

Demonstrating Autonomous Architectures for Microreactors Under Prototypic Conditions in PUR-1

2026 Microreactor Program Review

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Team Info

- **Purdue**

- Stylianos Chatzidakis (Assistant Professor and Associate Reactor Director, SRO)
- True Miller (Reactor supervisor, SRO)
- Brian Jowers (Electronics/I&C reactor staff, RO)
- V. Theos, Z. Dahm, K. Vasili, K. Gkouliaras, W. Richards (Grad students)



- **UNM**

- Mohamed El-Genk (Distinguished and Regents' Professor)
- Timothy Schriener (Research Associate Professor)
- Ahmad Shaheen (Grad student)



- **Collaborators**

- Robert Ammon (Curtiss-Wright)
- Rick Vilim (ANL)



- **TPOC: Ben Baker (INL)**



Goals & Objectives

Goal: Experimentally validate semi-autonomous control and demonstrate its use in PUR-1 and VSLIMM.

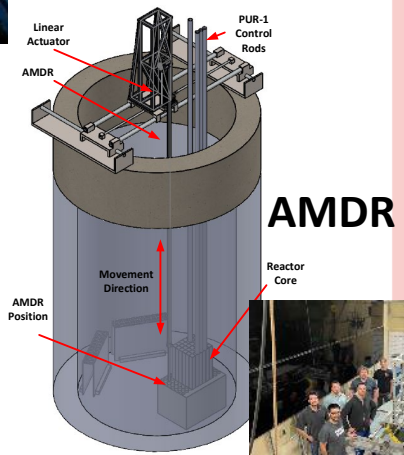
Objectives:

1. Develop a modular digital twin platform with various levels of automation using a remote workstation with AI/ML algorithms
2. Train AI/ML using physics-based models and real-time digital operation data collected from PUR-1
3. Perform testing and evaluate performance

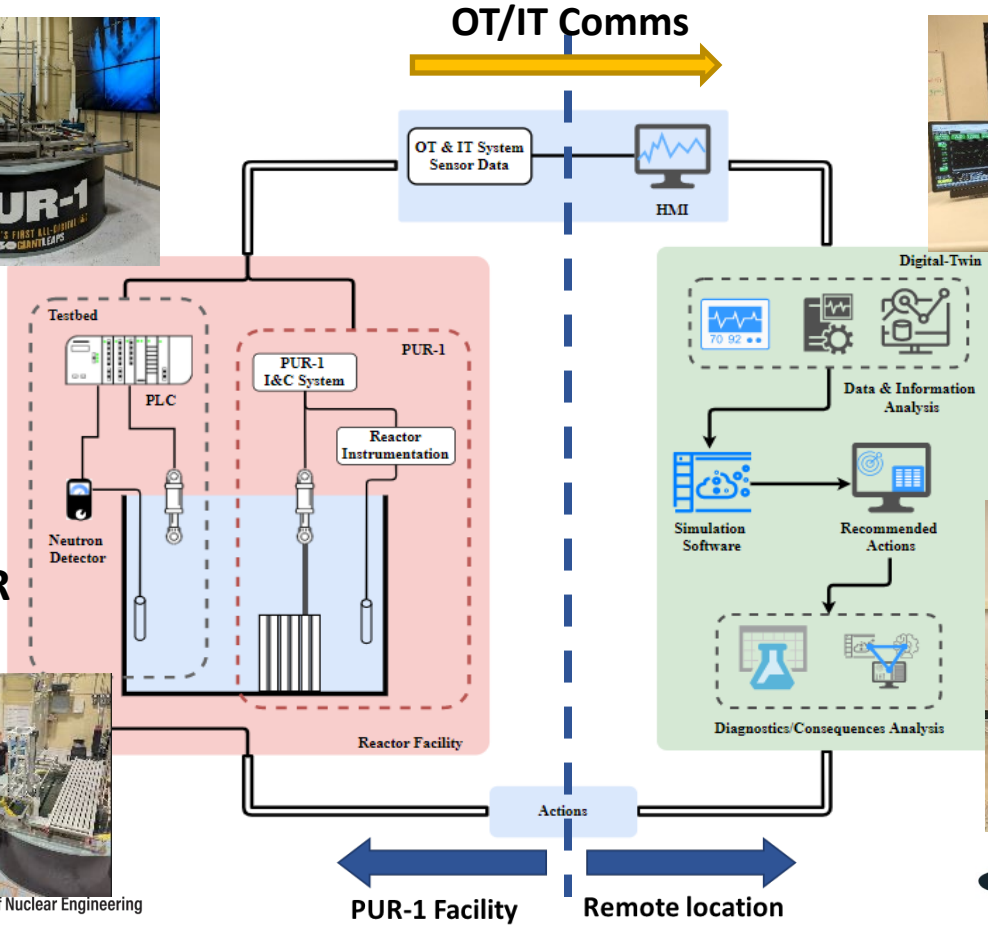
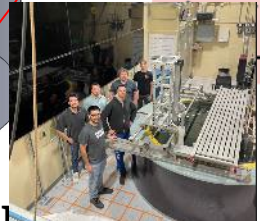
Towards a Real-Time Cyber-Physical Digital Twin



PUR-1



AMDR



PUR-1 Facility

Remote location

OT/IT Comms

OT & IT System Sensor Data

HMI

Digital-Twin

Data & Information Analysis

Simulation Software

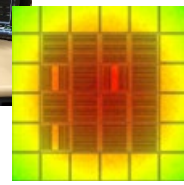
Recommended Actions

Diagnostics/Consequences Analysis

Actions



RMSS



Control rack



Digital/Cyber Remote Station

RTP 3000 TAS N+
Nuclear grade PLC
16 CH AI/AO
32 CH DI/DO

Field
Programmable
Gate Array

Power
distribution
unit

Actuator control

IT Monitoring

R-TIME GUI

Stats:
2000 parameters
1kHz sampling

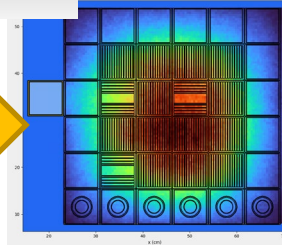
OpenMC
COMSOL
OpenFOAM

Real-time diagnostics

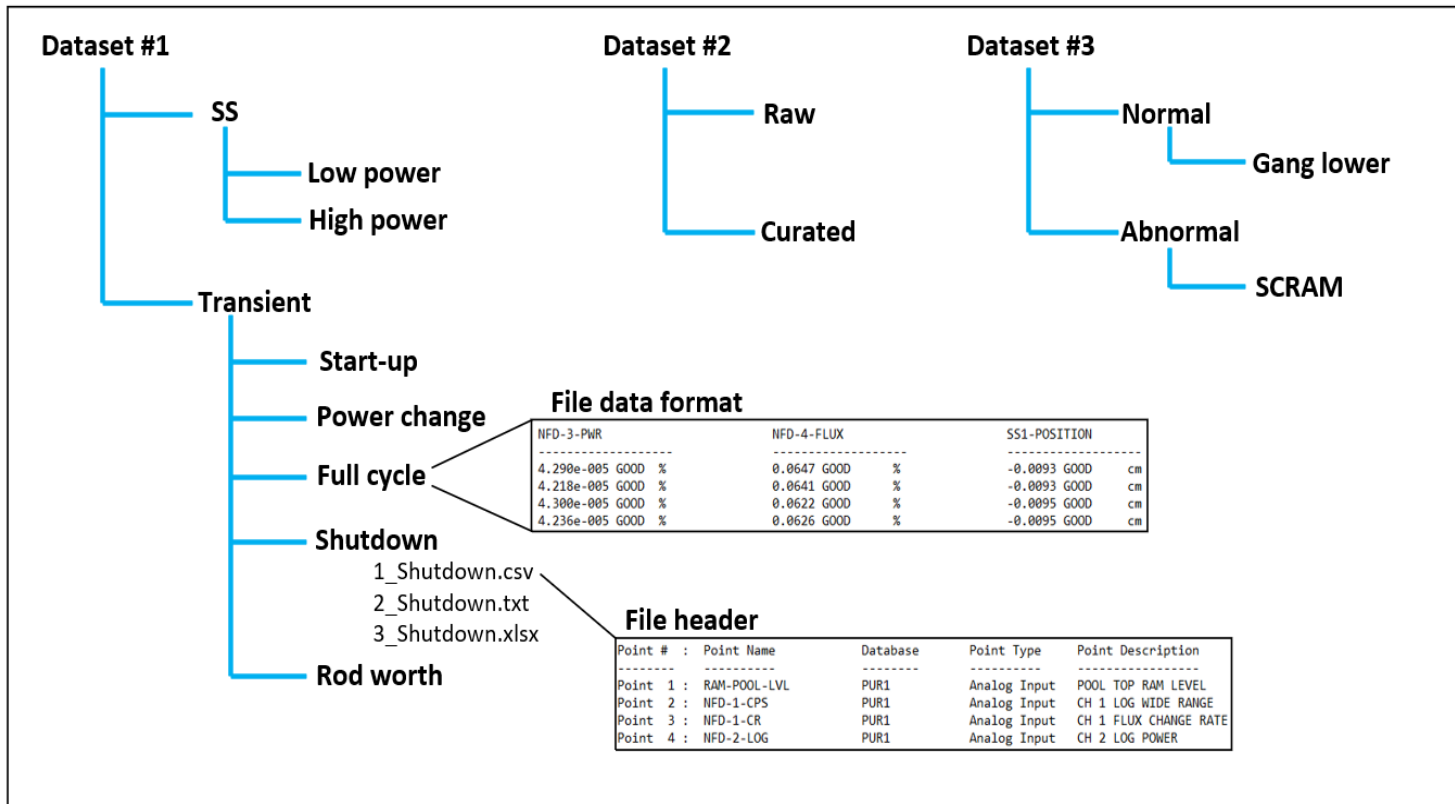
Siemens S7 PLC

UPS APC/1500

To GPU

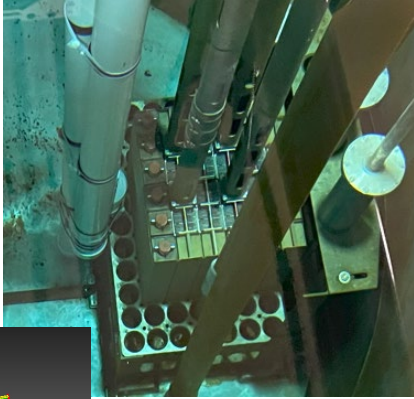
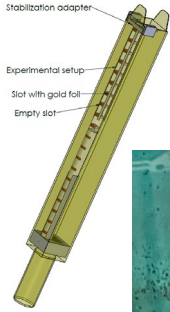


Datasets for Benchmarking

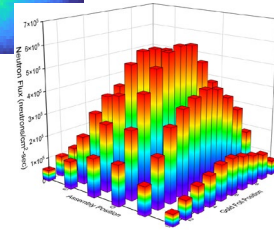
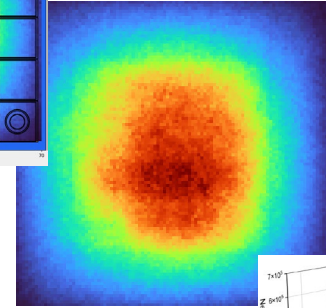
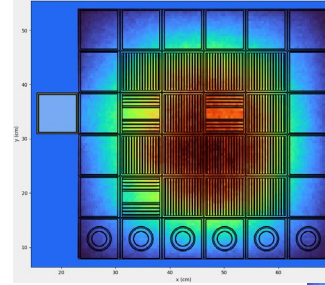


Modeling and Simulation

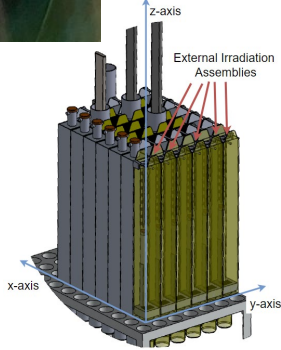
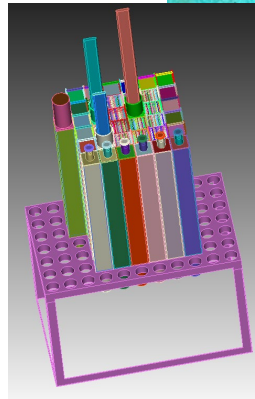
PUR-1



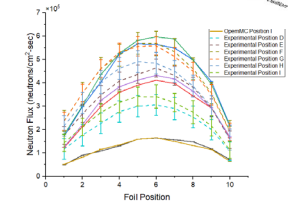
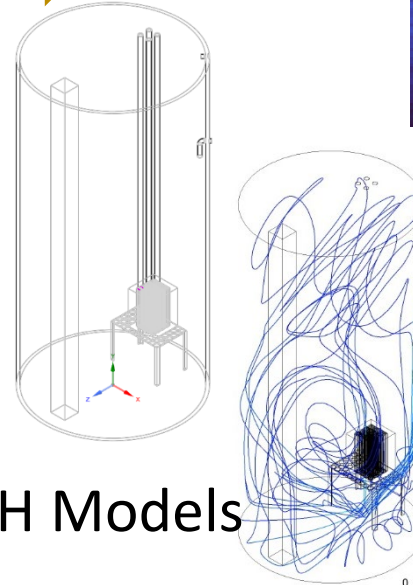
Neutronics + PKE Models



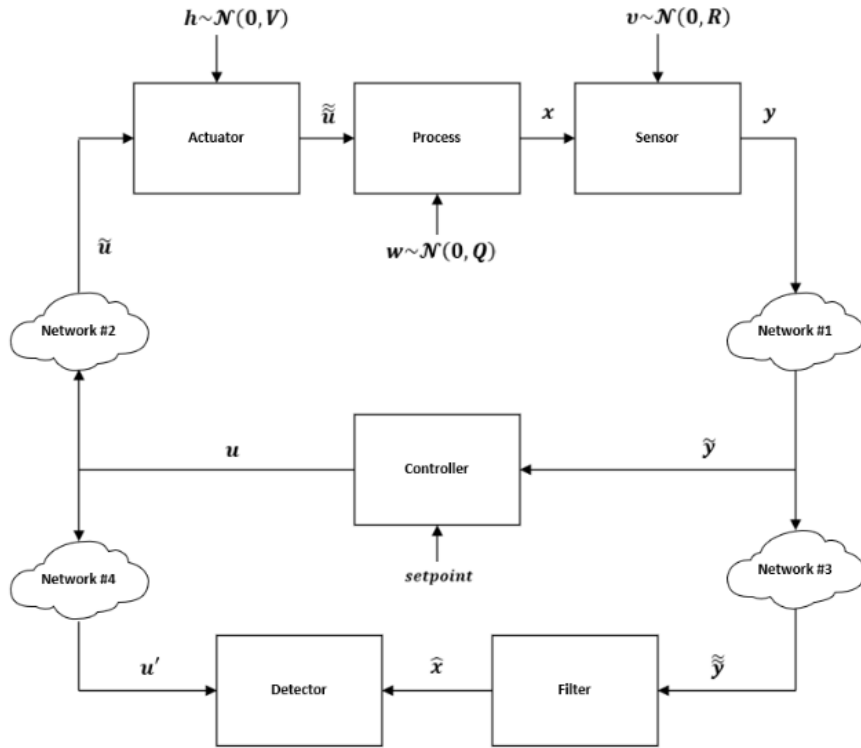
CAD Model



TH Models



Network Communications Model



Sensor

$$y_k = Cx(t_k) + v_k, v_k \sim \mathcal{N}(0, R)$$

Network

$$\tilde{y}_k = \begin{cases} y_{k-d_k} + h_k^{(net)}, & w.p. 1 - p_l \\ \tilde{y}_{k-1}, & w.p. p_l \text{ (hold)}, \end{cases}$$

Latency

$$t_{net} = t_{ser} + t_{prop} + t_{queue} + \sum t_{dev}$$

Controller

$$u_k = K_p e_k + K_i \sum_{j=0}^k e_j + K_d \frac{e_k - e_{k-1}}{\Delta t}$$

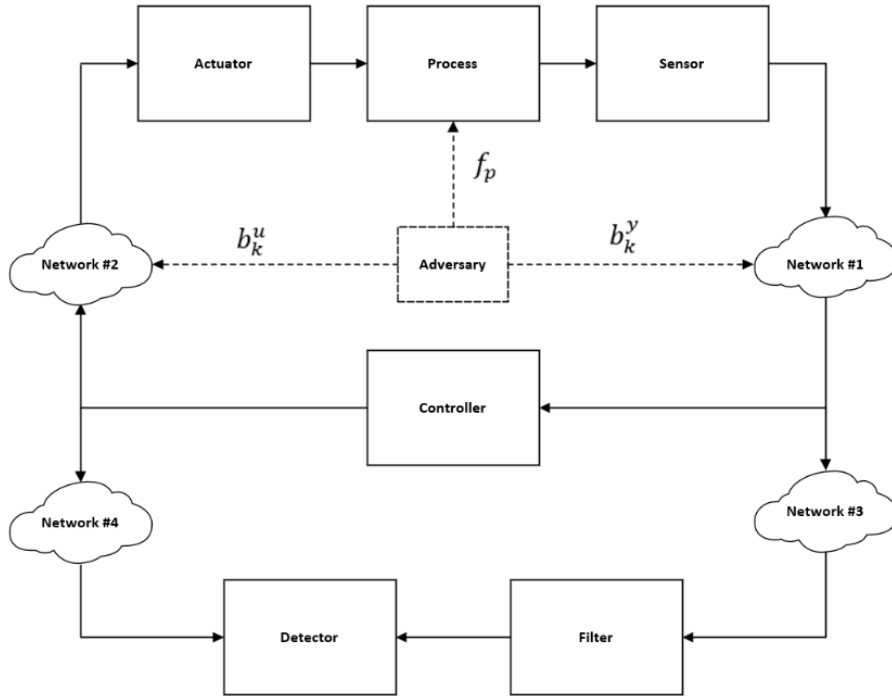
Actuator

$$r_{k+1} = r_k e^{-T_s/\tau_{act}} + \tilde{u}_k^{cmd} (1 - e^{-T_s/\tau_{act}})$$

Command

$$u_k^{cmd} = sat(r_{k-1} + u_k, r_{min}, r_{max})$$

Network Communications w/ Adversary Model



Fault vector

$$f_k = [f_k^p \ f_k^a \ f_k^c \ f_k^s]^T$$

$$y_k = Cx(t_k) + v_k + F_k^s f_k^s, v_k \sim \mathcal{N}(0, R)$$

Attack vector

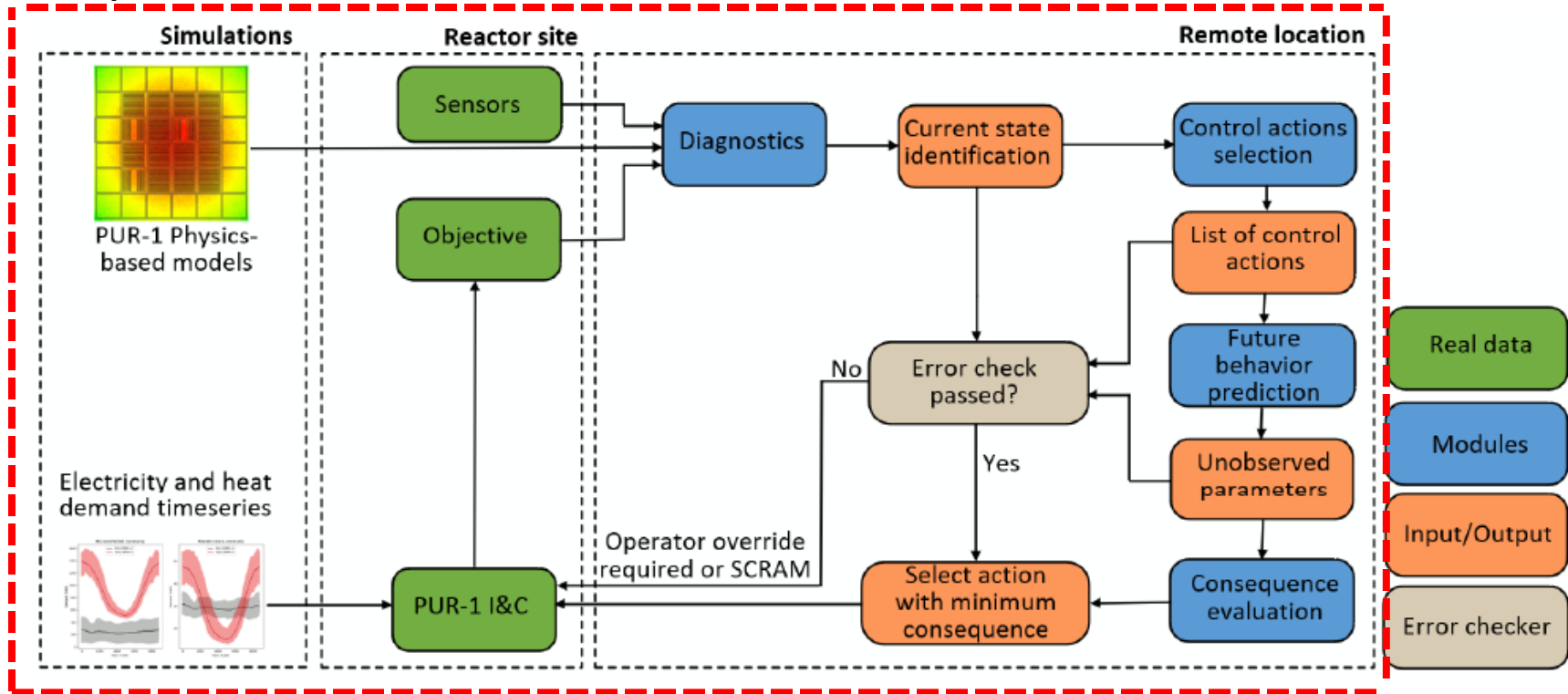
$$a_k = [b_k^y \ b_k^u]^T$$

$$\tilde{y}_k = y_k + \Gamma_k^y b_k^y$$

$$\tilde{u}_k = u_k + \Gamma_k^u b_k^u$$

Semi-autonomous Architecture

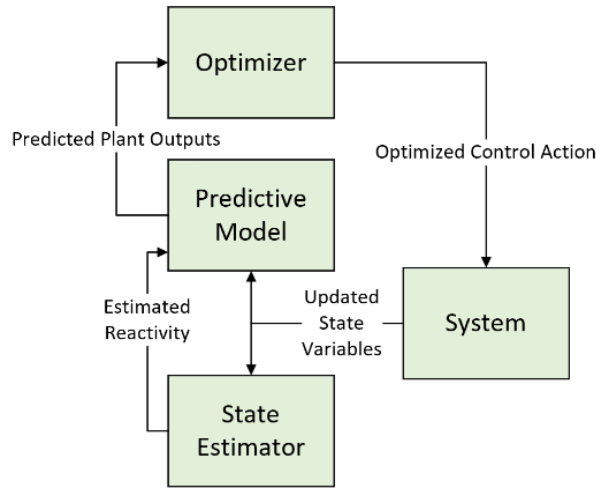
Completed



Semi-autonomous Architecture

- **Diagnostics**
 - Random Forest to identify state ID, e.g., startup, shutdown, constant power etc.
 - Autoencoders to reconstruct radiation sensor data, LSTM and GRU to reconstruct reactor power, and XAI for anomaly detection
- **Control Actions Selection**
 - Rule-based limitation on control action space
- **Future behavior prediction**
 - Transformer with future covariates incorporated from selected control actions
- **Consequence evaluation**
 - Fuzzy logic system to assign score to each forecasted control action, then highest score action is chosen
 - Actions which exceed safety constraints are ruled out entirely

Performance Evaluation - Load Following



$$\min_{u_0:N_c} \sum_{k=0}^{N_p} (|\hat{n}_k - n_{set}| + c_1(u_k - u_{k-1})^2 + c_2(\hat{n}_k - \hat{n}_{k-1})^2)$$

$$\text{subject to: } \hat{x}_0 = x_0,$$

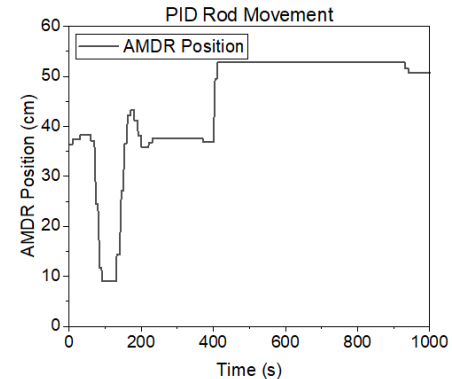
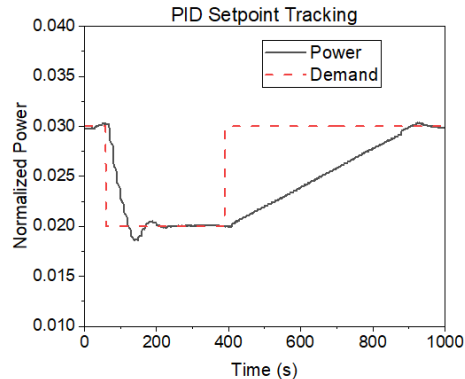
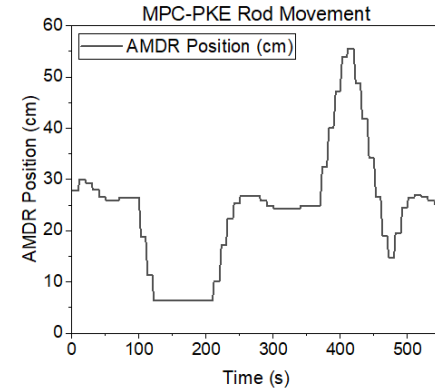
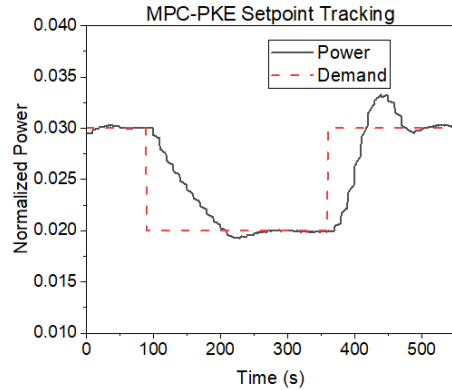
$$n_{lb} \leq \hat{n}_k \leq n_{ub} \forall k = 0, \dots, N_p$$

$$u_{lb} \leq u_k \leq u_{ub} \forall k = 0, \dots, N_p$$

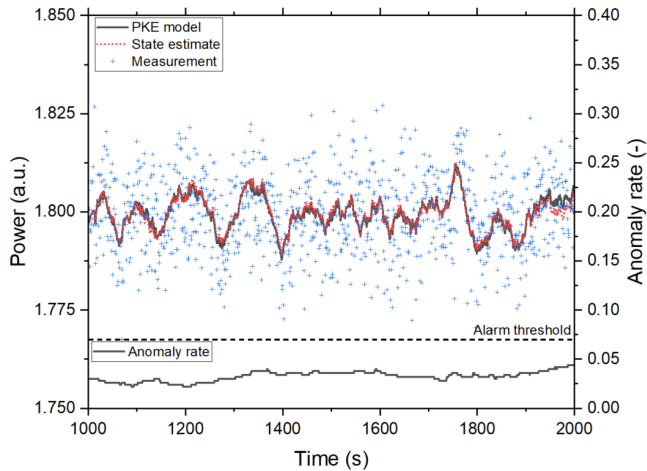
$$|u_k - u_{k-1}| \leq \Delta u_{ub}$$

$$\hat{n}_k - \hat{n}_{k-1} \leq \Delta n_{ub}$$

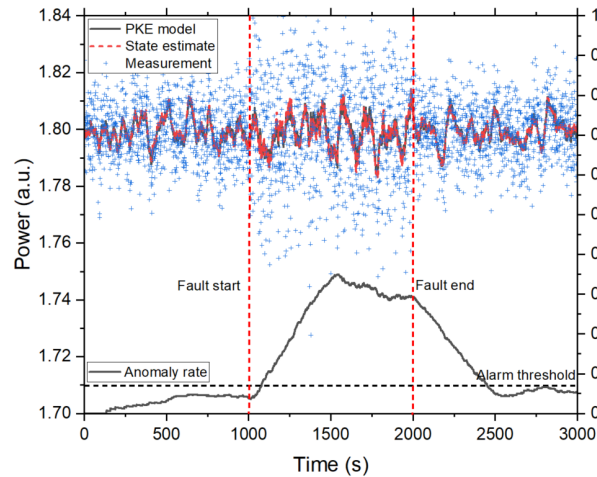
$$\hat{x}_{k+1} = f(\hat{x}_k, u_k), \forall k = 0, \dots, N_p$$



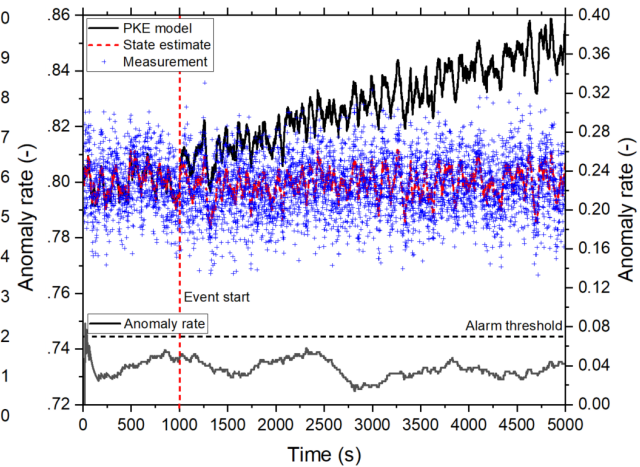
Performance Evaluation – Bias Injection Attack



Normal conditions



Increased sensor noise



Low level bias injection

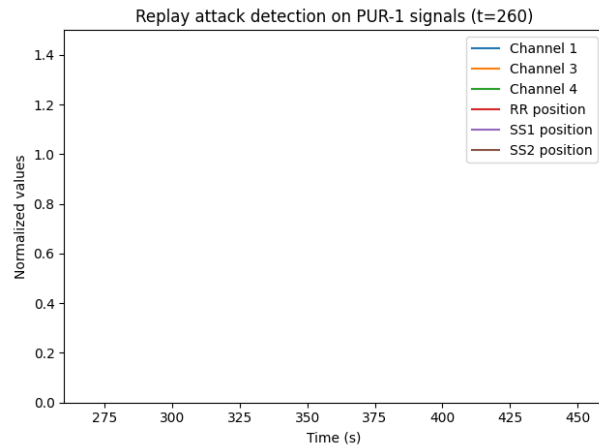
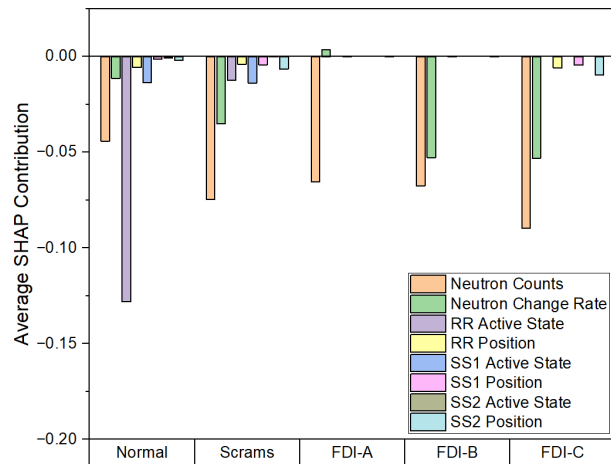
Performance Evaluation – Cyber Event Detection

AI/ML can be trained with data extracted from normal and abnormal system states

Maximum achievable performance depends strongly on algorithm and data available

Amount of abnormal data available can be a limiting factor

SHAP can identify source of FDI



Acknowledgements

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Questions?