Crosscutting Research Review Meeting

April 10, 2018

Omni William Penn Hotel, Pittsburgh, PA

Advanced Controls Development for Hybrid Systems

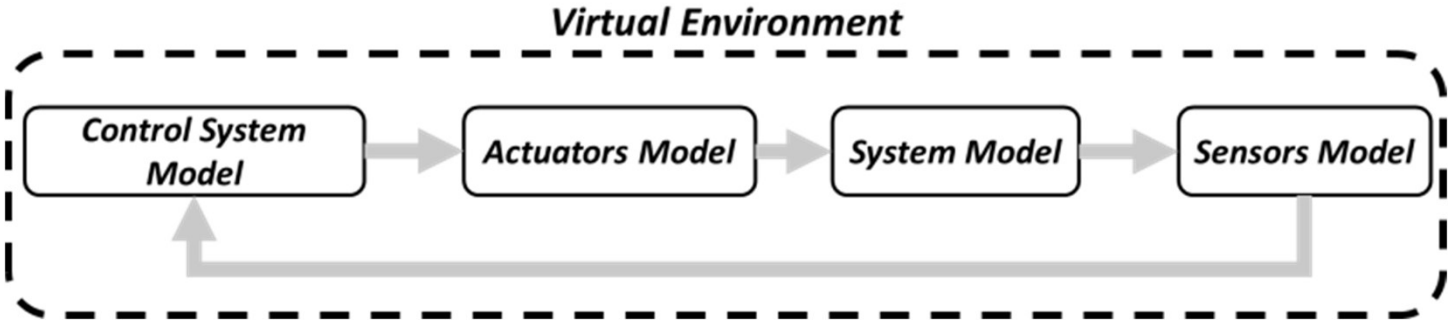
Cyber-Physical Systems: A New Paradigm for Energy Technology Development

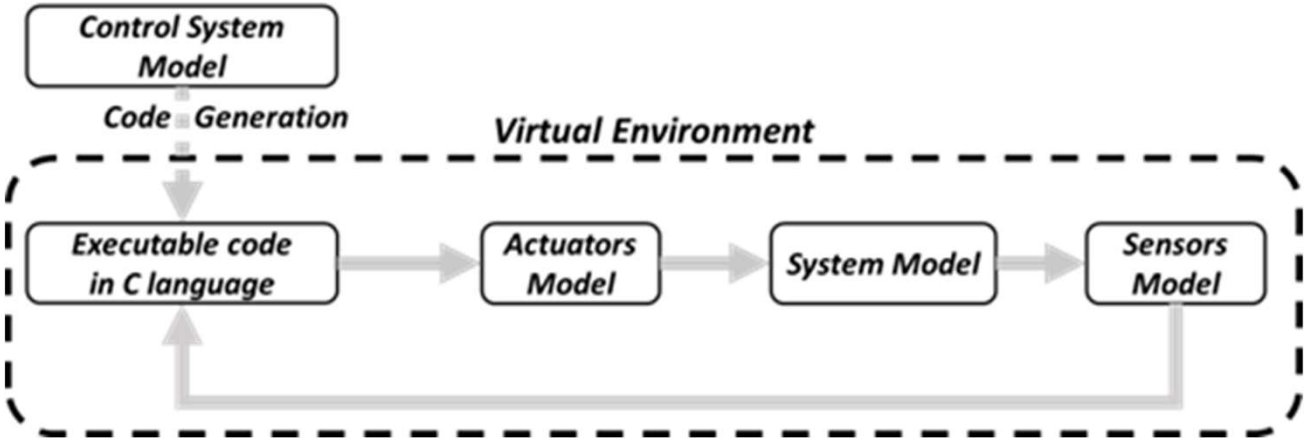
David Tucker, NETL
Larry Shadle, NETL
Farida Harun, NETL
Nana Zhou, NETL

K. Mark Bryden, Ames Laboratory
Paolo Pezzini, Ames Laboratory
Harry Bonilla, Ames Laboratory
Hao Chen, Chongqing University

Solutions for Today | Options for Tomorrow

Model in the Loop vs. Software in the Loop

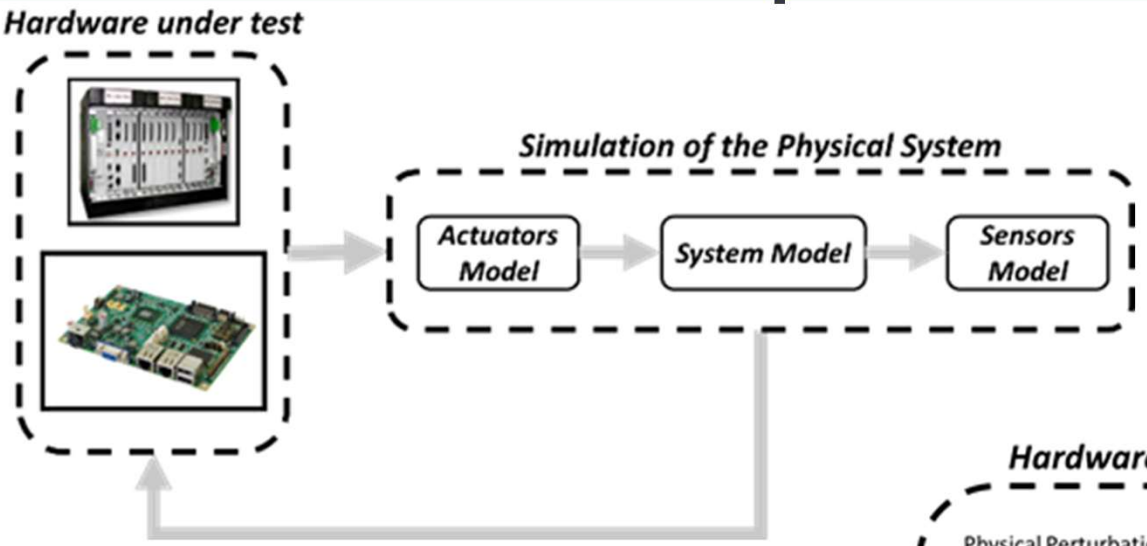




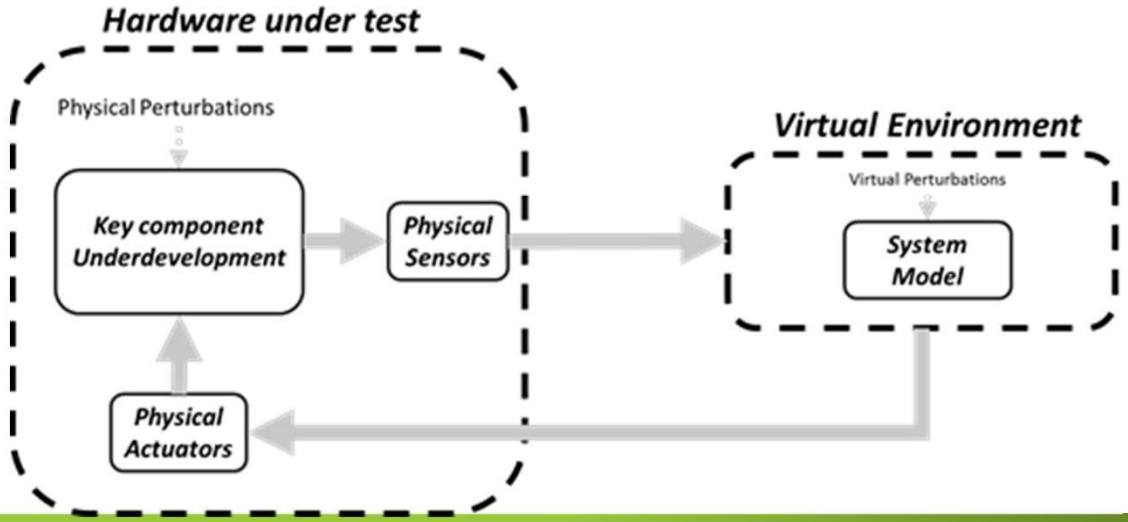
Hardware in the Loop

NATIONAL ENERGY TECHNOLOGY LABORATORY

Typical Application for Controls Testing



Engineering Application for Component Testing



Hardware in the Loop

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Automobile Simulation Model

Hardware Under Test

Length

s, d, x, y, z

$C = 2\pi r$

$s = \theta r$

$\theta = \frac{s}{r}$

Angle

θ (radians) = (rad)

Speed

$v = \frac{d}{t} = \frac{x}{t} = \frac{\Delta x}{\Delta t}$

$v = \frac{dx}{dt}$

$v = r\omega$

$\omega = \frac{v}{r}$

Angular Velocity

$\omega = \frac{\Delta \theta}{\Delta t}$ (rad / sec)

$\omega = \frac{d\theta}{dt}$

Acceleration

$a = \frac{\Delta v}{\Delta t} = \frac{dv}{dt} = \frac{d^2x}{dt^2}$

$a = r\alpha$

$\alpha = \frac{a}{r}$

Angular Acceleration

$\alpha = \frac{\Delta \omega}{\Delta t} = \frac{d\omega}{dt} = \frac{d^2\theta}{dt^2}$ (rad / sec^2)

Kinematic Equations

(1) $x = x_0 + v_0 t + \frac{1}{2} a t^2$

(2) $v = v_0 + at$

(3) $a = const.$

(4) $v^2 = v_0^2 + 2a(x - x_0)$

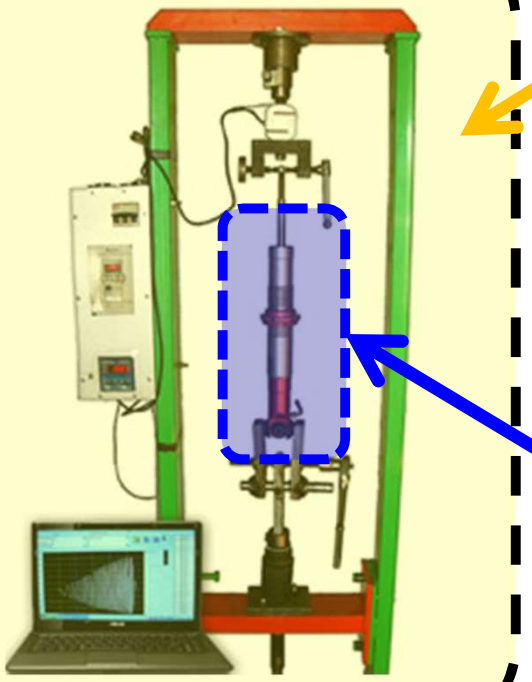
Kinematic Equations

(1) $\theta = \theta_0 + \omega_0 t + \frac{1}{2} \alpha t^2$

(2) $\omega = \omega_0 + \alpha t$

(3) $\alpha = const.$

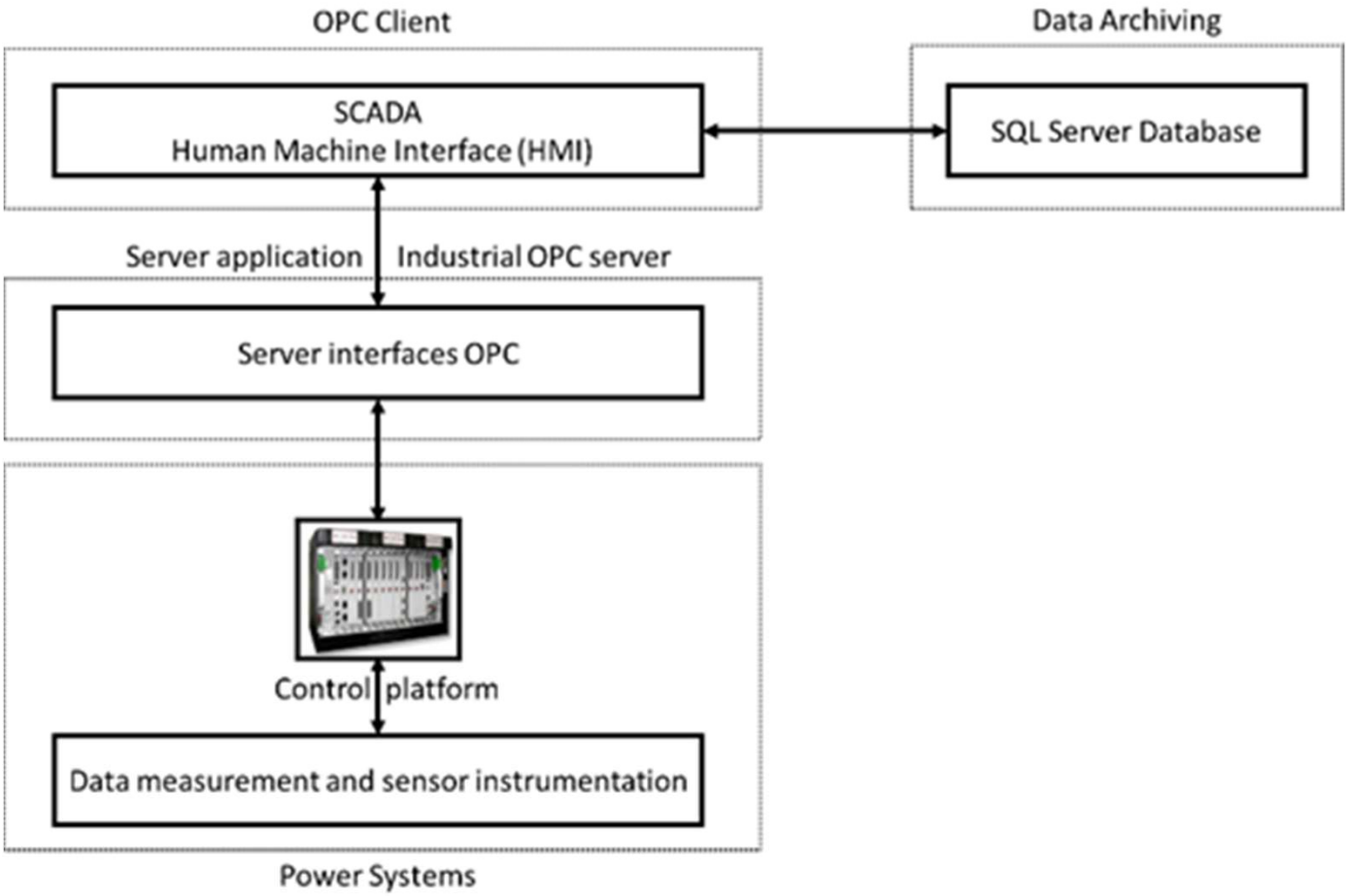
(4) $\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$



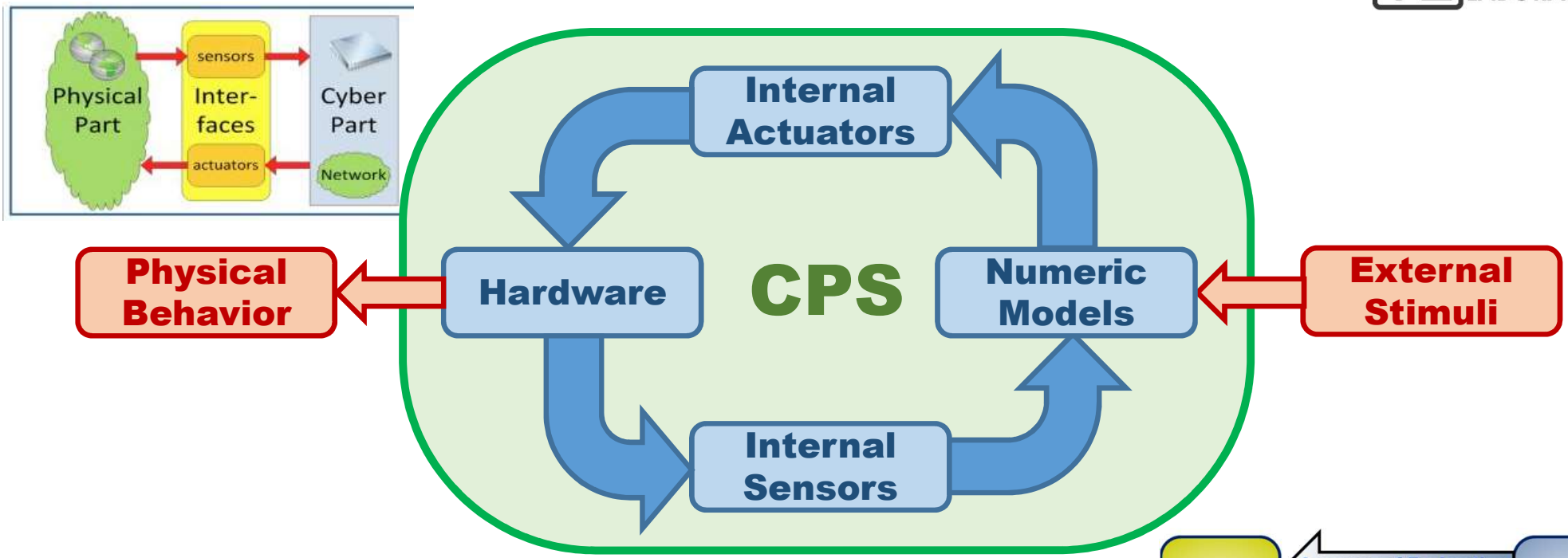
Interface and Middleware

Key Component Under Development (Shock Absorber)

SCADA- Supervisory Control and Data Acquisition



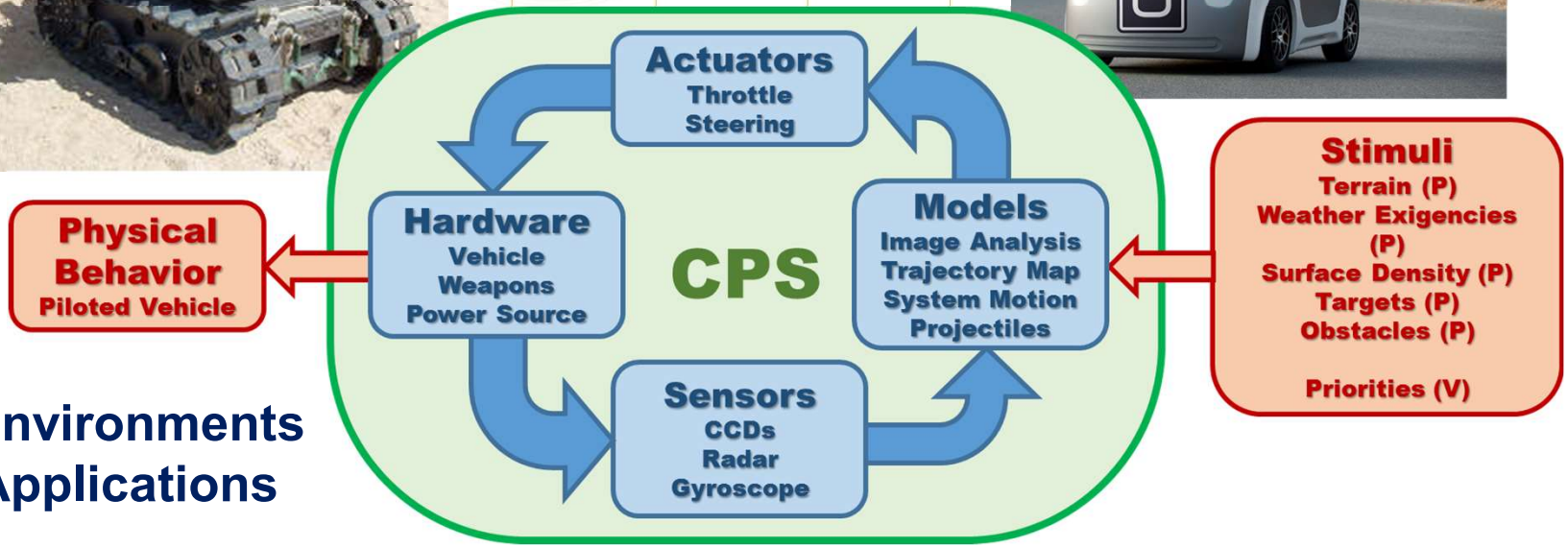
Cyber-Physical Systems



Cyber Physical Systems are used to replace physical systems that:

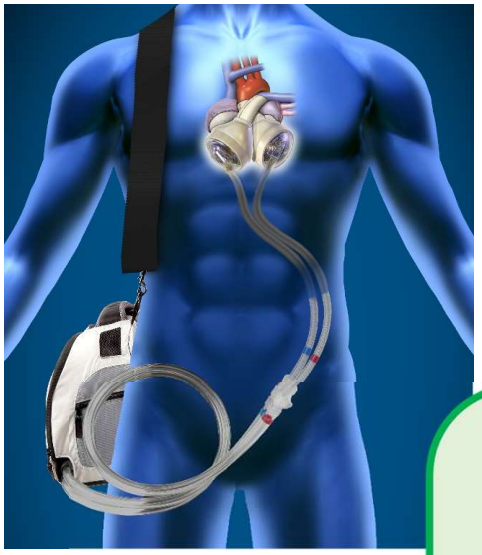
1. are irreplaceable,
2. are expensive,
3. can't meet performance targets.
4. don't exist…yet

Example: Autonomous Vehicles

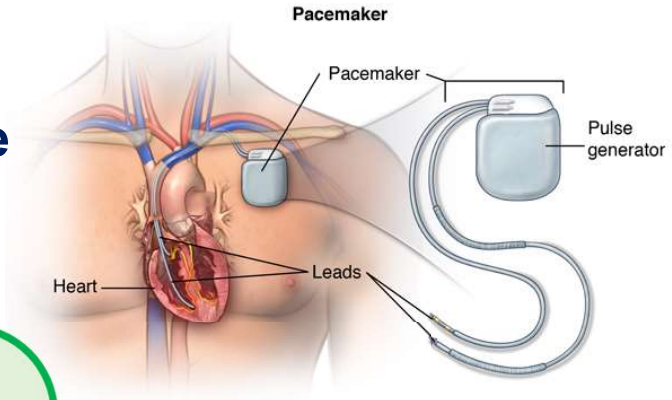


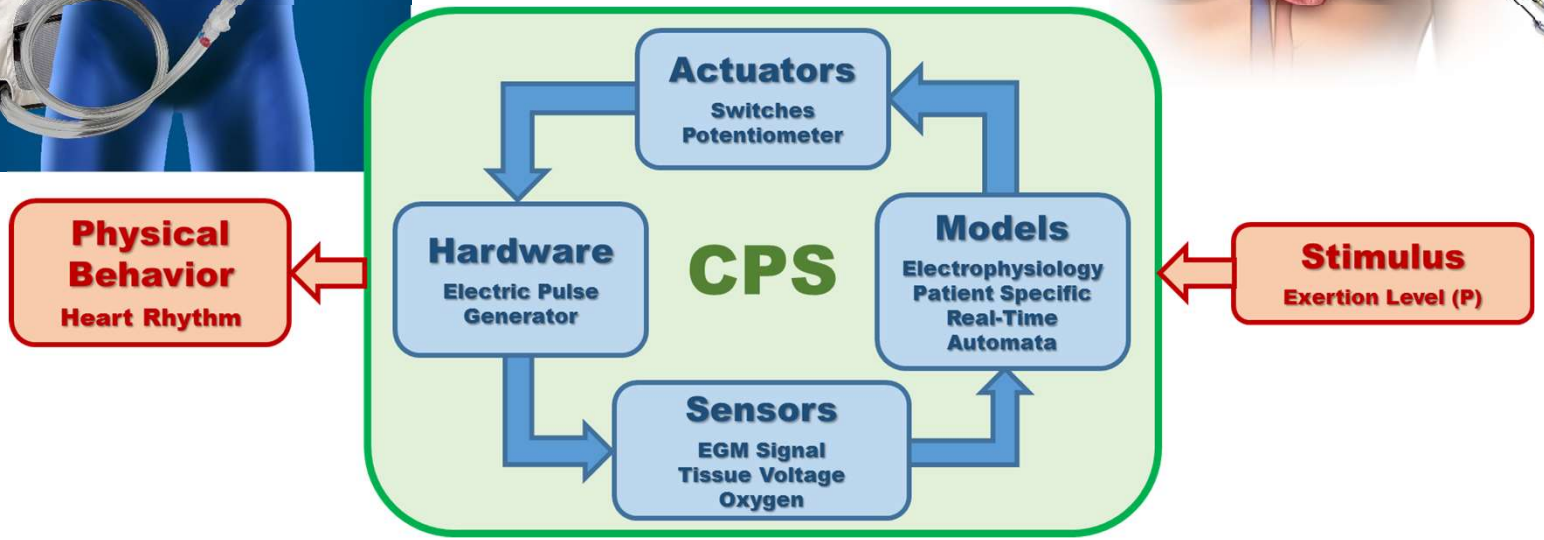
Hostile Environments
Military Applications

Example: Artificial Heart



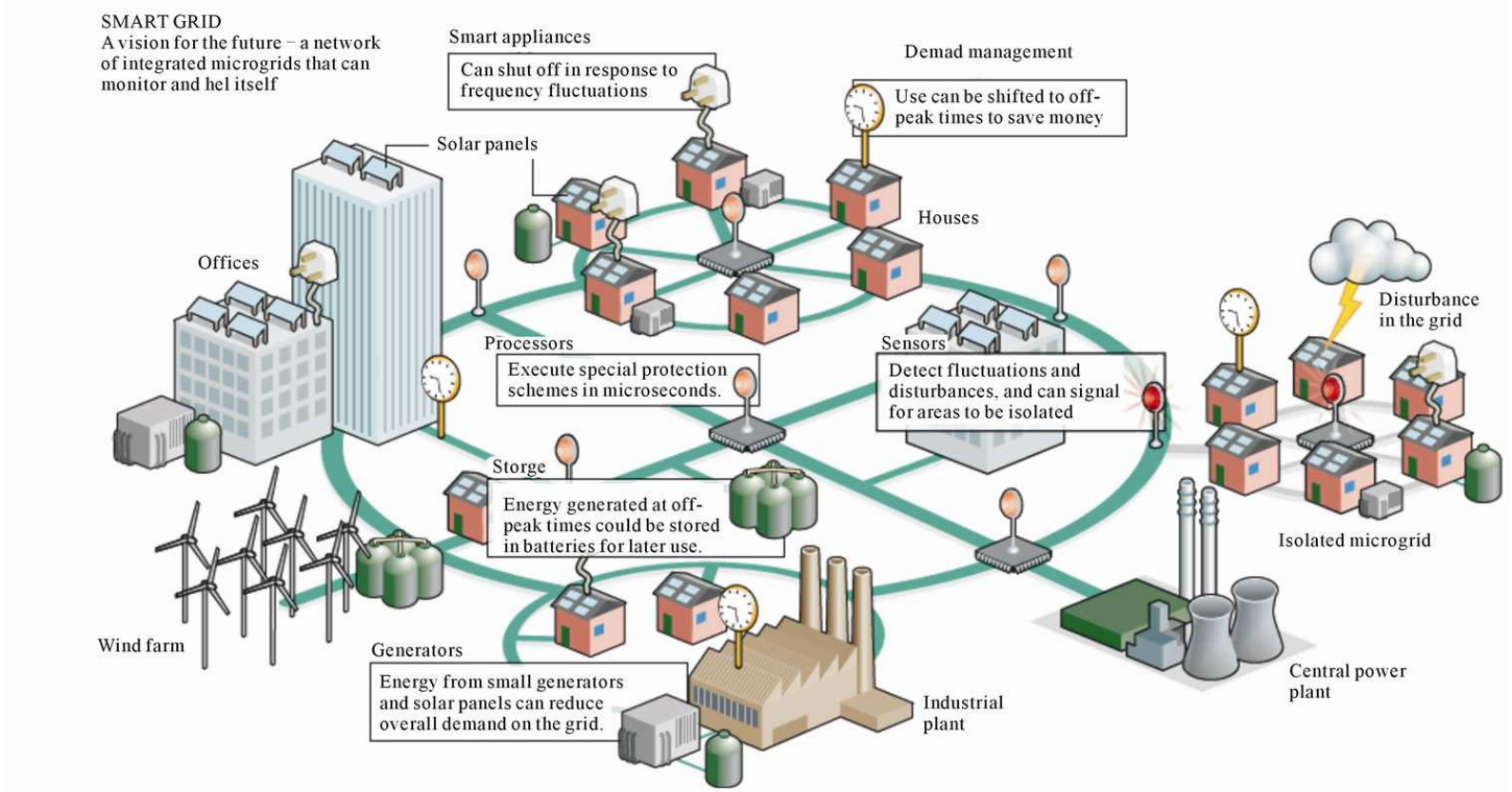
Replacing the Irreplaceable





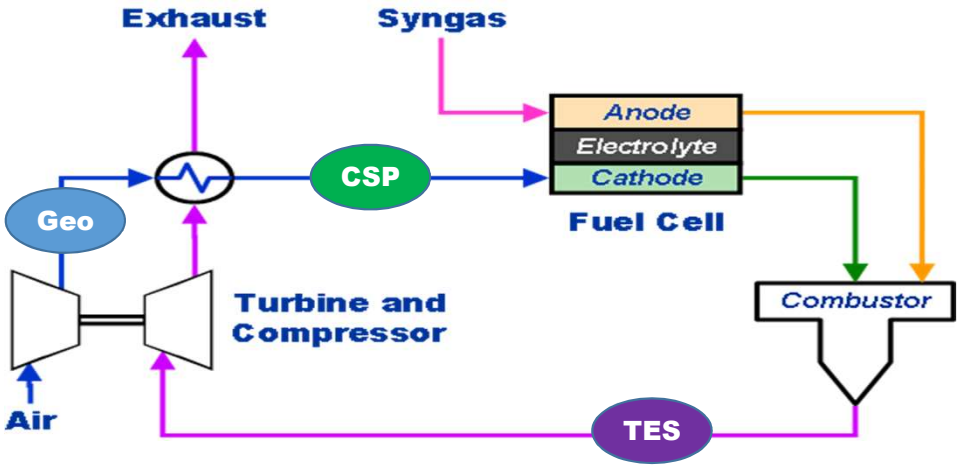
Example: Smart Grid

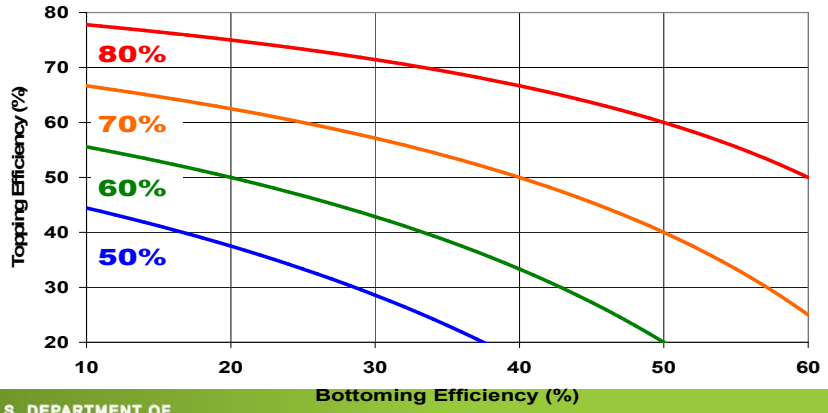
The Only Example in Energy



Advanced Power Systems

Achieving the Maximum Efficiency and Flexibility

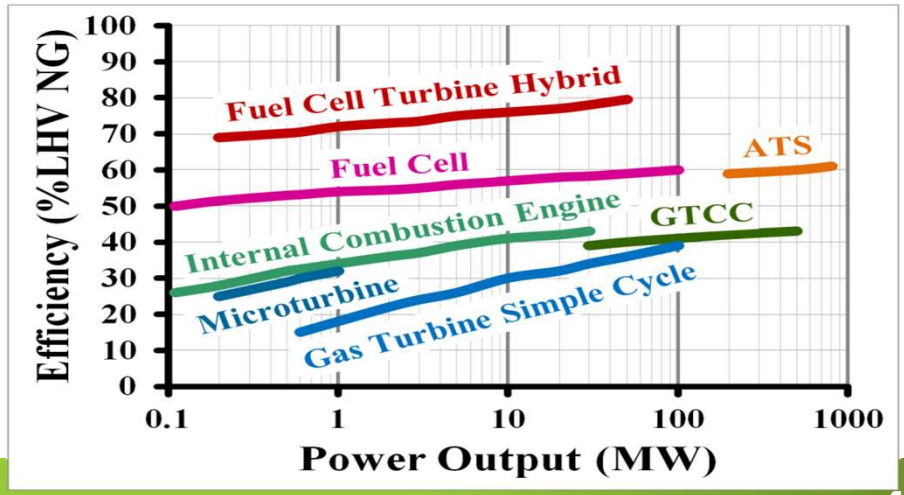




Geo Geo Thermal Steam

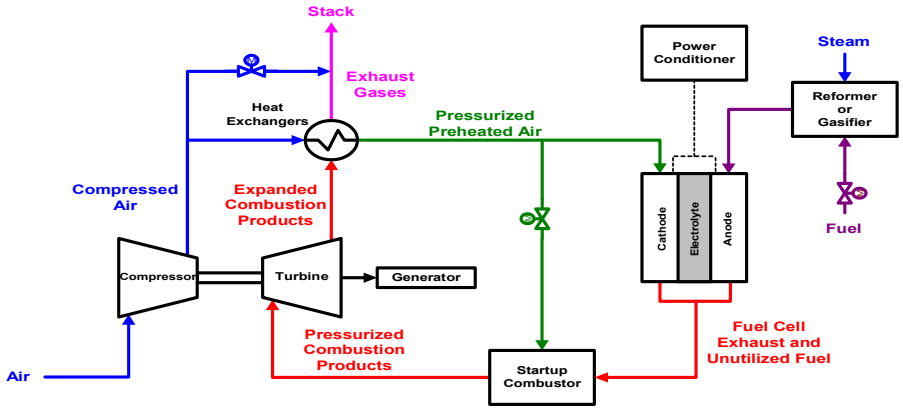
CSP Concentrated Solar Power

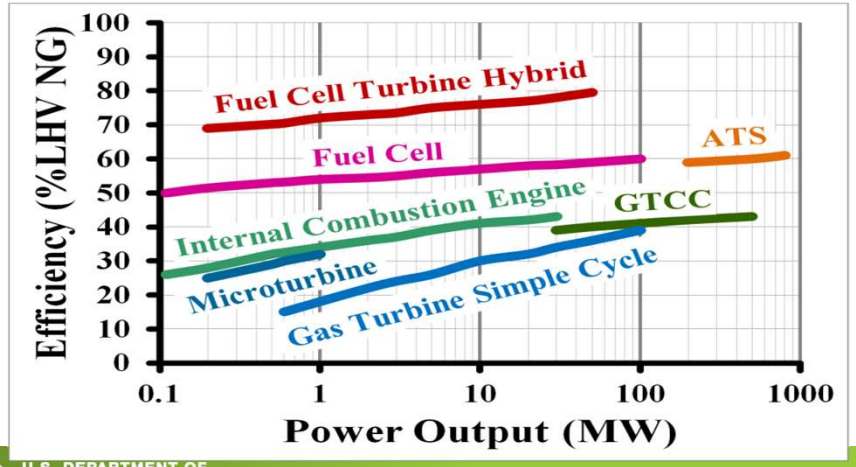
TES Thermal Energy Storage

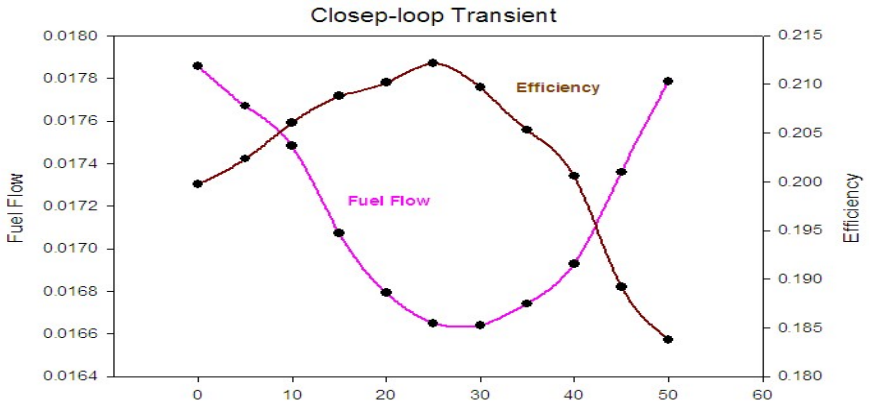


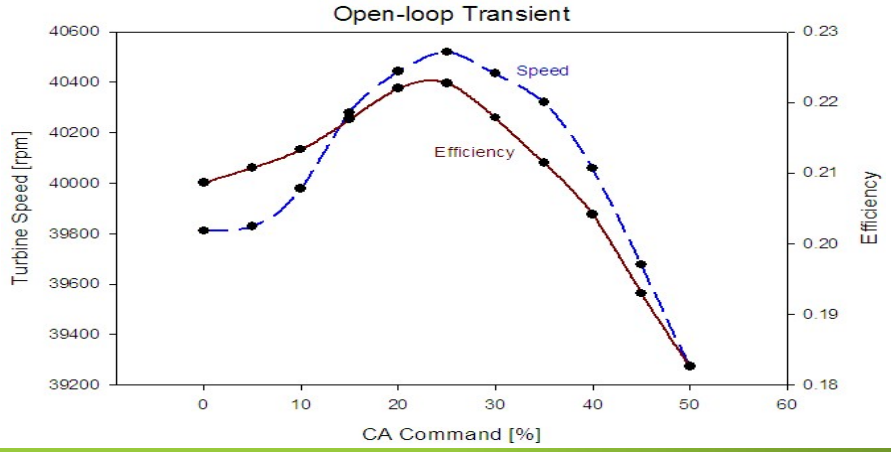
Advanced Power Systems

So What's the Problem?

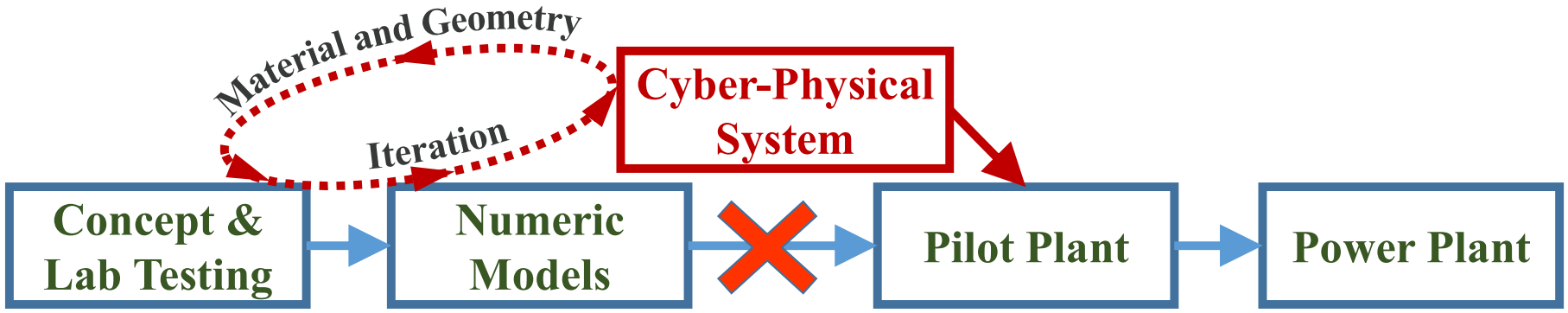




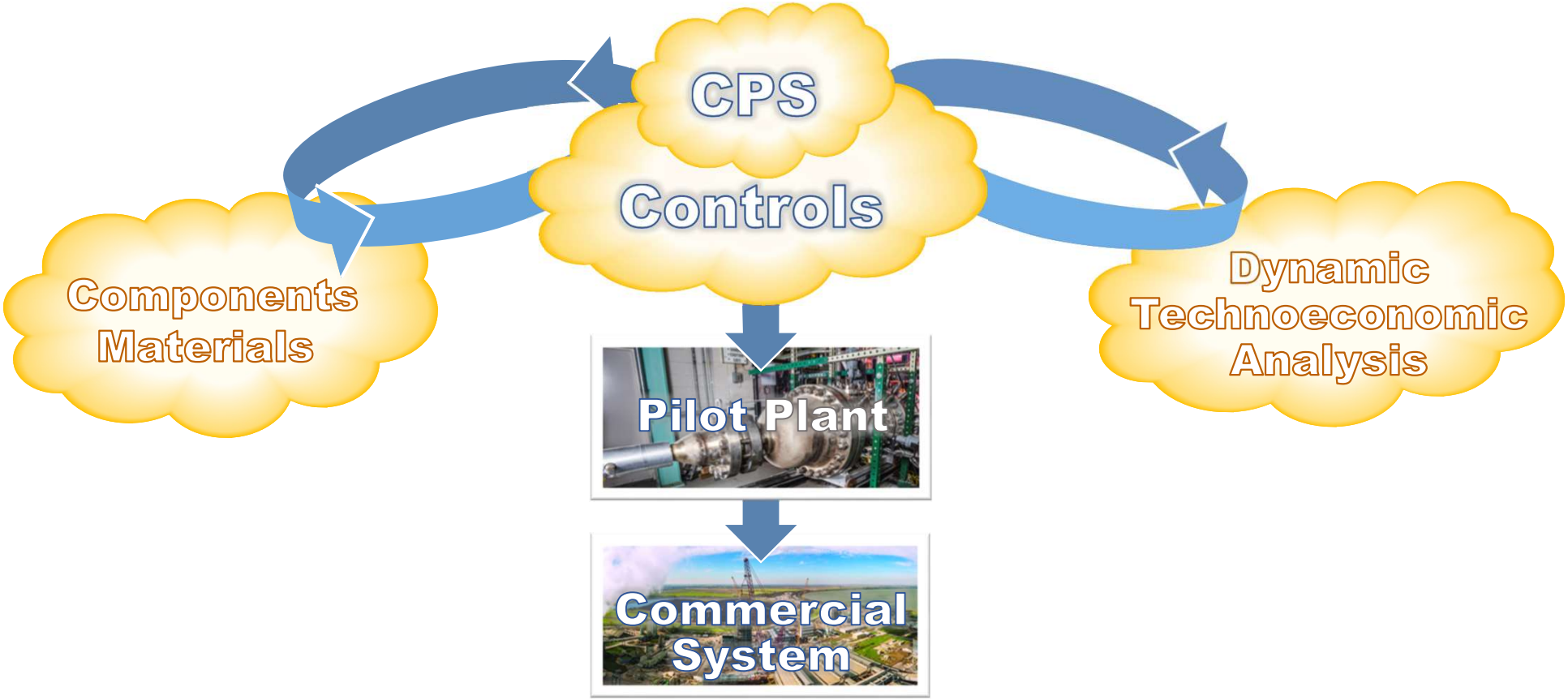




Technology Development

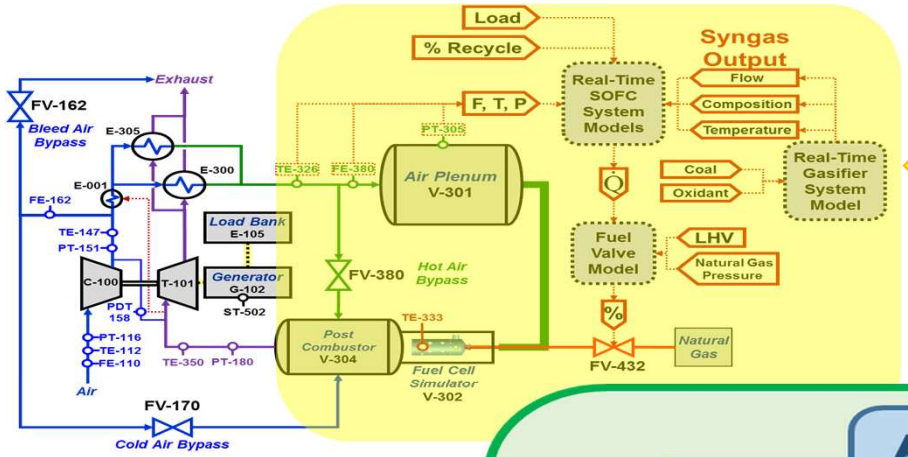


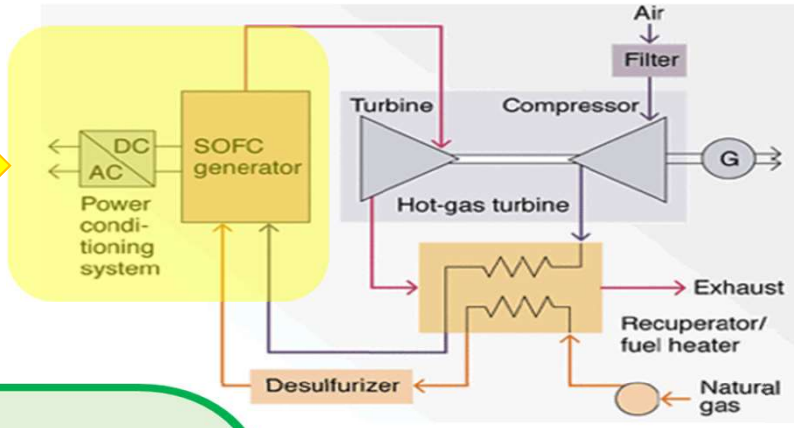
Technology Development

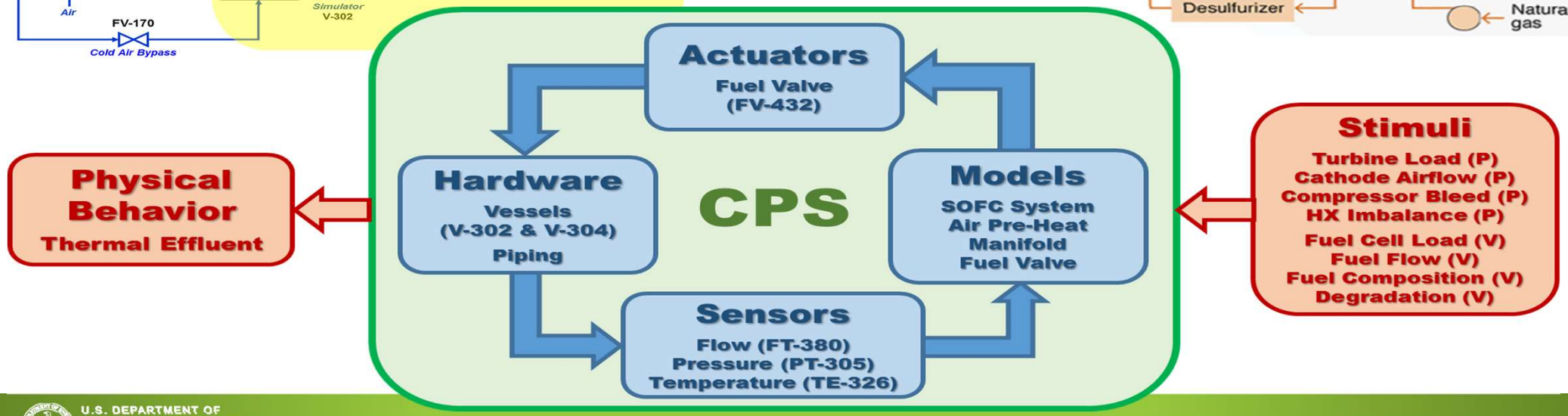


The Hybrid Performance Project Facility

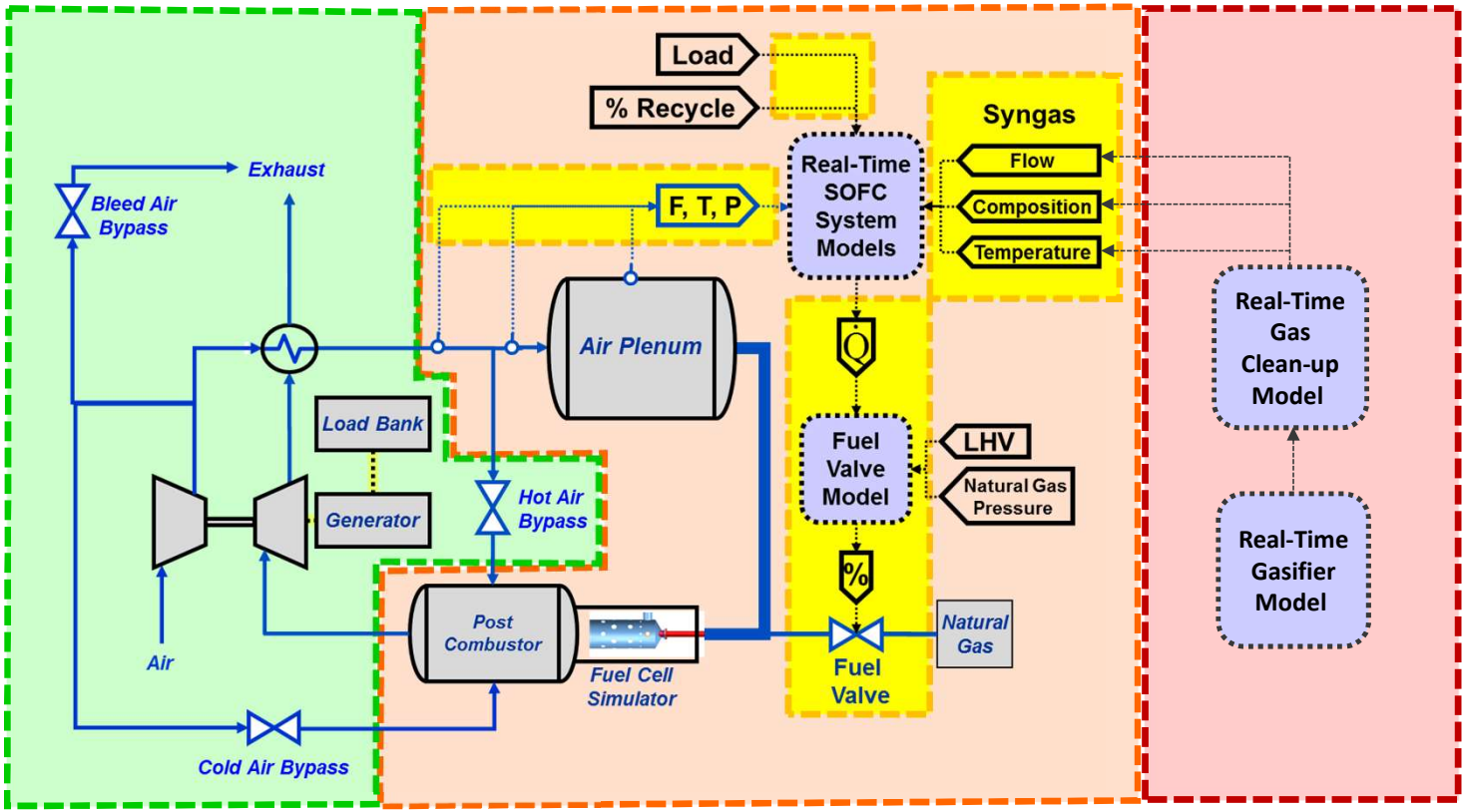
Replacing Components that Don't Exist…Yet

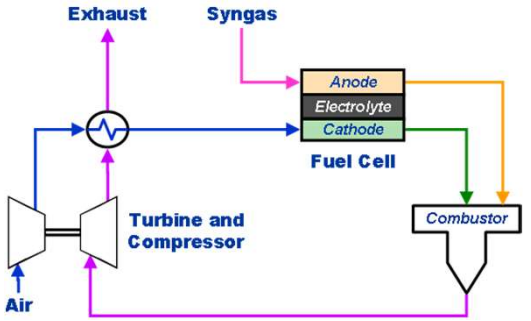






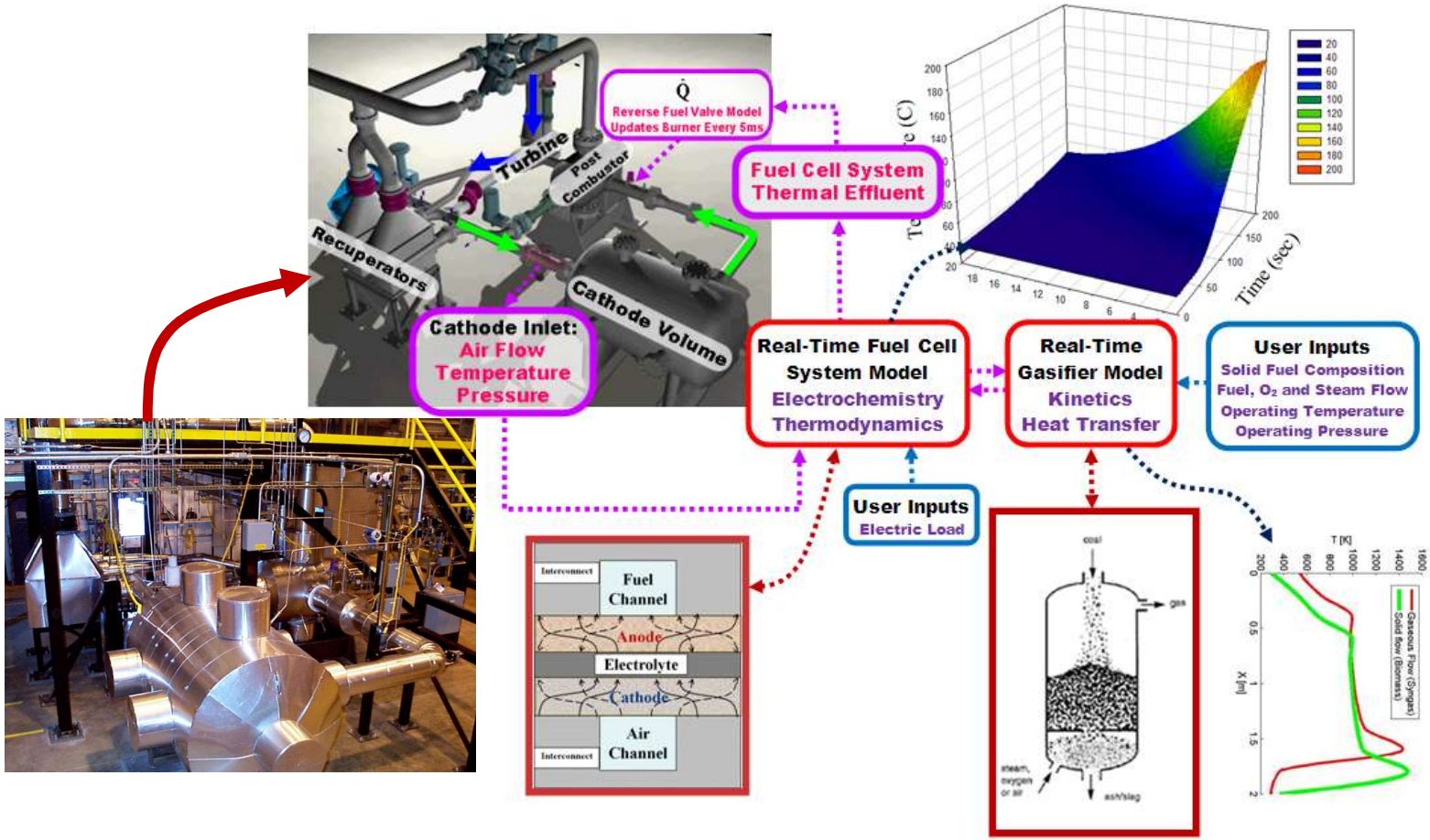
The Hybrid Performance Project Facility



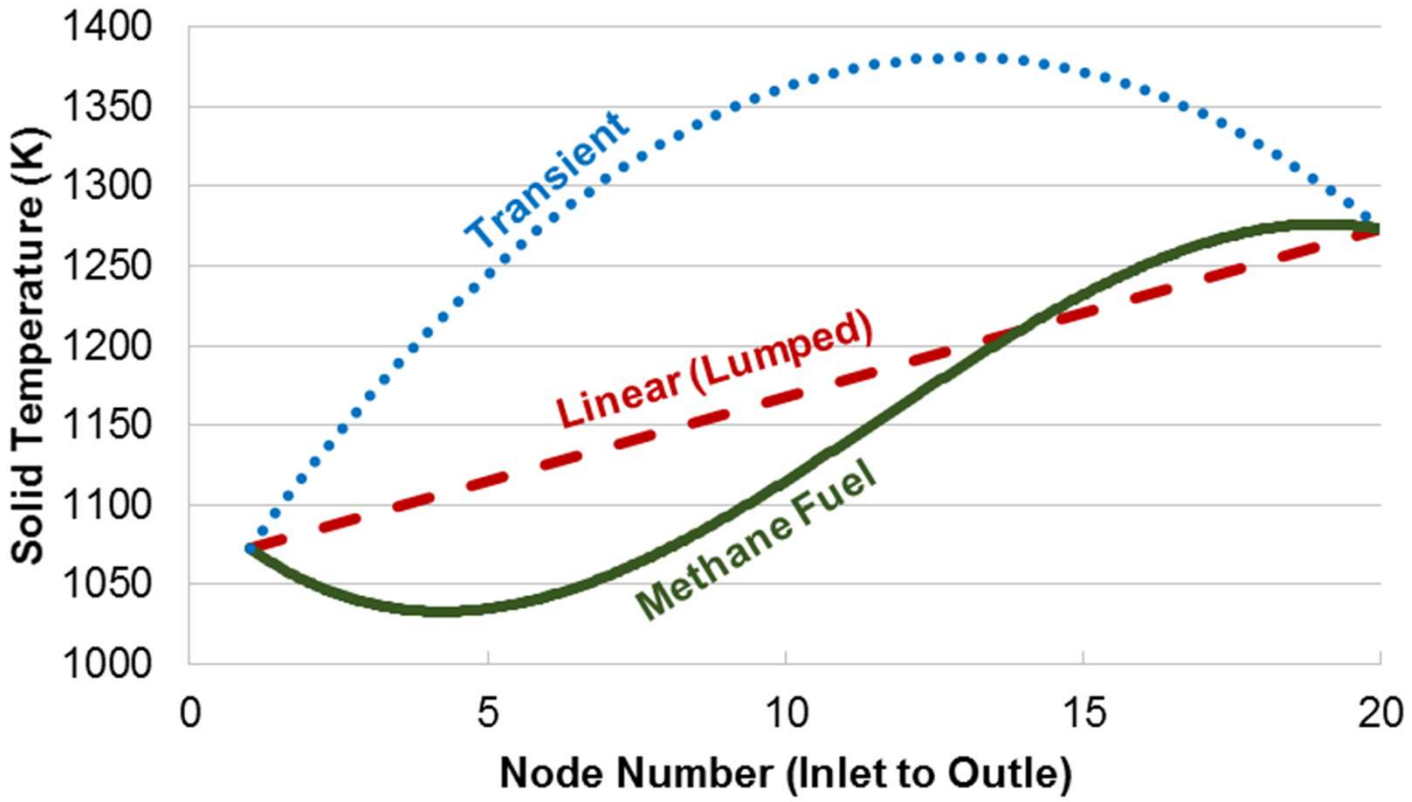


Interface and Middleware

The Hybrid Performance Project Facility

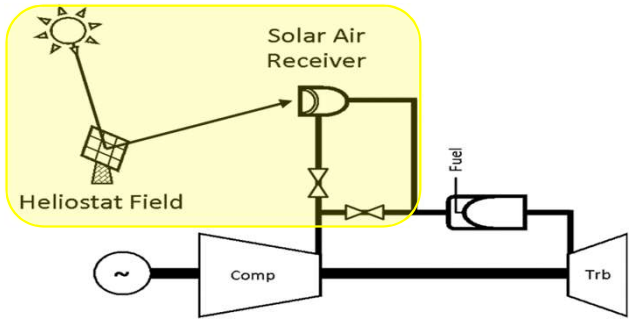


Lumped vs. Distributed for Controls

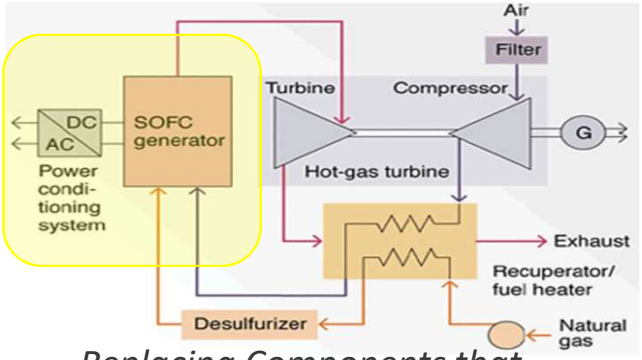


Future Opportunities for CPS at NETL

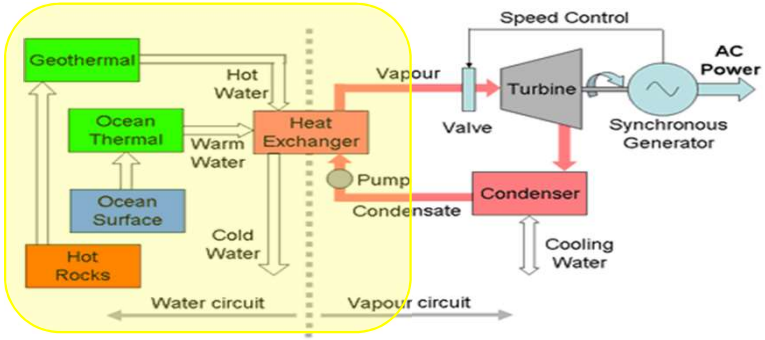
Mitigating Pilot Scale Risk



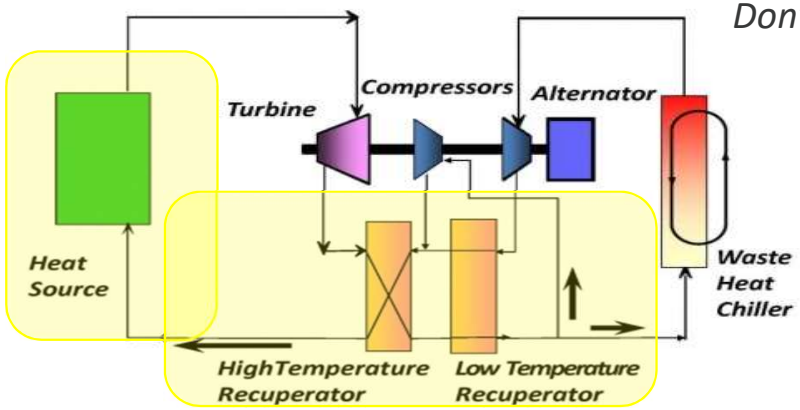
Hyper From Fuel Cells to Concentrated Solar Power



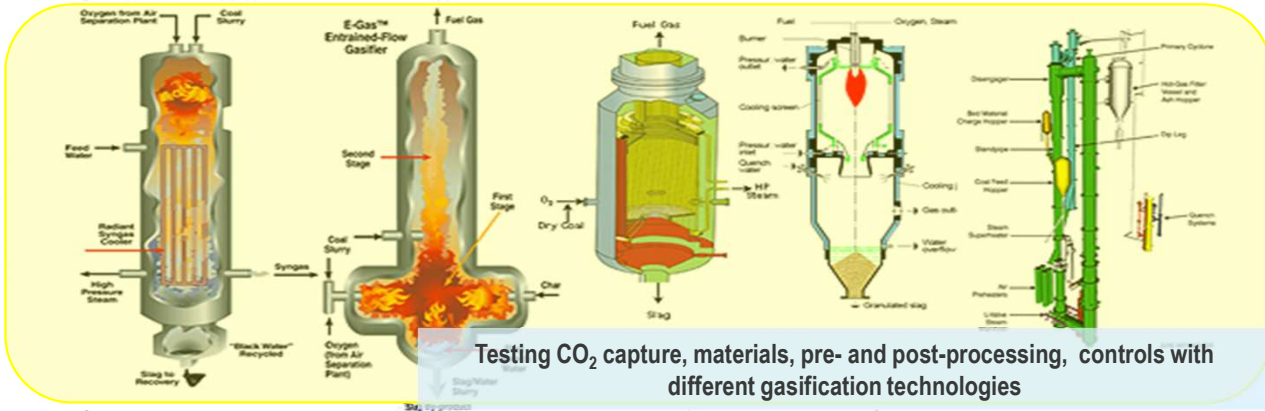
Replacing Components that Don't Exist…Yet



Geothermal Electric Power Hybrid



Supercritical CO_2 Cycles *Taking Advantage of Reconfigurable CPS*

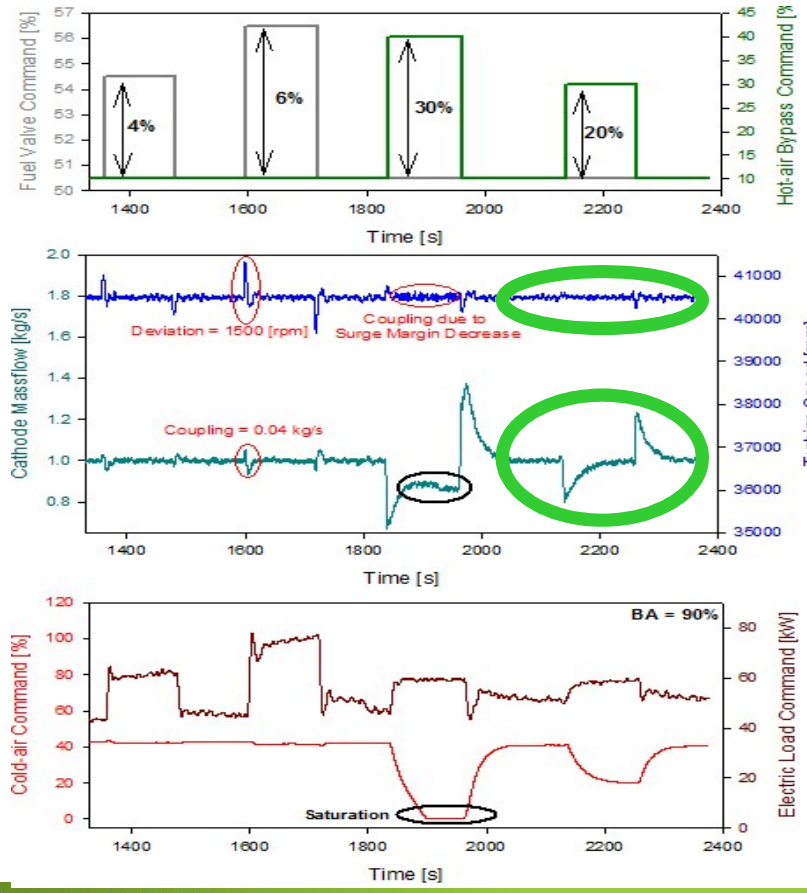


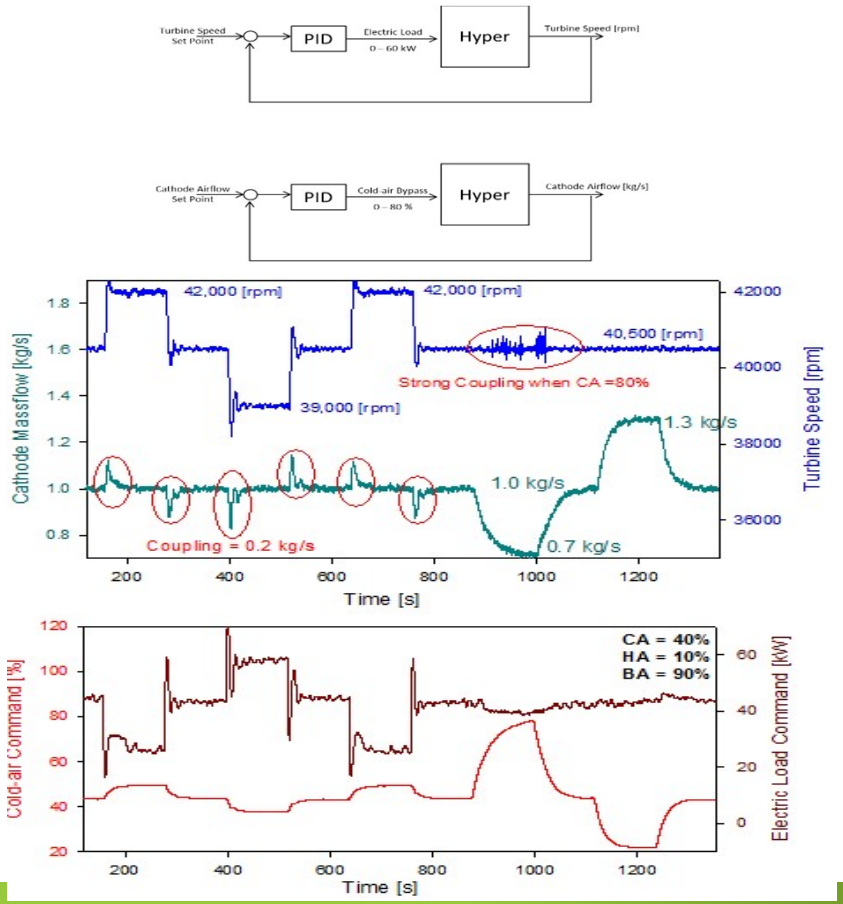
Gasification *Converting Coal to Syngas without a Gasifier*

Multivariable Controls Development

Working toward the development of dynamic controls to achieve the highest degree of disturbance rejection

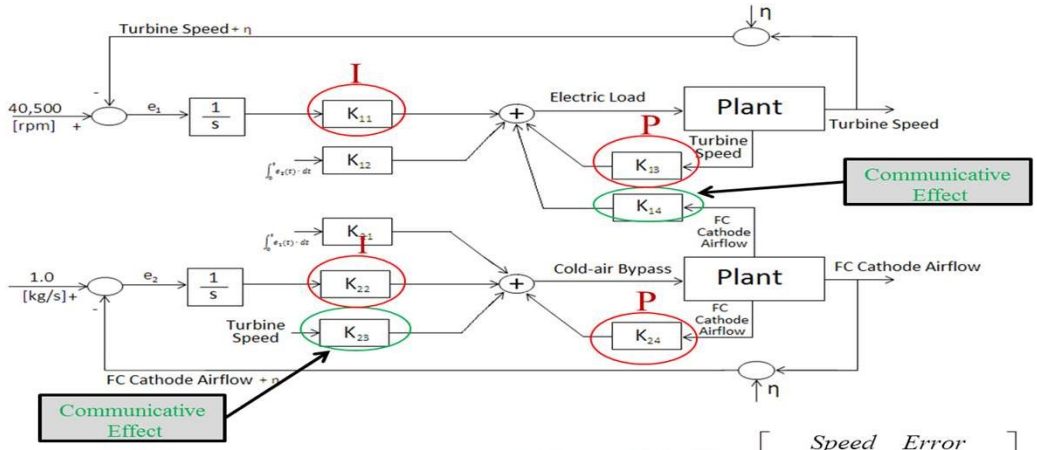
Decentralized Control Optimization





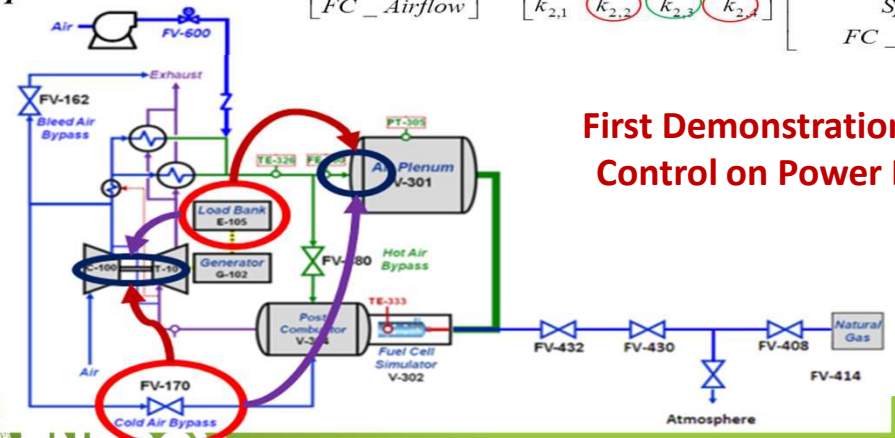
MIMO Control Implementation

Journal of Applied Energy 2016

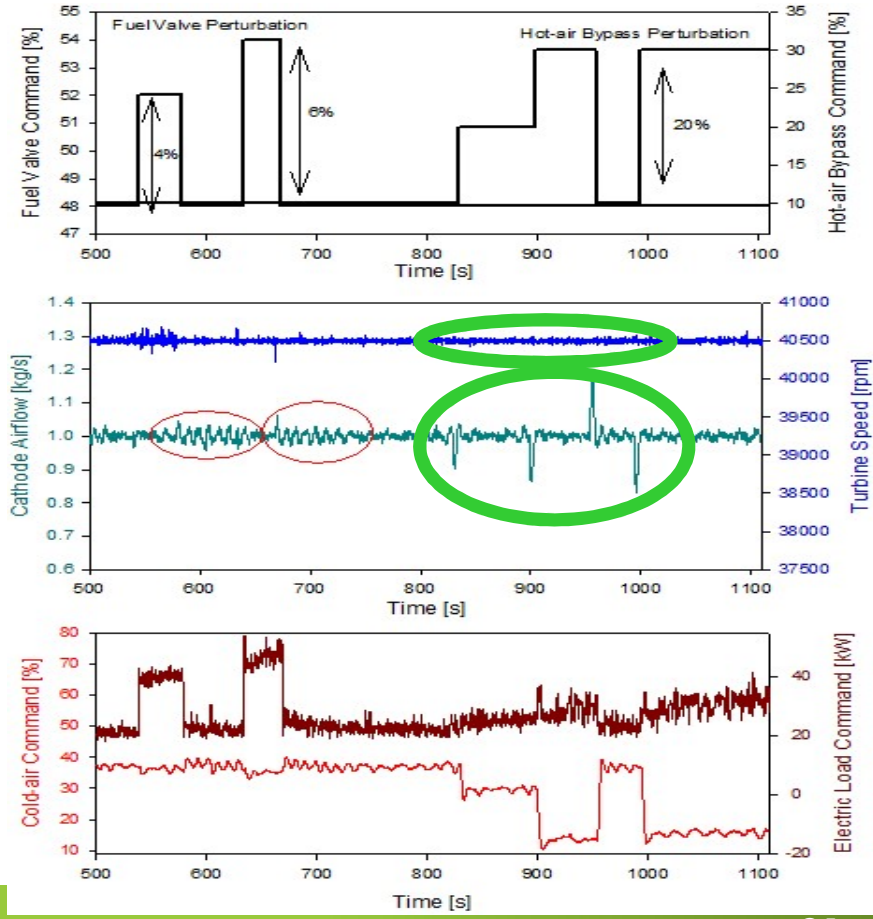


➢ ***Hyper Control Law:***

$$\begin{bmatrix} Speed \\ FC\_Airflow \end{bmatrix} = -\begin{bmatrix} k_{1,1} & k_{1,2} & k_{1,3} & k_{1,4} \\ k_{2,1} & k_{2,2} & k_{2,3} & k_{2,4} \end{bmatrix} \cdot \begin{bmatrix} Speed\_Error \\ FC\_Airflow\_Error \\ Speed \\ FC\_Airflow \end{bmatrix}$$

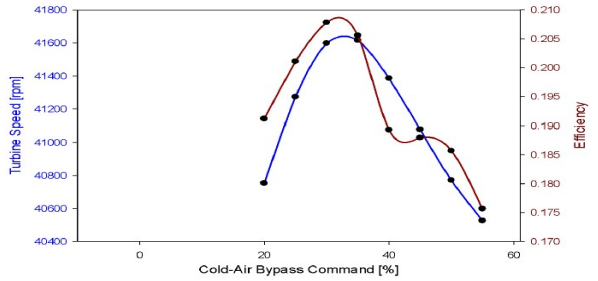


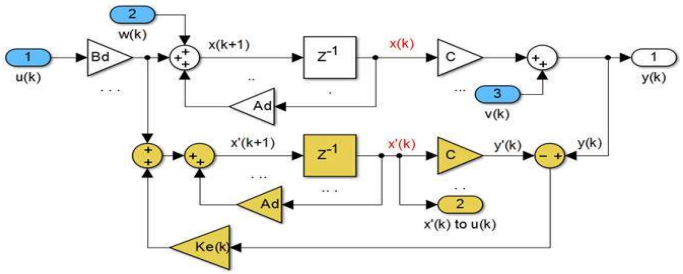
First Demonstration of MIMO Control on Power Hardware

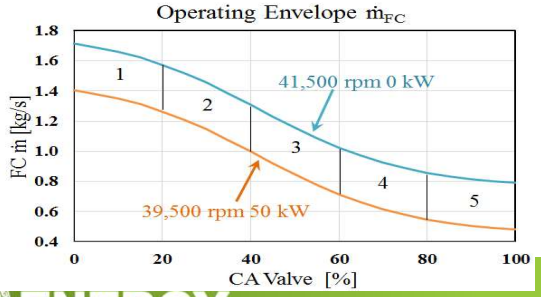


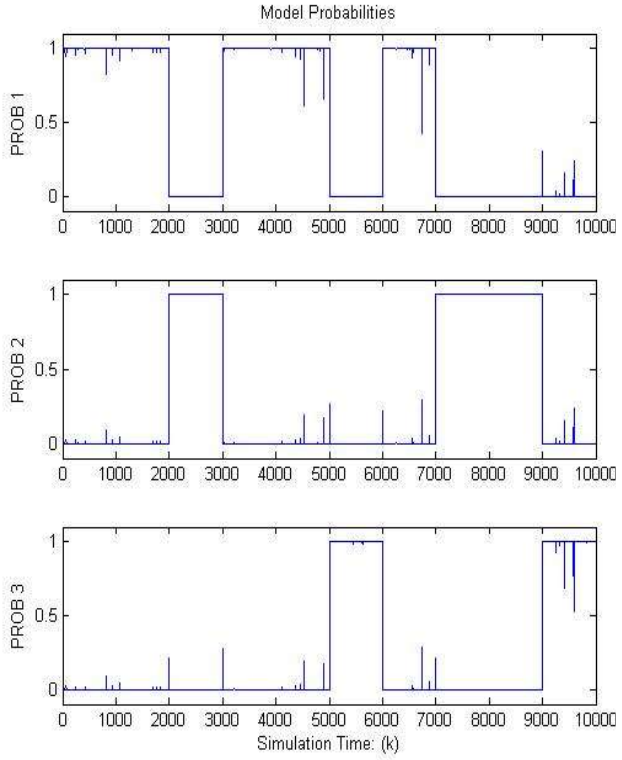
Multiple Model Adaptive Estimation

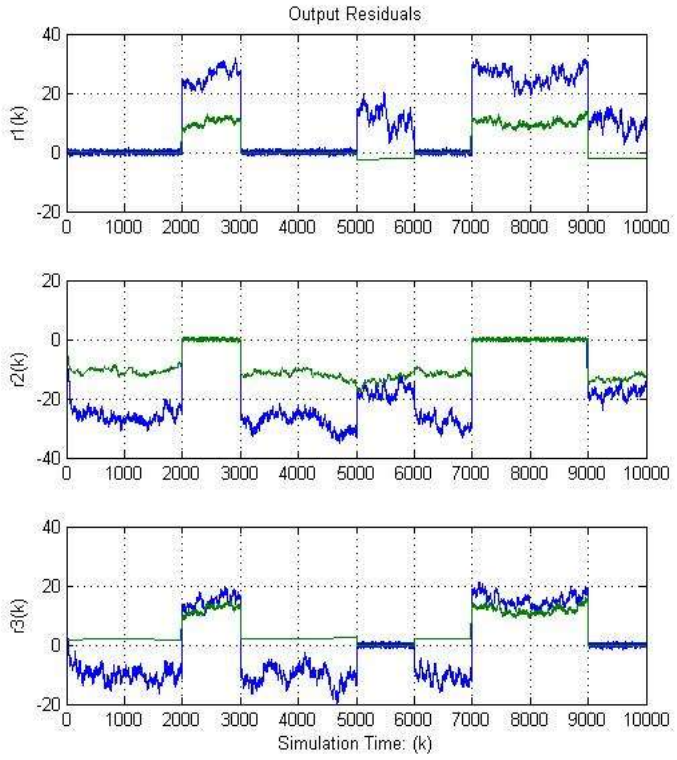
ASME Power and Energy 2016







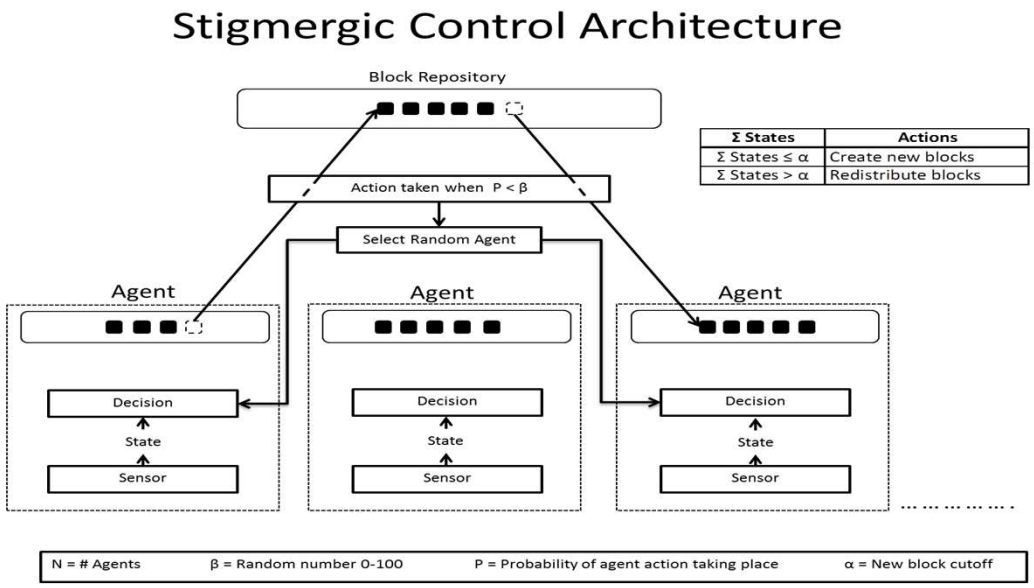




Stigmergy Testing (Biomimetic Control)

A Collaboration with Ames Laboratory

- **Stigmergy controller in the MicroNET**
  - Used for multivariable agent-based control of Hyper
  - Behavior is confined by state function blocks in the Hyper control system

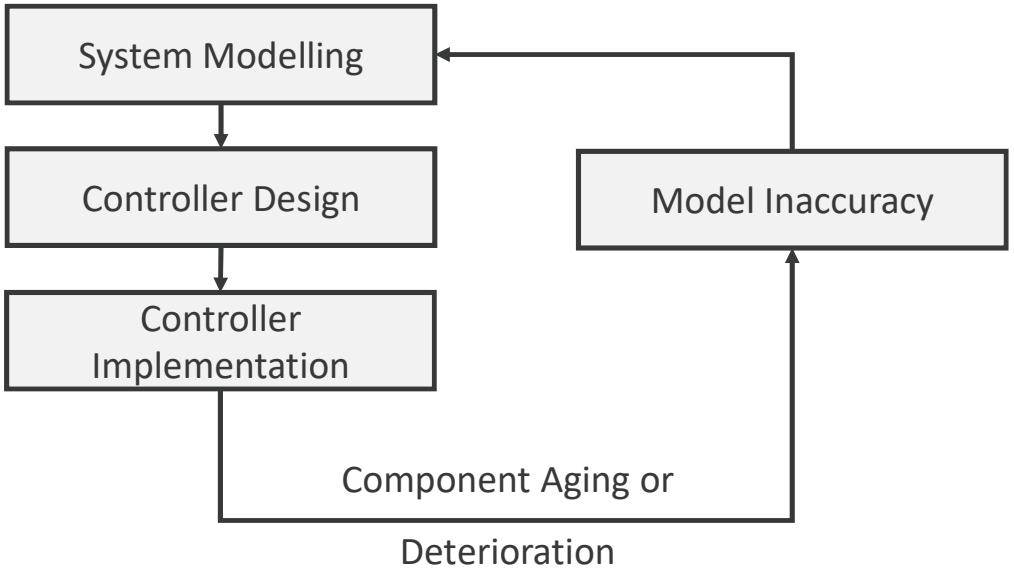


First Demonstration of Agent-Based Control on Hardware

On-Line System Identification

Adaptive dynamic control for future and existing power systems flexibility and availability as well as a novel method for component degradation monitoring

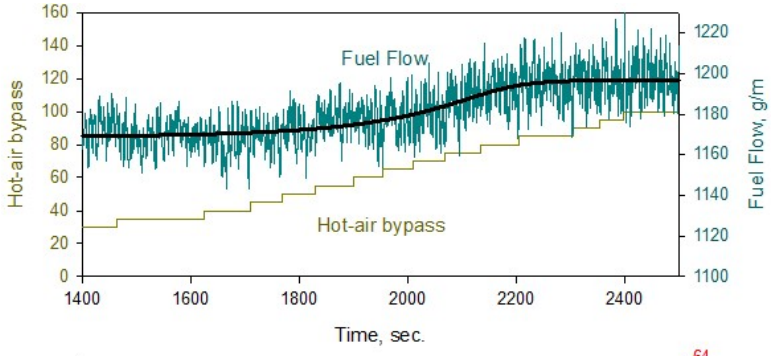
Component Degradation during Aging

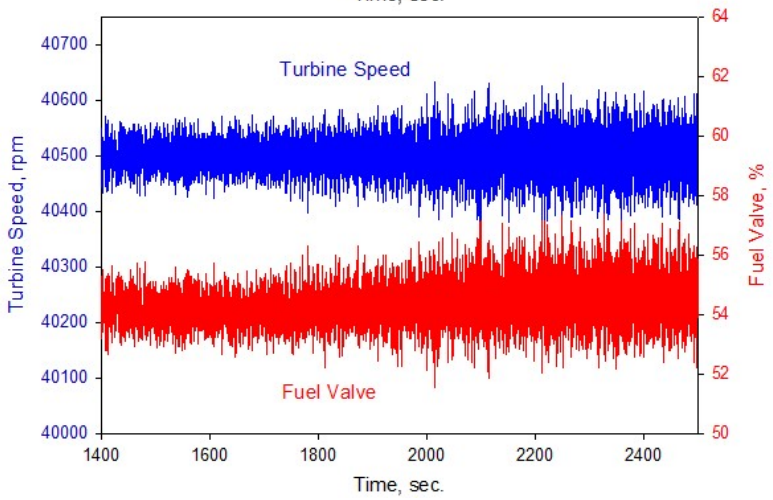


- In a multivariable environment disturbances due to degradation occur
- Controller parameters must be adaptively tuned
- System remodeling maybe required

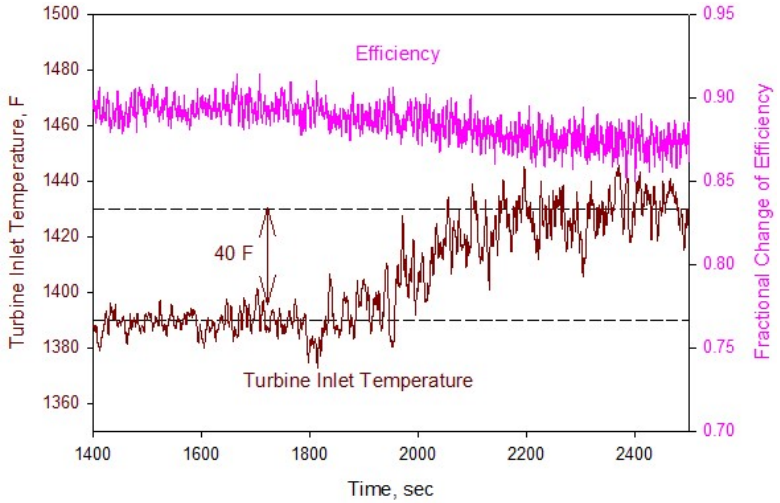
Component Aging Emulation

Testing on the Hyper Facility to explore additional operating states



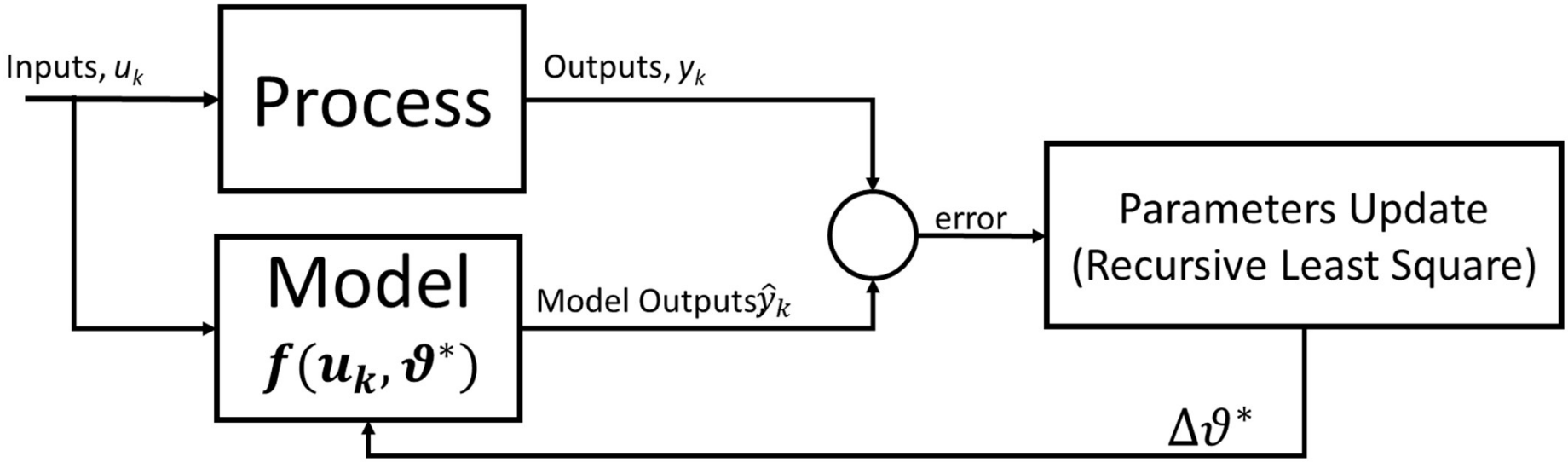


- Cathode airflow and combustion air decrease
- Fuel lean mixture approaching stoichiometric (Eq. ratio 0.43 – 0.85)
- Fuel valve ringing
- Robust controller, but different operating state



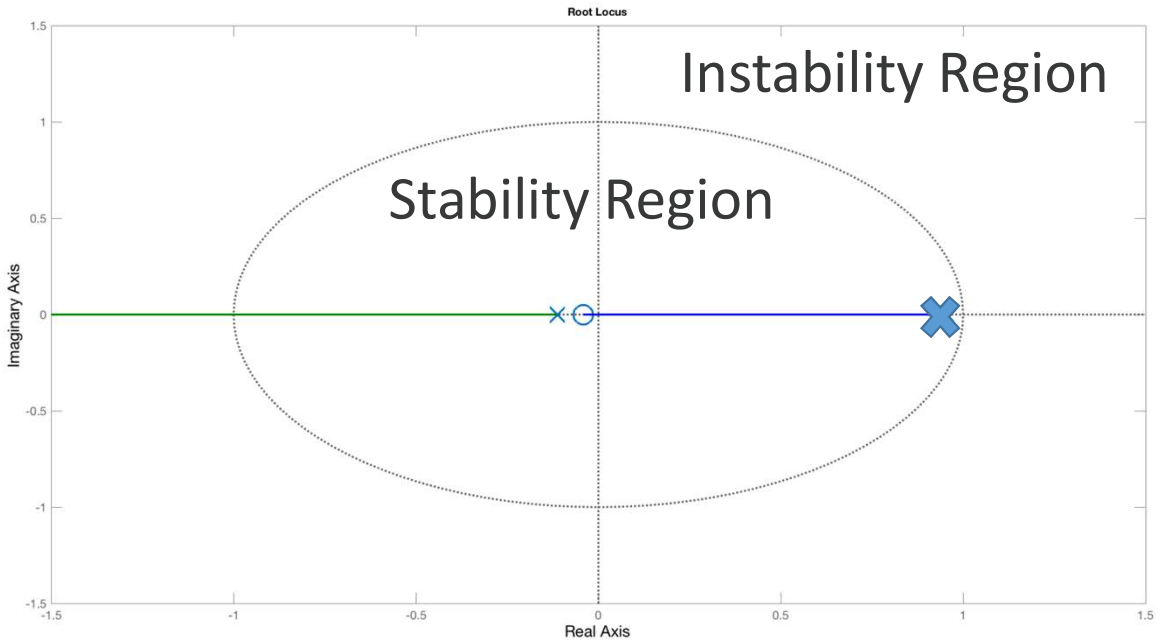
5% Drop!!

On-Line System Identification



0.5% in a Transfer Function Parameter

Fuel valve → $\dfrac{0.00766z+0.0003164}{z^2-0.931z+0.1068}$ → Turbine speed



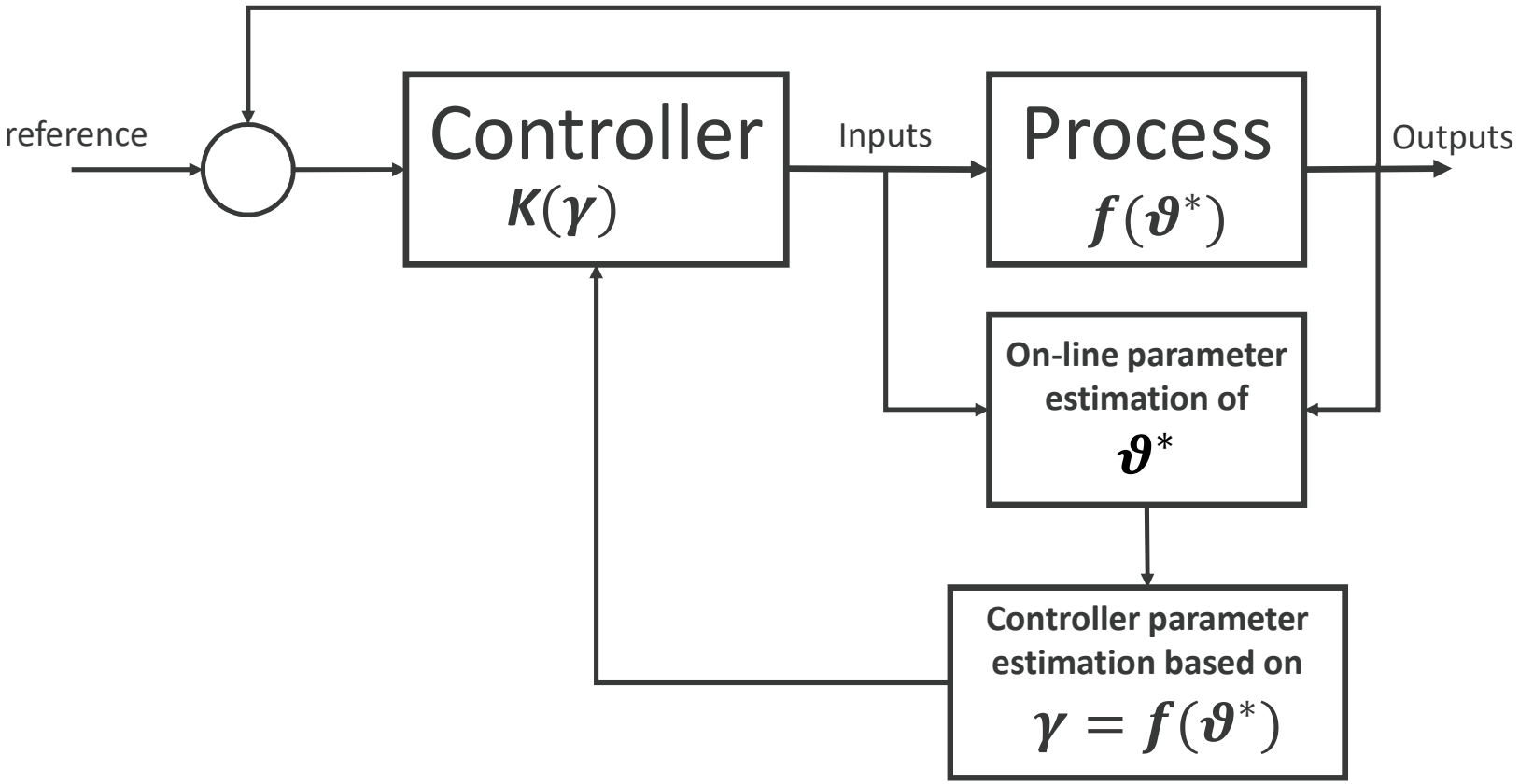
2 roots (poles) in the denominator

z_1=0.898, z_2=-0.0116

1 root (zero) in the numerator

z_3= - 0.04

On-Line Adaptive Control



2017 Summer at NETL

NATIONAL ENERGY TECHNOLOGY LABORATORY

Thank You

David Tucker
U.S. Department of Energy
National Energy Technology Laboratory
Morgantown, WV 26507-0880
David.Tucker@netl.doe.gov