) pilot plant program.

*Cyber-physical modeling can provide the flexibility of computational modeling and the “ground truth” of physical modeling at much lower cost while substantially reducing the time from concept to realization.*
Cyber-physical energy system models

Systems models composed of one or more cyber-physical modules.

Compressed air energy storage

Challenges
- Improve round trip efficiency
- Reduce cost
- Enable heat addition from various sources (natural gas, solar, geothermal, …)
- Dynamic controls and integration

Co-design
Cyber-physical energy system models

Systems models composed of one or more cyber-physical modules.
Cyber-physical energy system models

Systems models composed of one or more cyber-physical modules.
Developing a cyber-physical model

1. Define the purpose of the cyber-physical model
2. Identify the essential functions of each component of the system
3. Determine how to best represent each component of the system
   [Physical, computational or cyber-physical]
4. Determine the system requirements and the interface requirements between the components
5. Build the physical, computational, and cyber-physical components
6. Assemble and build the cyber-physical model
Solid oxide fuel cell - internal combustion engine hybrid

Colorado School of Mines
(US Patent US 11,145,880 B2)

University Wisconsin-Madison
Chuahy and Kokjohn et. al., 2018

Stony Brook University
Ran et. al., 2021
Solid oxide fuel cell - internal combustion engine hybrid
SOFC-ICE Cyber-physical model

\[
\dot{m}_{air}, p_{air}, T_{air} \quad \text{Middleware Layer} \quad \Delta Q \quad \Delta h_c
\]

\[
\dot{m}_{fuel} = \frac{\Delta Q}{LHV} \quad \dot{m}_{fuel,ICE}
\]

- Thermal
- Pressure
- Mass flow
- Thermal
Cyber Layer - SOFC module

System model inputs
\( m_{\text{fuel}}, p_{\text{fuel}}, T_{\text{fuel}} \)

Live sensors
Physical Layer
\( m_{\text{air}}, p_{\text{air}}, T_{\text{air}} \)

\( h_{\text{in}} \)

Preheater Model

Anode Model

Electrolyte Model

Cathode Model

Combustor Model

Condenser Model

\[ \Delta Q = h_{\text{out}} - h_{\text{in}} \]

\( h_{\text{out}} \)

Turbine Inlet

ICE Mixer

\( \Delta Q \)

\( \Delta h_c \)

Physical Layer - Control System
Middleware Layer

- **dSPACE**
- **OPAL-RT**
- **INL**
- **ES-NET**
- **VPN**
- **High speed Transducer**
- **Industrial CAN BUS No.1**
- **Industrial CAN BUS No.2**
- **Electric Load Bank Modbus**
- **MicroNet Woodward**
- **ICE CAN bus**
- **Serial Communication**
- **Bently Nevada**
- **High speed transducers**

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What about hardware-in-the-loop?

Hardware-in-the-loop …

… a real-time simulation that contains both computational and physical components that share information. Generally, this information share is focused on the performance of one of the components that is being tested and often does not fully address the performance of other components within the system.
What about digital twins?

Digital twin …

… a term used to describe a virtual model that accurately mimics (twins) a physical system, such as a power plant. The goal is that this digital twin is tightly coupled to the physical power plant during operation and information is shared bidirectionally in real time to provide a mirroring response to real-time changes in either the physical or virtual plant.

The virtual representation is developed concurrently with the physical plant and is deployed alongside it, changing throughout the lifecycle of the plant.
A trade-off between ‘ground truth’ and flexibility

Cyber-physical user facility
with established models and methods, integrated computational modeling, and machine learning tools

System detail

Cost and time
Energy system development platform

Integrated Cyber-Physical Energy System Development Platform

- Concept
- Component(s)
- Testing
- Modeling
- Digital twin
- Cyber-physical component models
- System modeling
- Systems modeling
- Bench-scale testing
- Lab-scale testing
- Pilot-scale
- Demonstration
- Cyber-physical systems
- Hardware

Stage 1
Stage 2
Stage 3
Stage 4
Questions?

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