Advanced tools for cyber-physical systems and digital twins

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Development of tools in support of the concept of integrating cyber-physical systems and digital twins into the current energy system research and development process.

Project Goal

1. Middleware architecture to enable digital twin

2. Monitoring and control tools for existing power plants

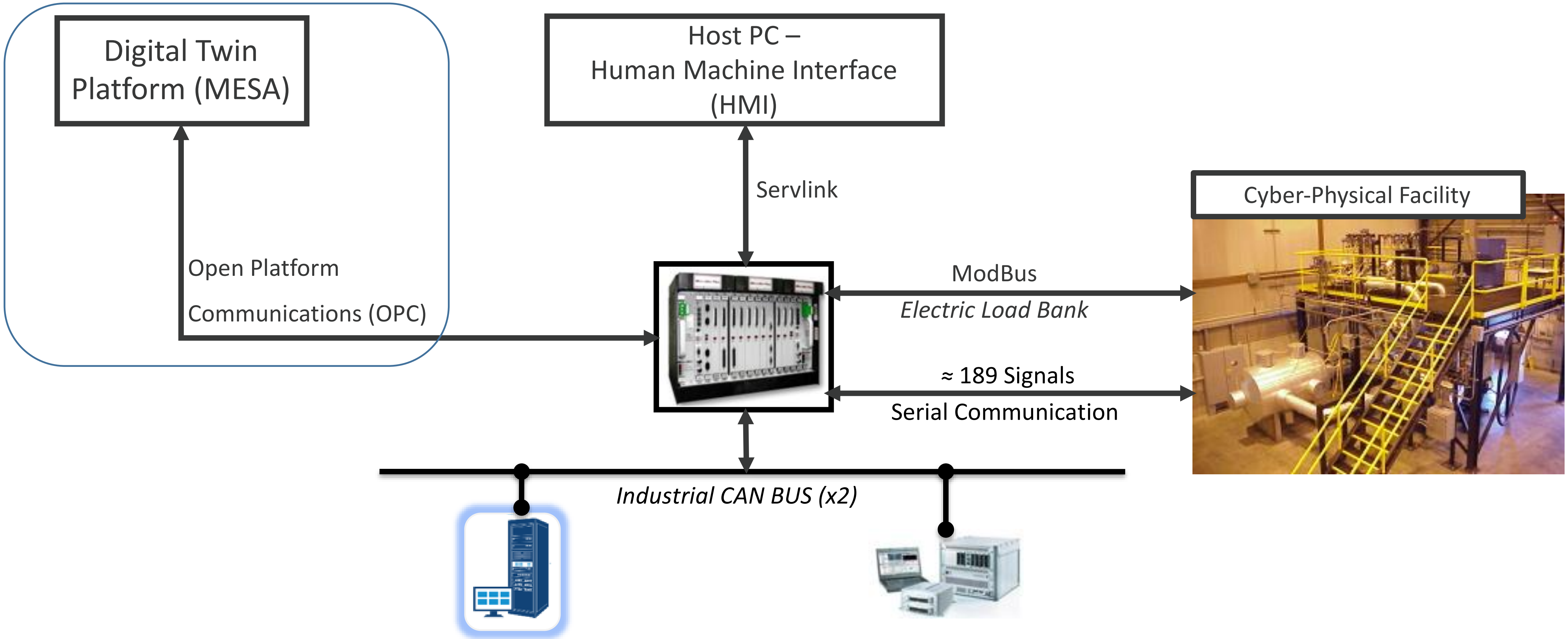
3. Diagnostic tools using machine learning concept

Research Objectives

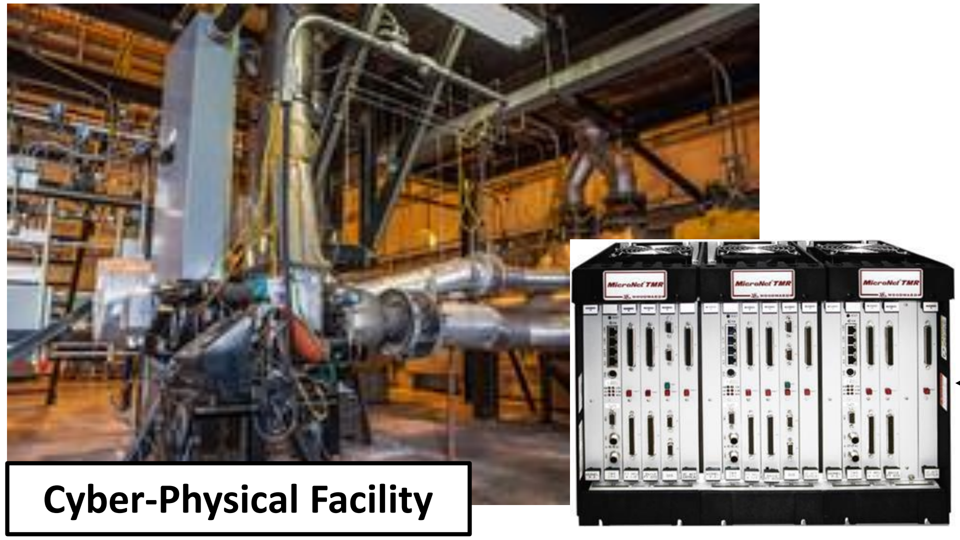
1. Middleware Architecture

Publisher and subscriber architecture used to exchange I/O variables in system automation through open source protocols

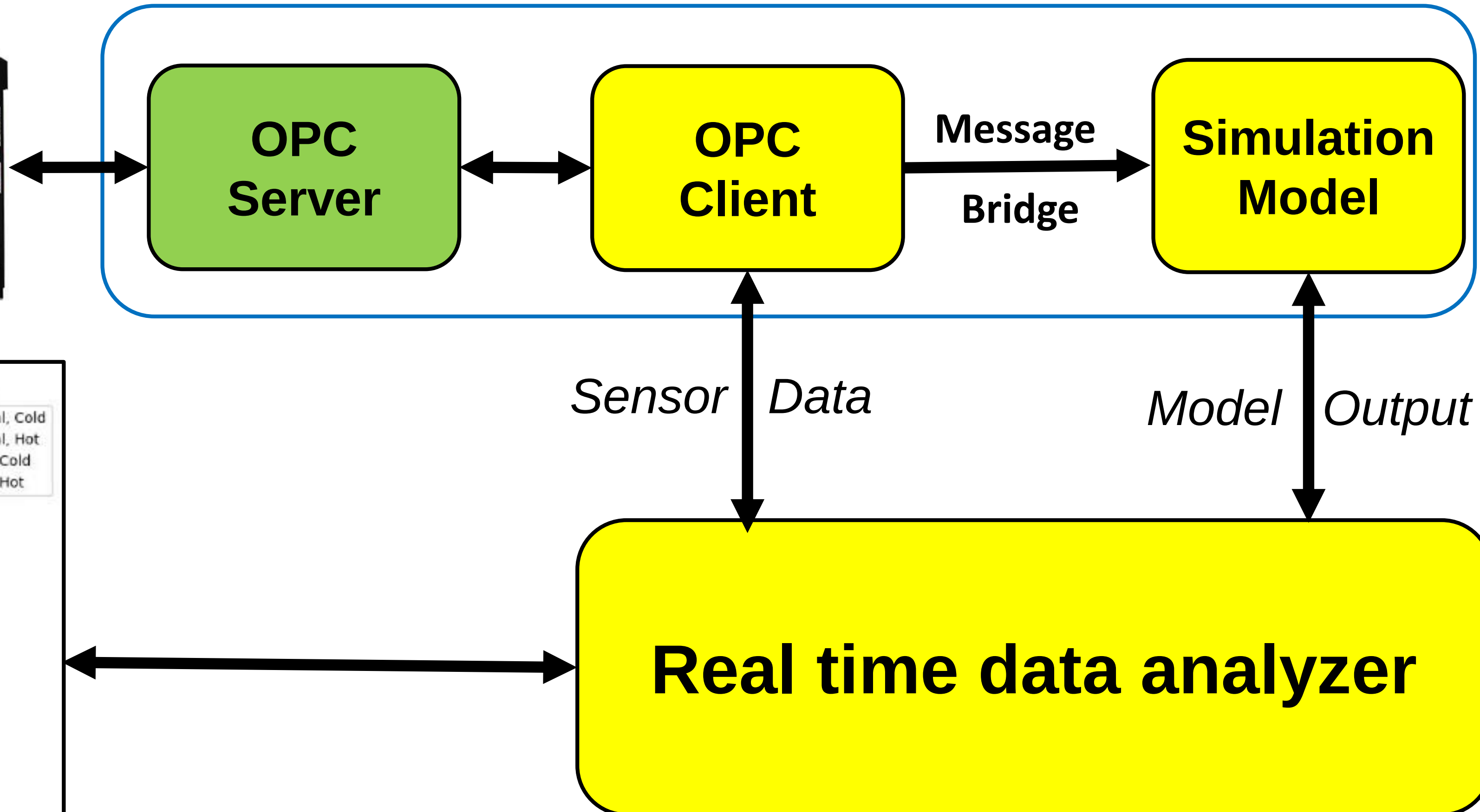
Middleware Architecture

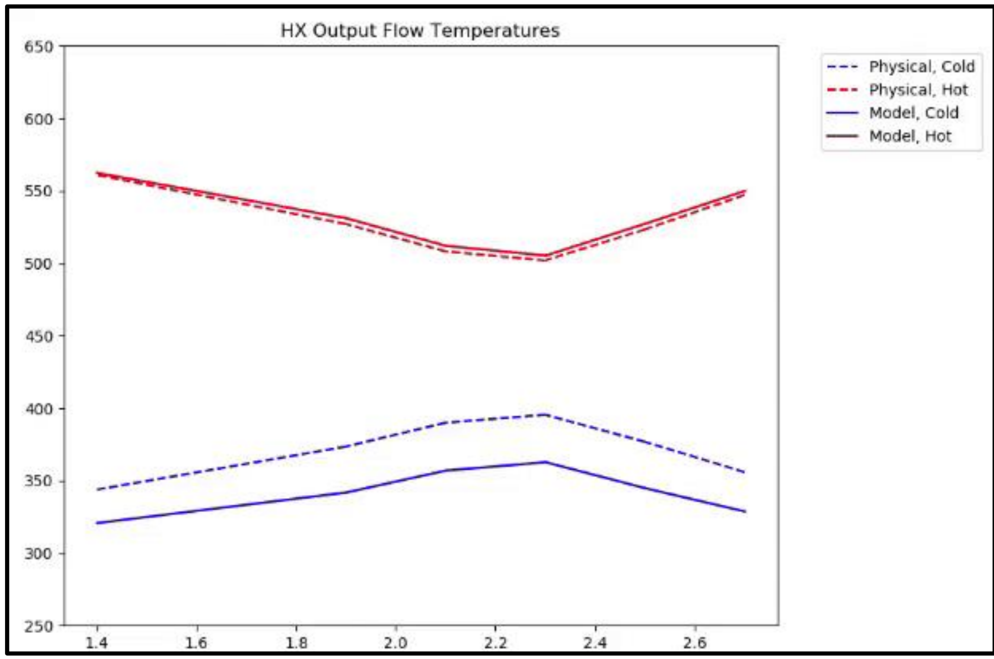


Middleware architecture: NETL’s cyber-physical facility



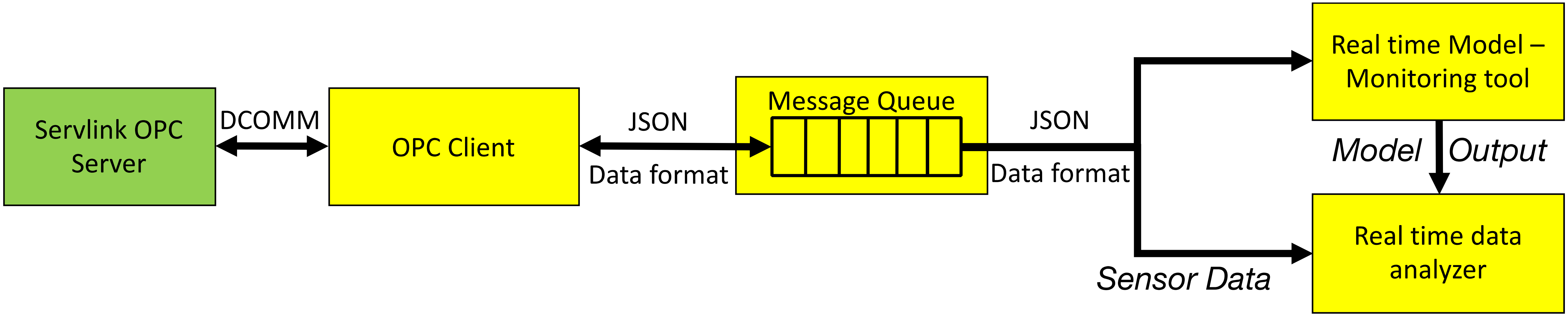
Middleware Architecture





Demonstrate a working environment for a digital twin

Merge Environment Simulation Analysis (MESA)

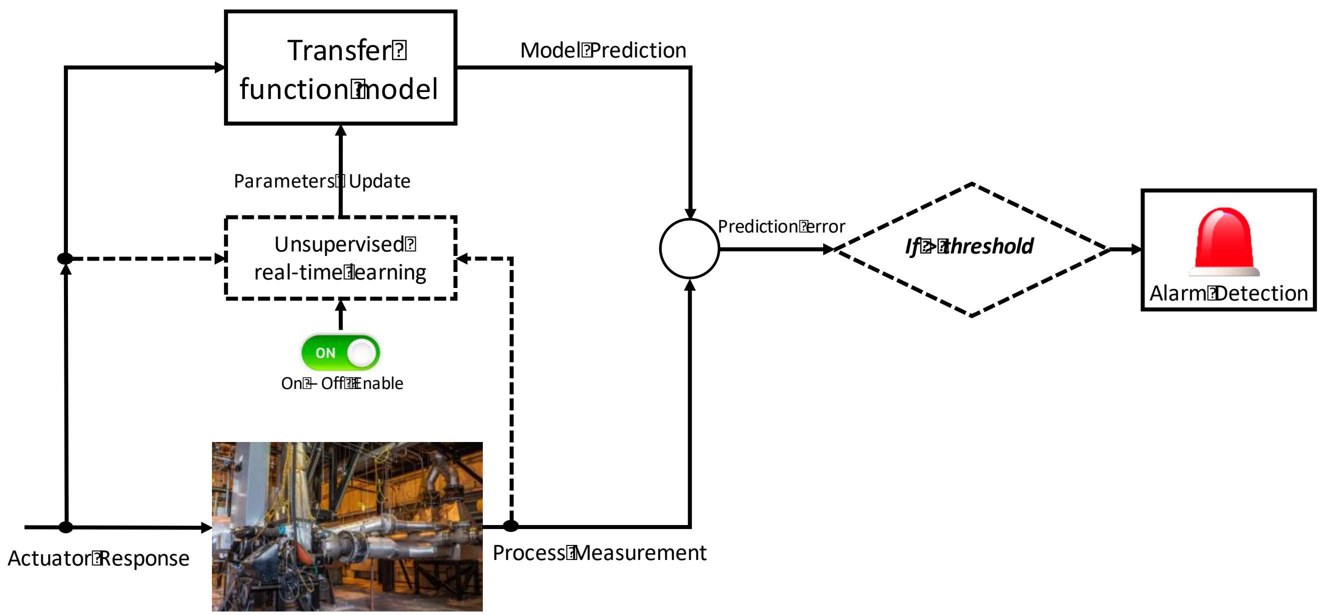


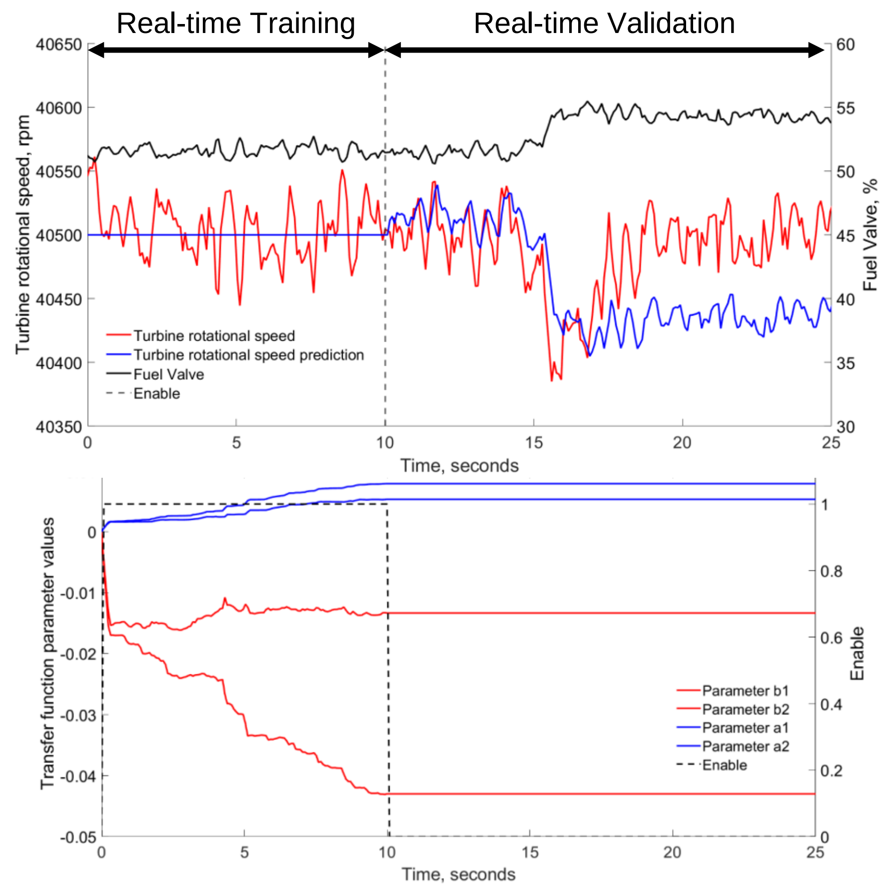
- OPC Client – Executable using “Go” language to read OPC data
- RabbitMQ - Message broker connecting OPC data to real time model
- Real time model of a Heat Exchanger
- Real time data analyzer

New tools developed

2. Monitoring and controls tools:

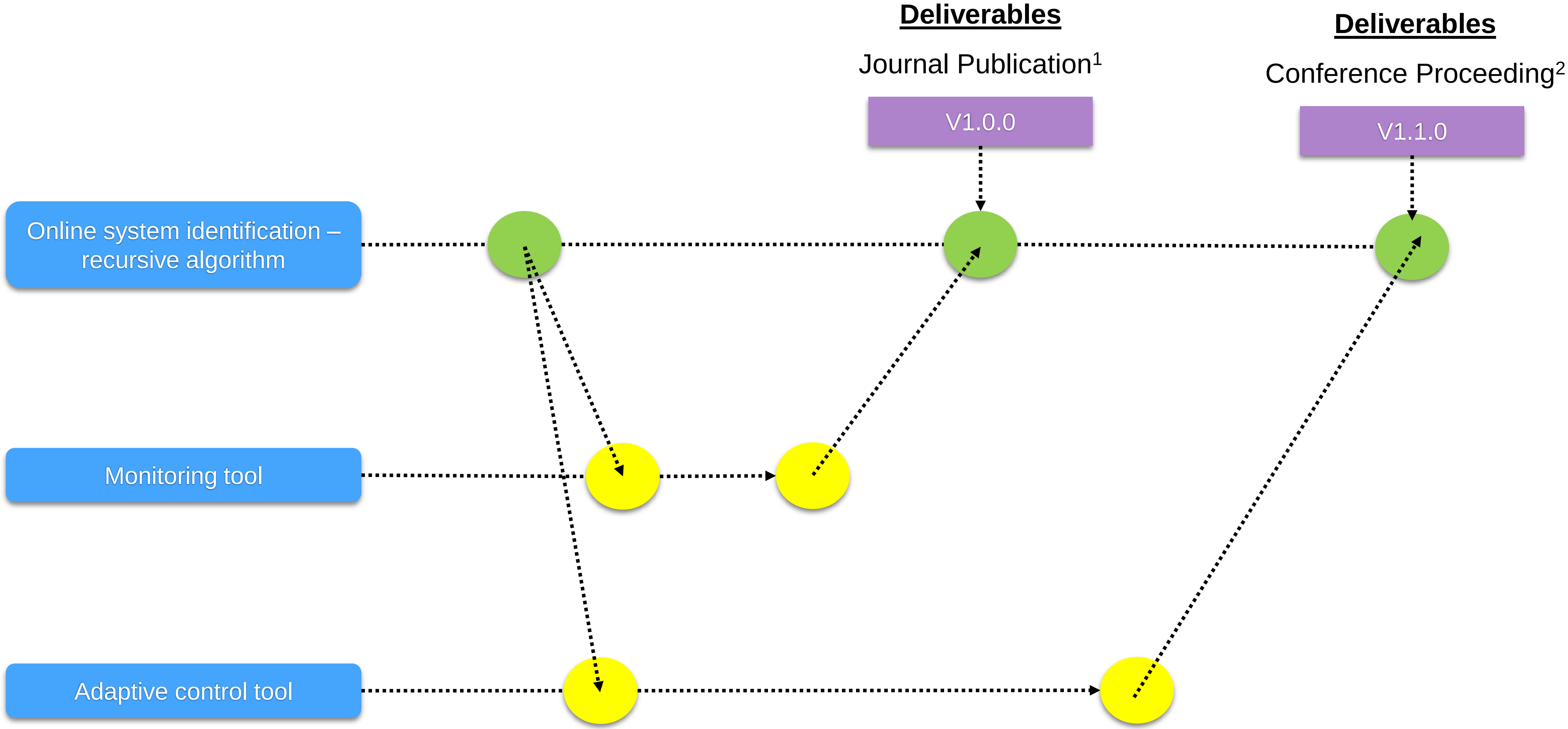
- Online system identification monitoring tool
- Model reference adaptive control (MRAC)
- Agent-based Control





- A sudden leak of 10% in the working fluid was reproduced
- An increase in the fuel flow was detected to maintain normal operation during the leak
- The leak was detected 5-7s after it occurred

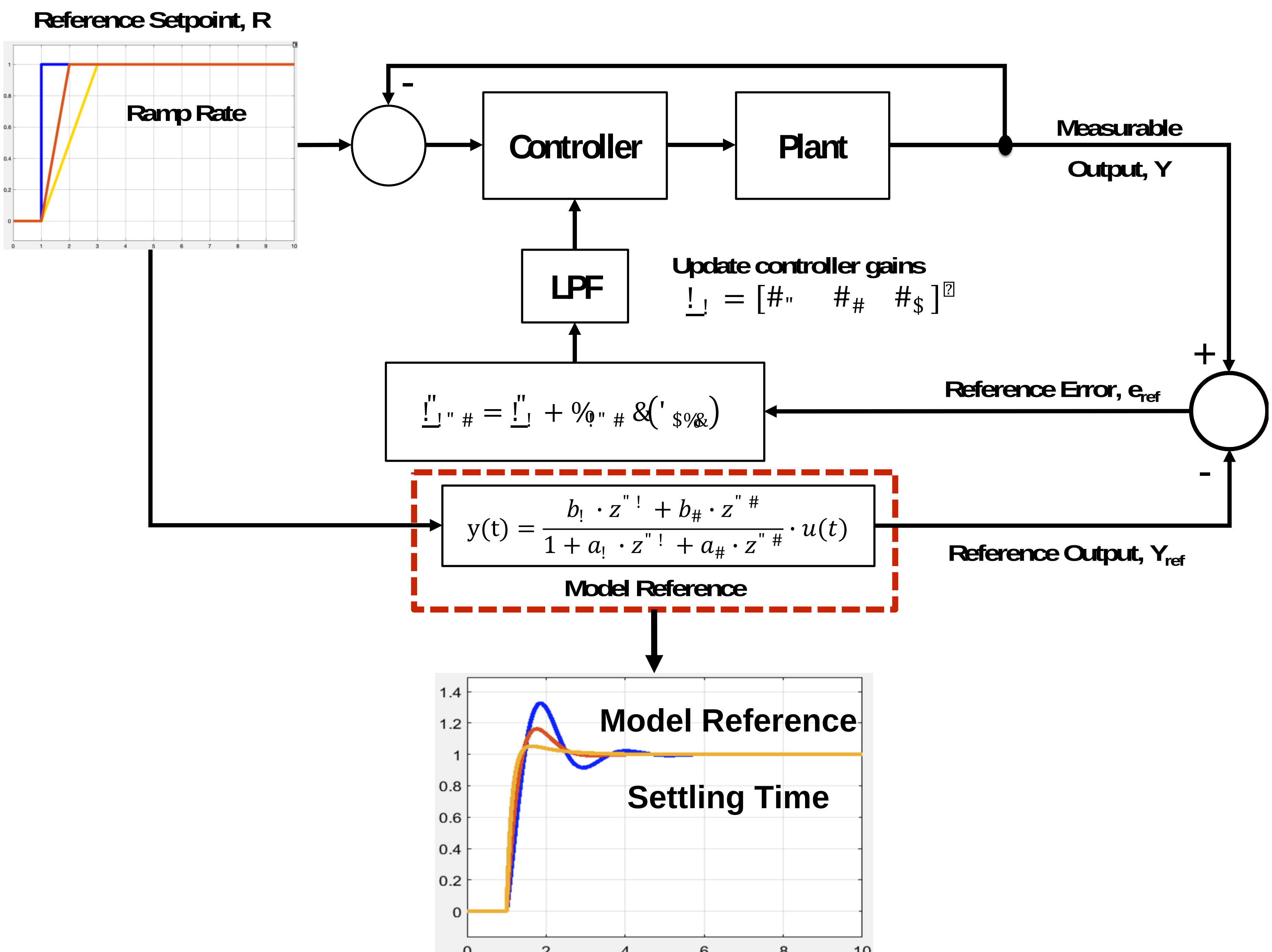
Experimental results – Online system identification tool



[1] H. Bonilla, K. M. Bryden, L. Shadle, D. Tucker, and P. Pezzini "Development of realtime system identification to detect abnormal operations in a gas turbine cycle," *ASME Journal of Energy Resources Technology*, JERT-19-1712, Jul 2020, 142(7): 070903 (10 pages), doi.org/10.1115/1.4046144. 3.

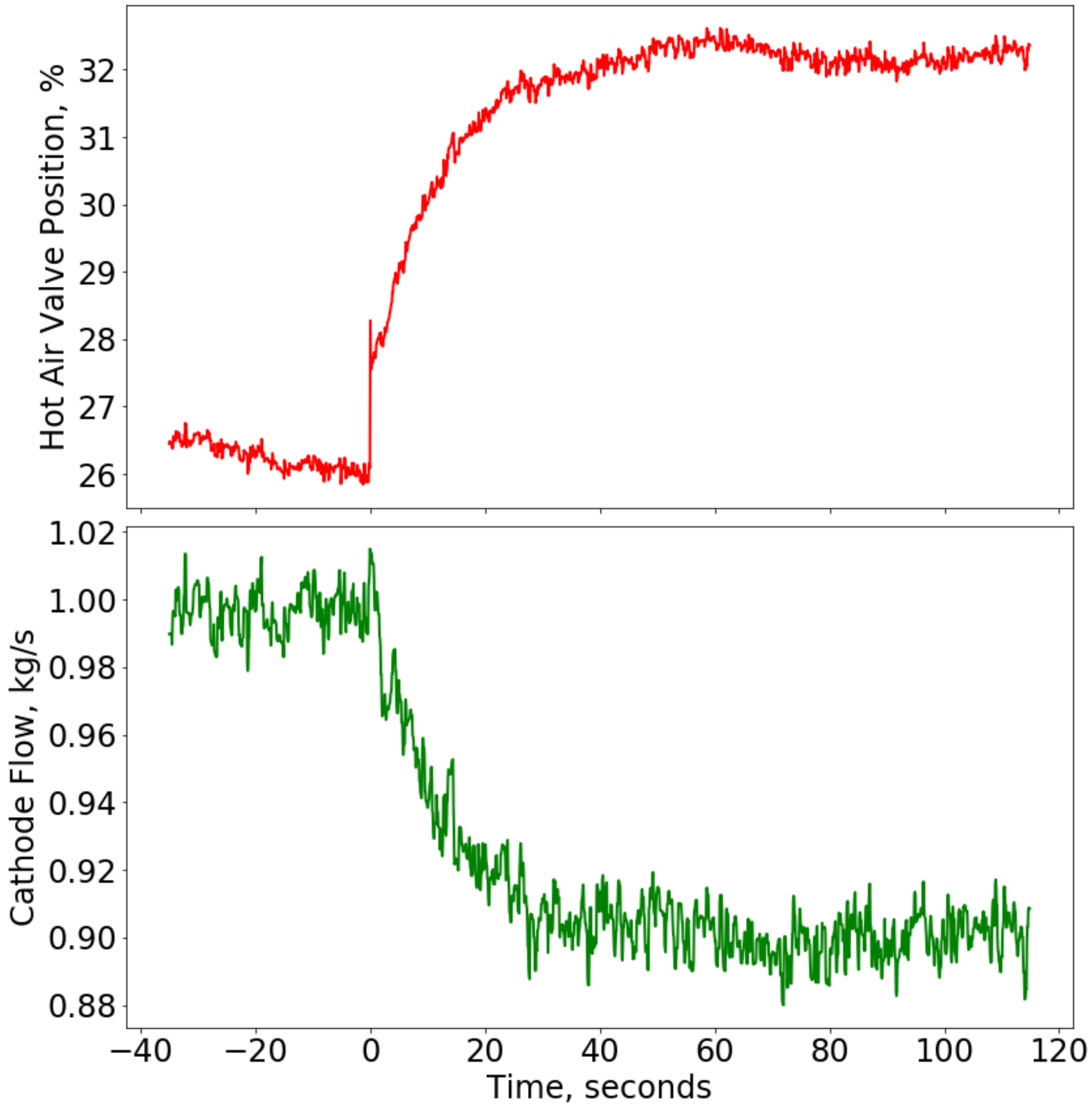
[2] H. Bonilla, P. Pezzini, L. Shadle, D. Tucker, and K. M. Bryden "Online Adaptive Control Tuning in a Gas Turbine Hybrid System," Proceeding of the 2020 ASME Power Conference, ICONE28-POWER2020-16534, Anaheim, California, USA

Recursive Algorithm implementation

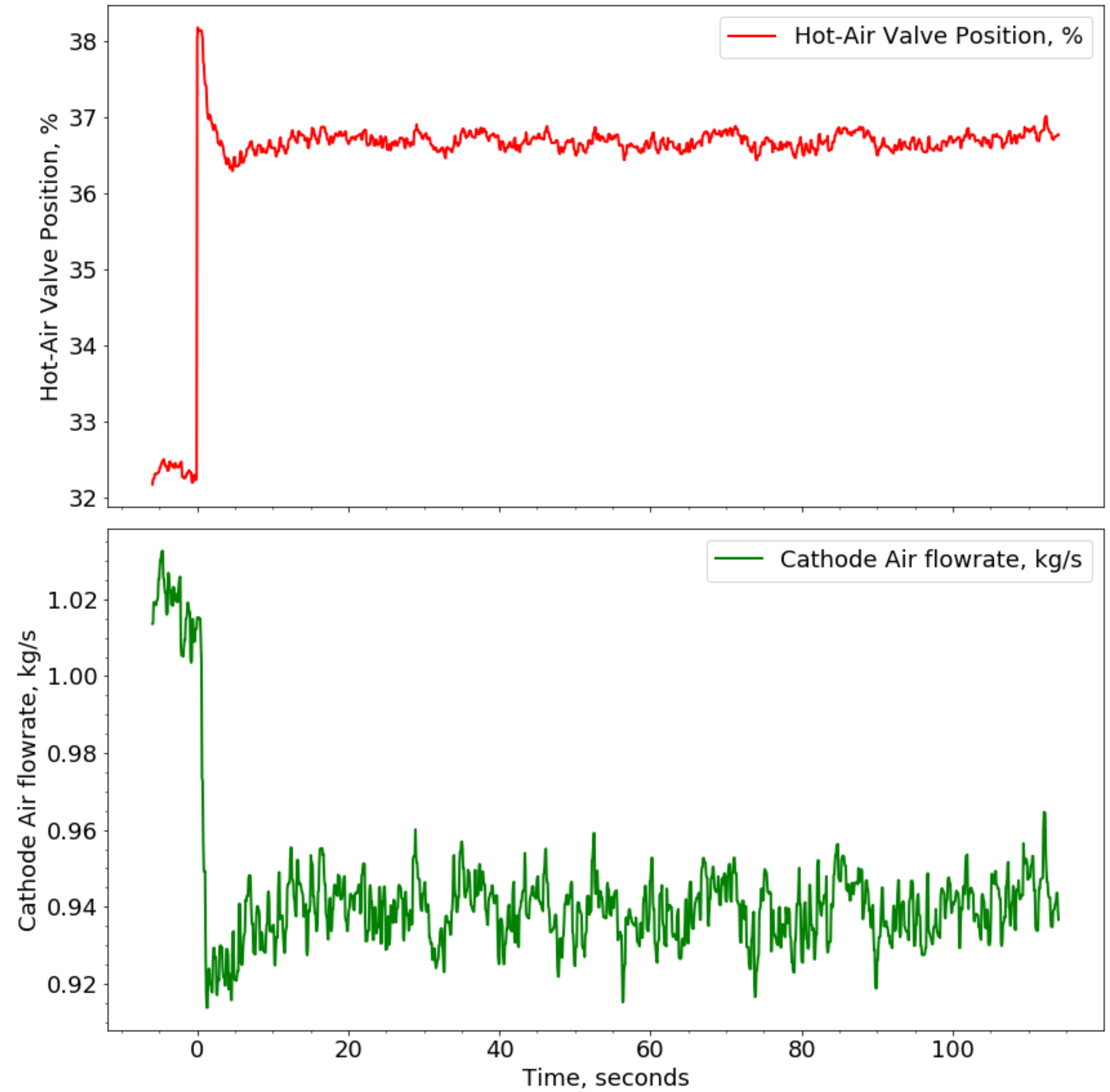


Adaptive control tool (MRAC)

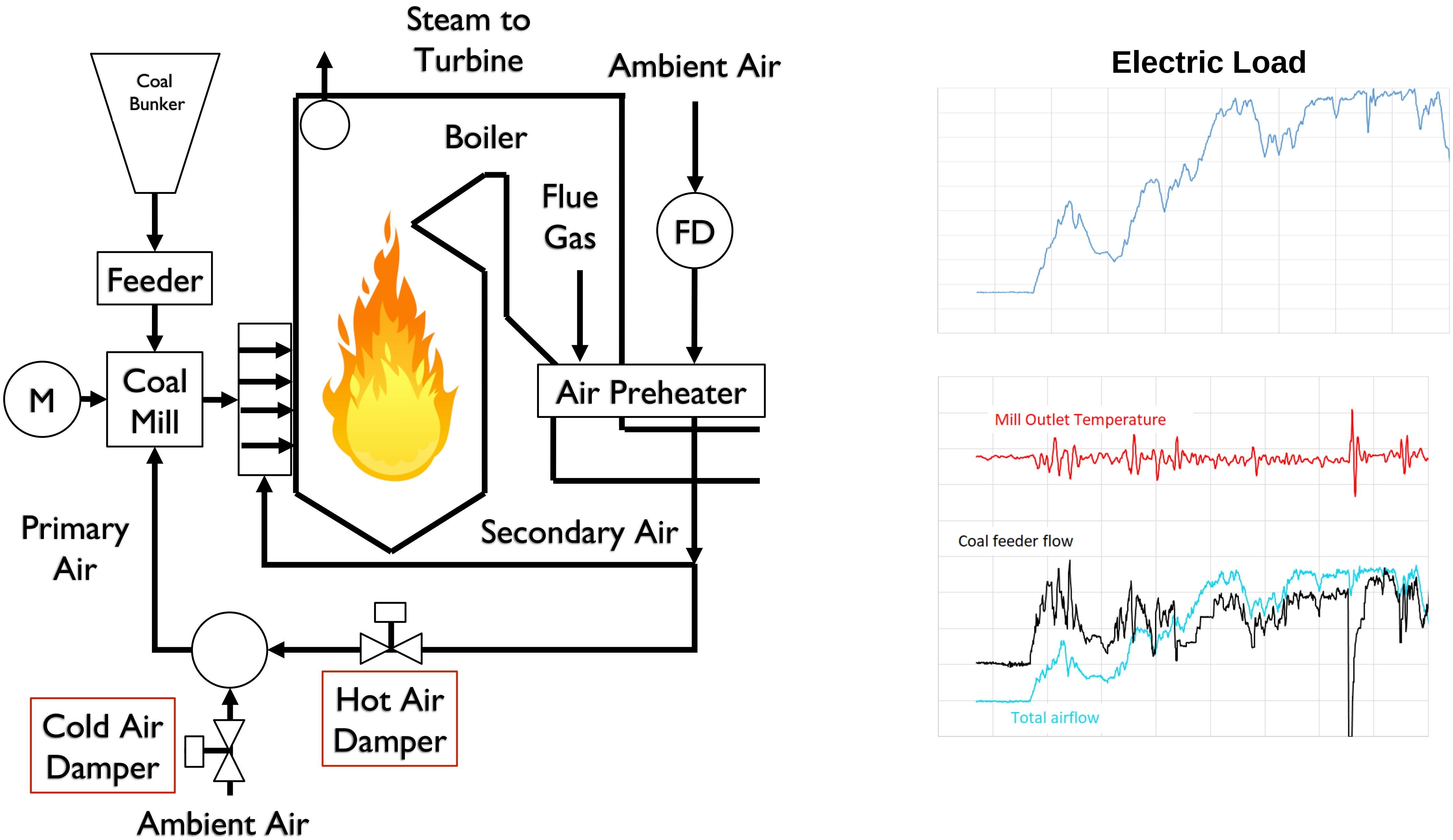
Existing PID Controller



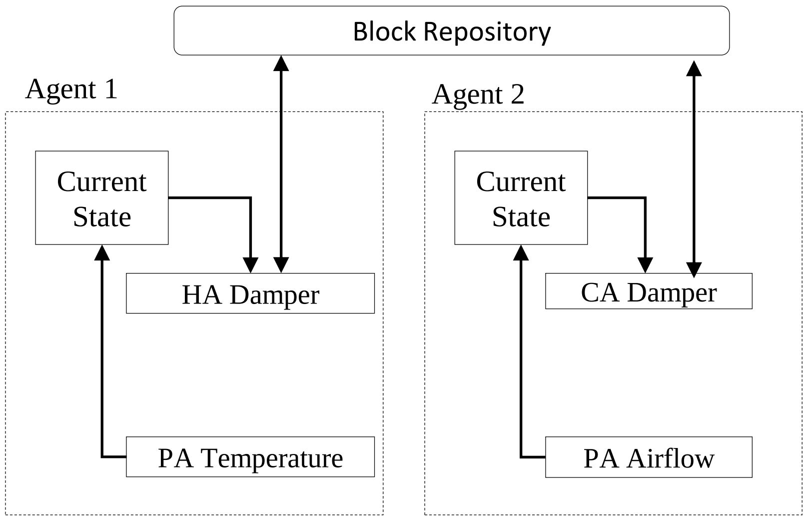
Model Reference Adaptive Controller

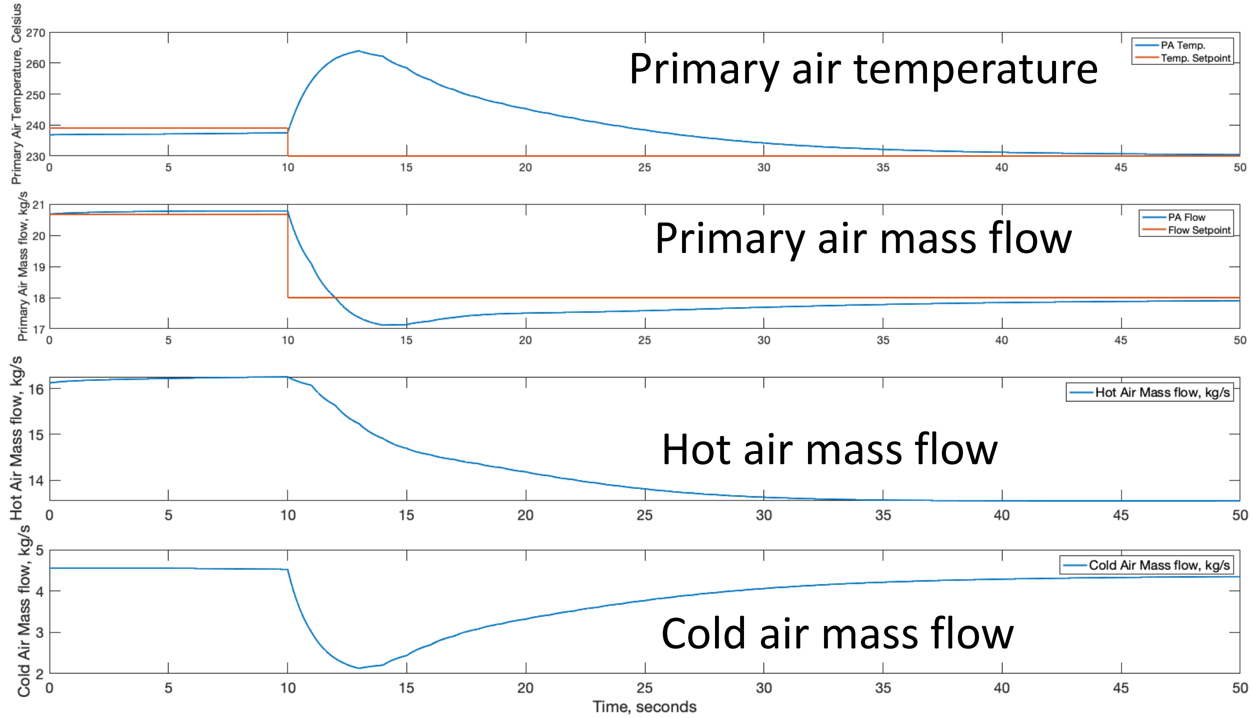


MRAC – Results



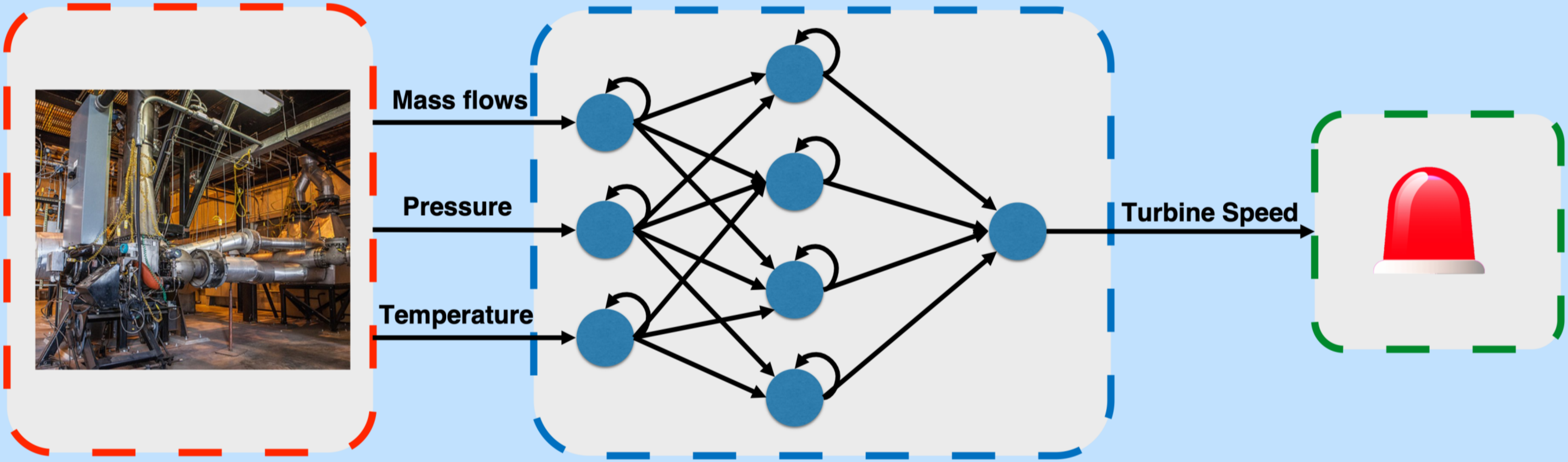
Coal mill outlet temperature control





- Multi-agents emulates intelligent control
- Agents can coordinate their behavior
- Agents are not limited to a set of models

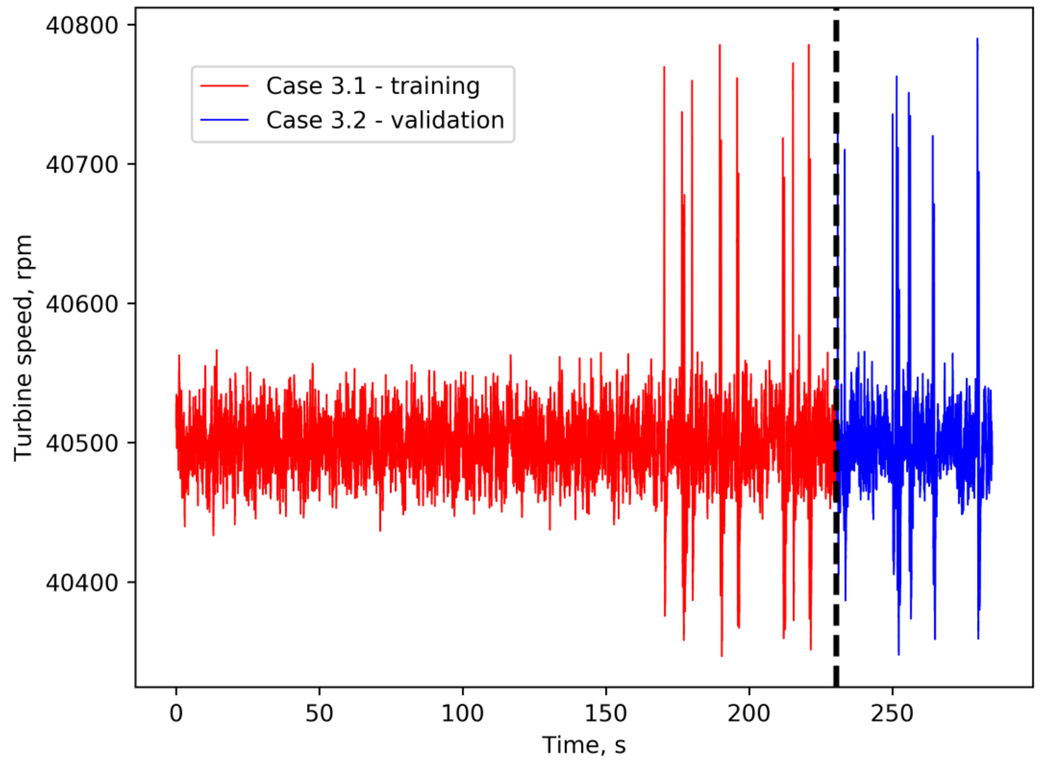
Preliminary results - Coal mill outlet temperature model



3. Machine Learning Diagnostic tools

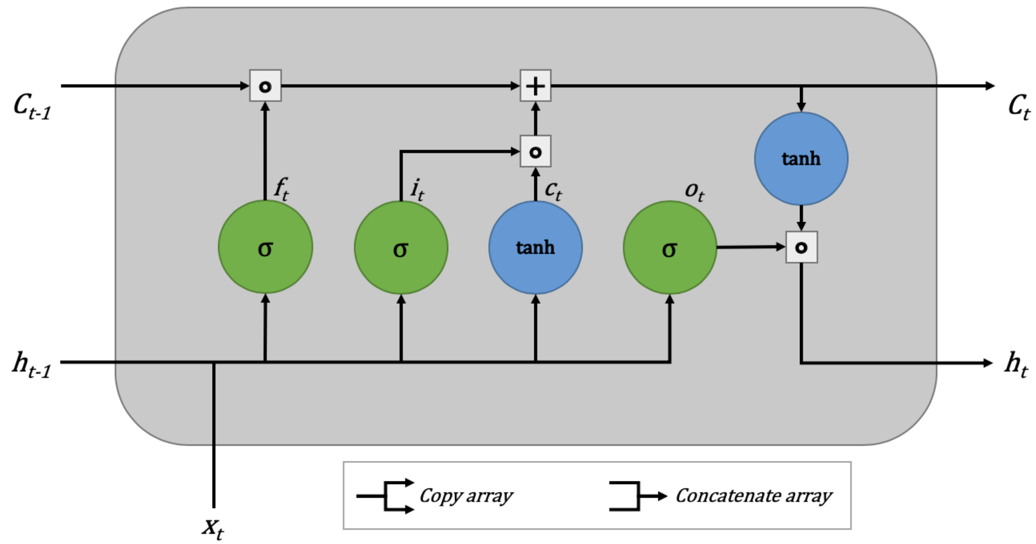
- Detection of unstable turbomachinery performance
- Increase model performance for a gas turbine system

Test Case	Data Points	Incipient Stall Events	Operating Conditions	Use in ML Model
1	7,692	2	Near stall	Training
2	9,216	0	Nominal	Training
3.1	46,080	8	Nominal to near stall	Training
3.2	10,880	7	Near stall	Testing



LSTM Hyperparameters

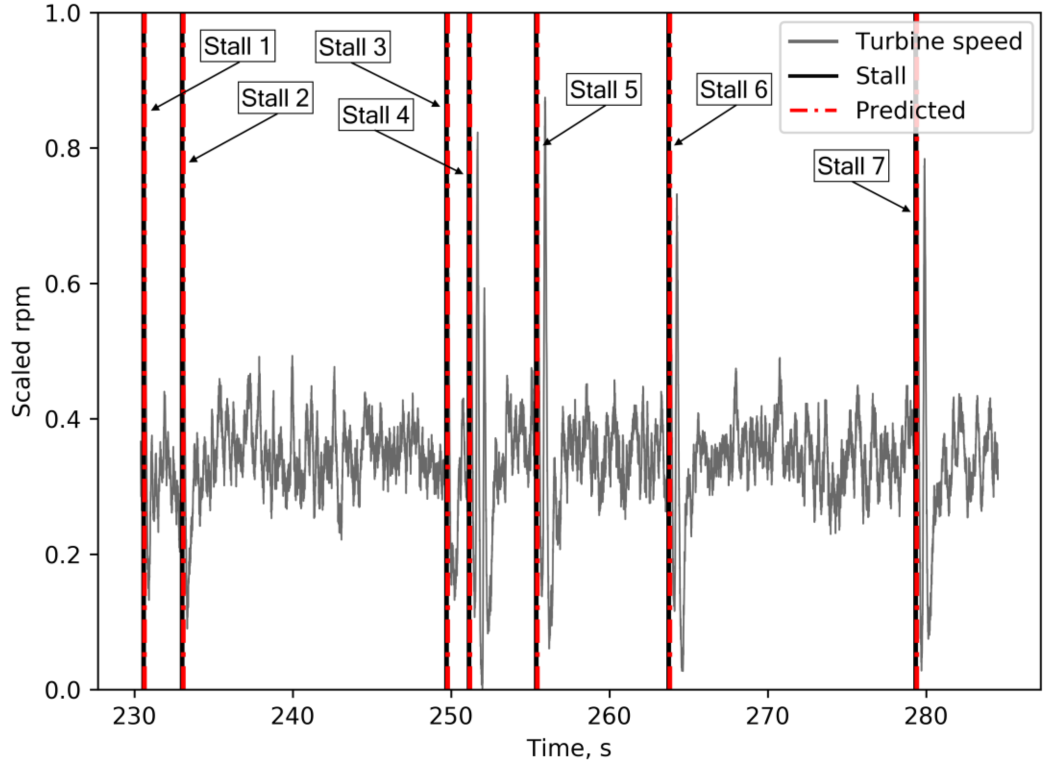
Input steps	40
Output steps	15 (75ms)
First layer size	32
Second layer size	64
Third layer size	32
Batch size	64
Learning rate	0.001
Dropout	20%



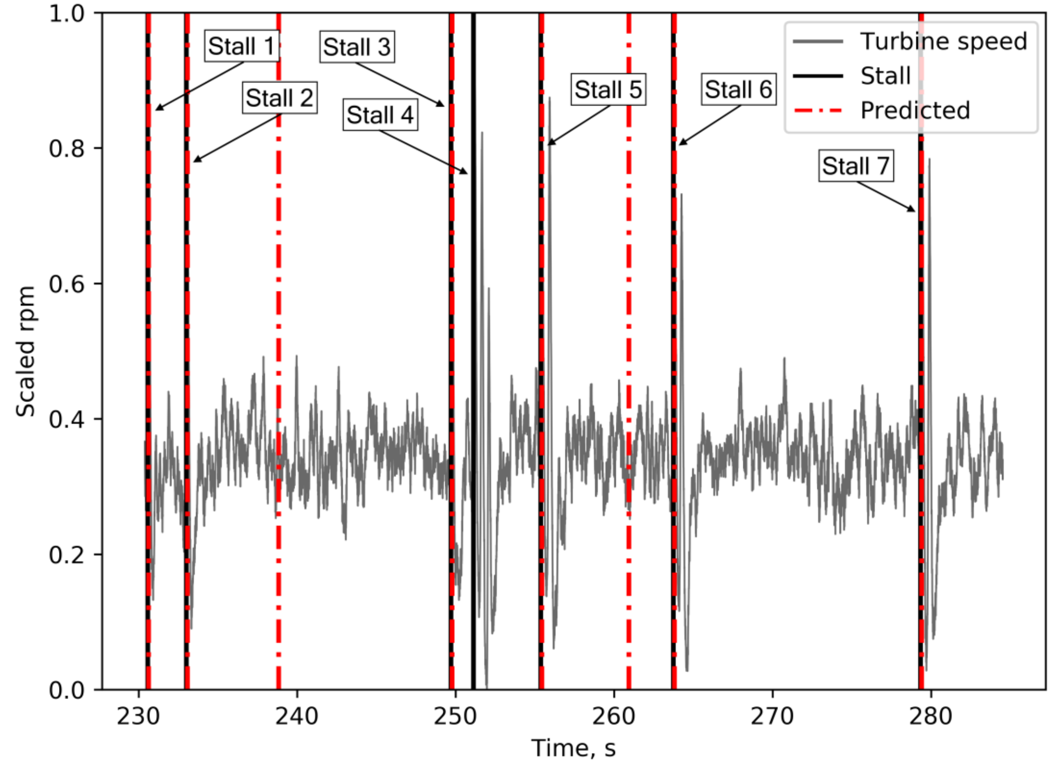
Long short-term memory (LSTM) implementation

Detection Results

16 epochs

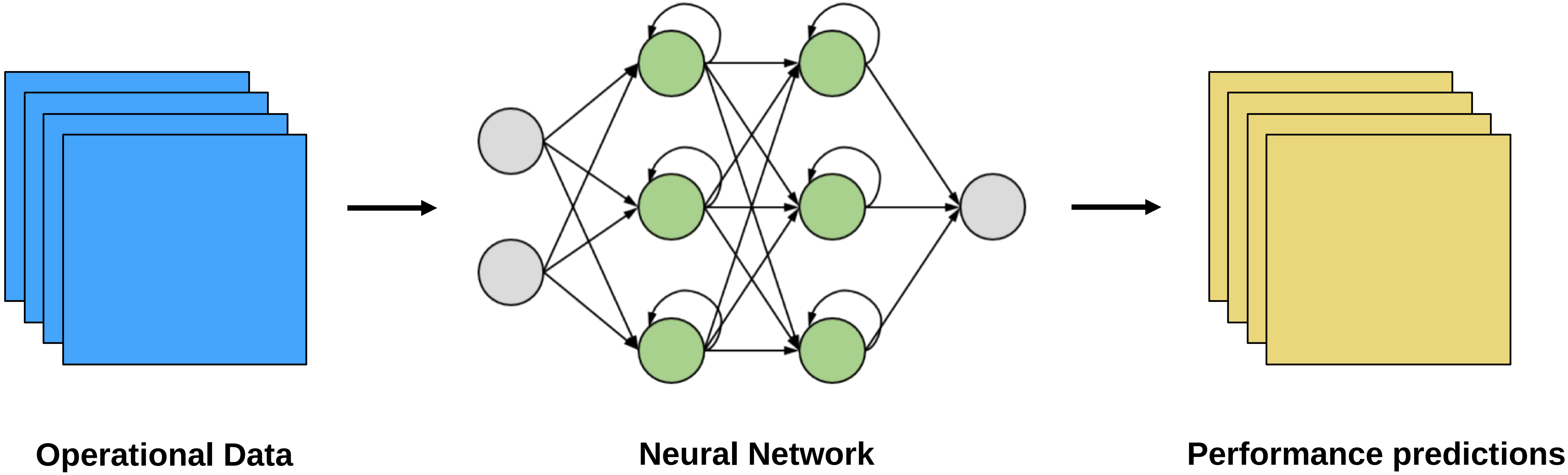


32 epochs

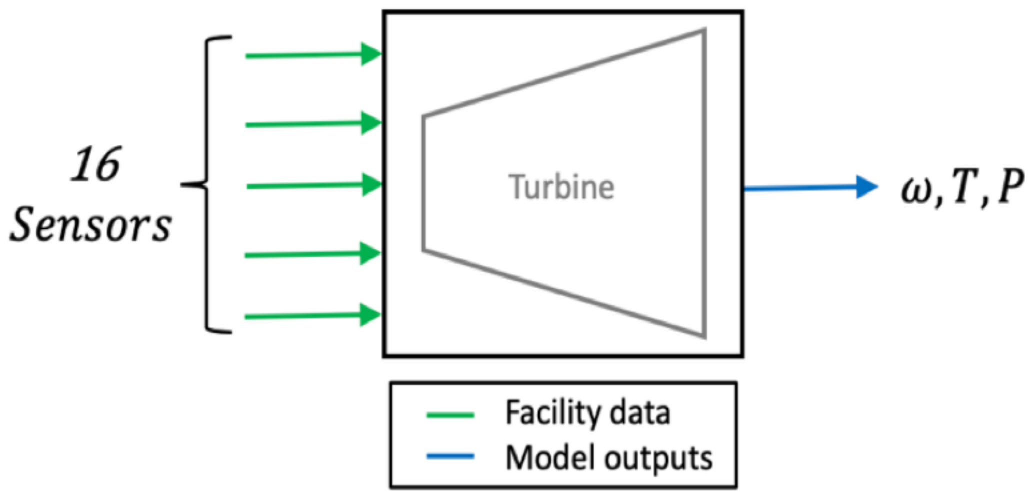


- Stall prediction tool enables 5 to 20 ms reaction time

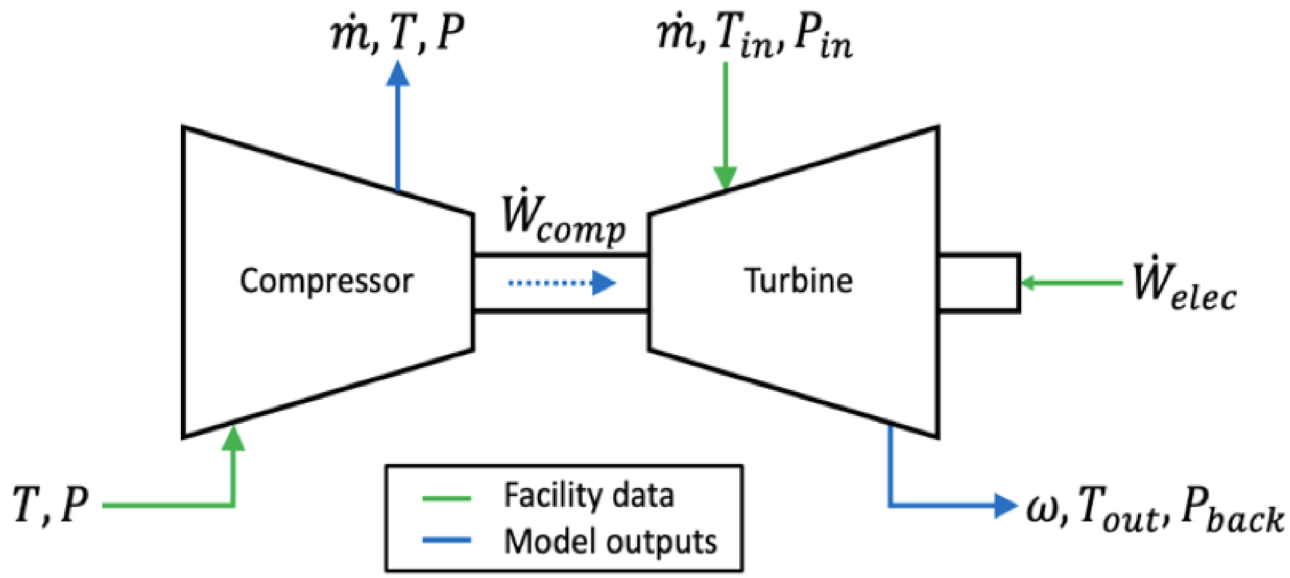
- Configured for online implementation in a digital twin concept



	Test Case	Data Points	Incipient Stall Events	Operating Conditions	Use in Models
Steady-State	1	9,216	0	Nominal	Training
	2.1	475,000	0	Nominal	Training
	2.2	10,400	0	Nominal	Testing
Stall	3	7,692	2	Near surge line	Training
	4.1	46,080	8	Nominal to near surge line	Training
	4.2	10,880	7	Near surge line	Testing

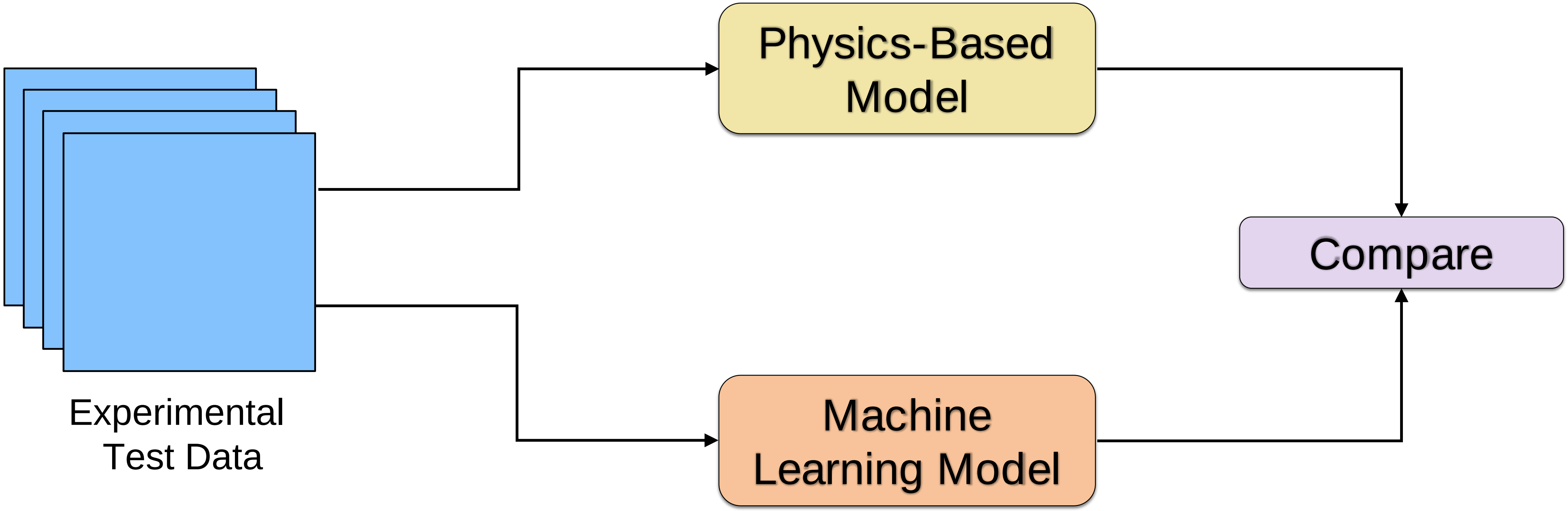


Machine learning model for a gas turbine system



Traditional Euler turbomachinery equations

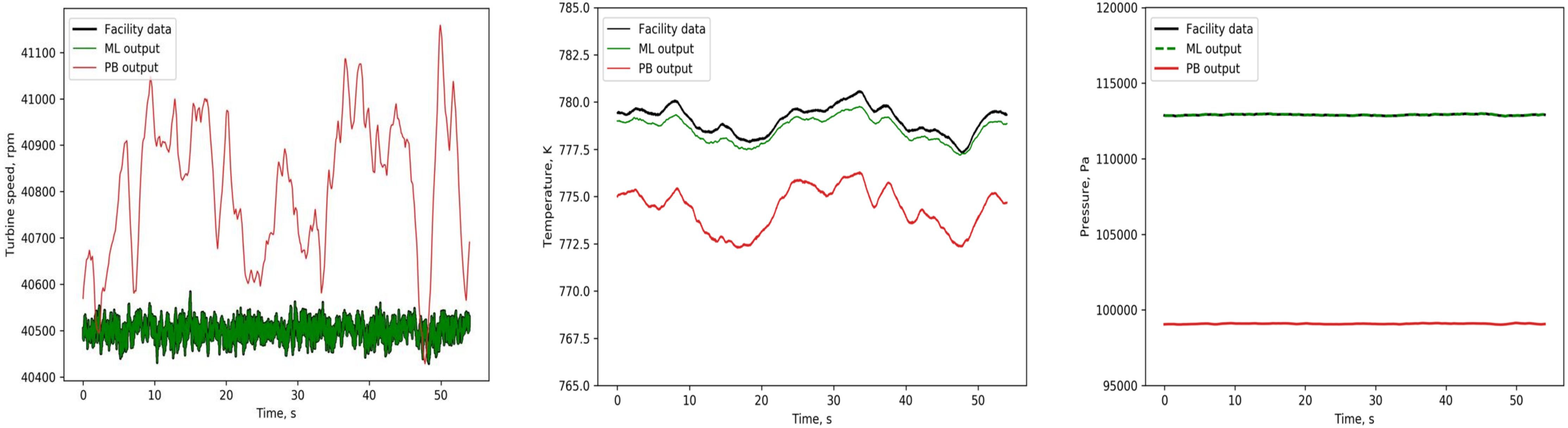
- **Turbine speed –** Turbine work, inertia, shaft load, and rotational losses
- **Rate of turbine work –** Turbine pressure ratio, turbine inlet mass flow, temperature, and specific heat
- **Rate of compressor work** – change in the rate of the angular momentum
- **Temperature outlet –** Pressure ratio and specific heat ratio for compressor and turbine



- Real-time analysis with different computational models
- Performance evaluation during live operation

Machine learning vs physics-based tools

Steady-State Test Data



1. Middleware architecture implemented on a pilot system

2. Monitoring and control tools successfully tested on a pilot system

3. Diagnostic tools using machine learning concept were developed using pilot system data

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Acknowledgments