Data-Driven Refinement of a Native Modelica Model Predictive Controller for Multi-Variable Gas Turbine Hydrogen Blending Control

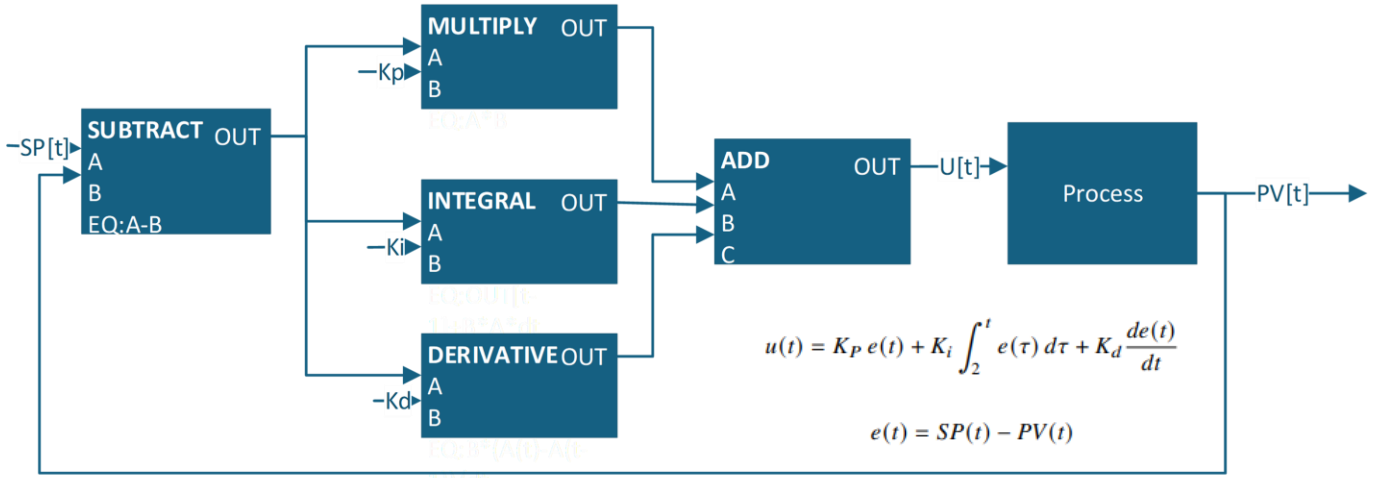
GAS TURBINE MODEL PREDICTIVE CONTROLLER DEVELOPMENT IN MODELICA SYSTEMS MODELING LANGUAGE

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Paolo Pezzini (EPRI)

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PID Limitations and MPC Opportunities

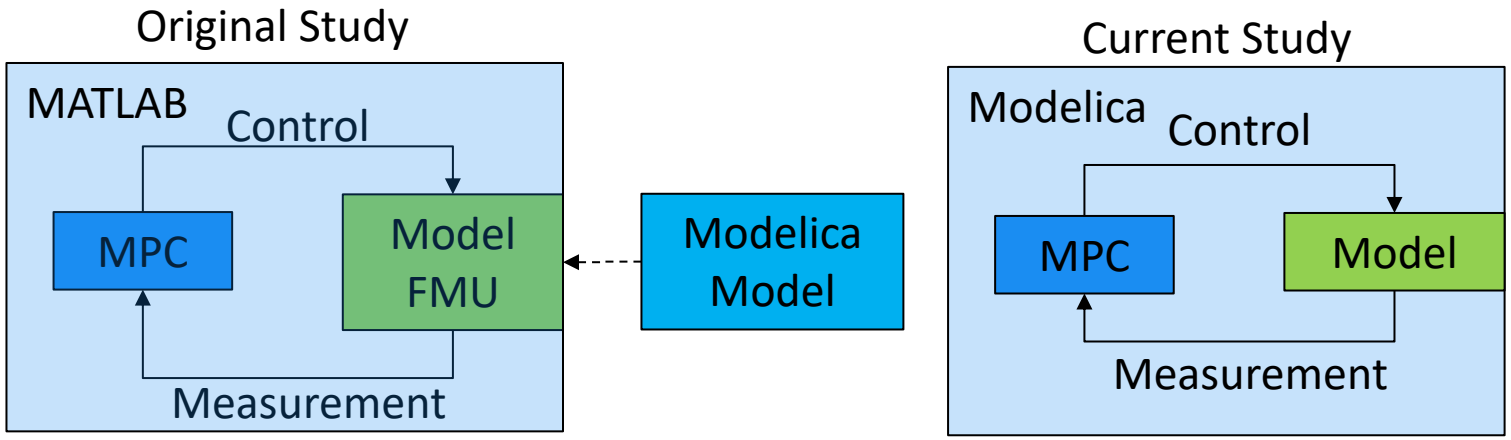
- PID: simple, low cost, fast for SISO - but can't handle constraints, lacks prediction, struggles with MIMO coupling
- In GT systems:
  - IGV affects both temperature AND load;
  - H_2 blend control affects both blend AND load
- MPC: explicit model-based prediction, constraint handling, MIMO coordination



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Why not MATLAB Simulink?

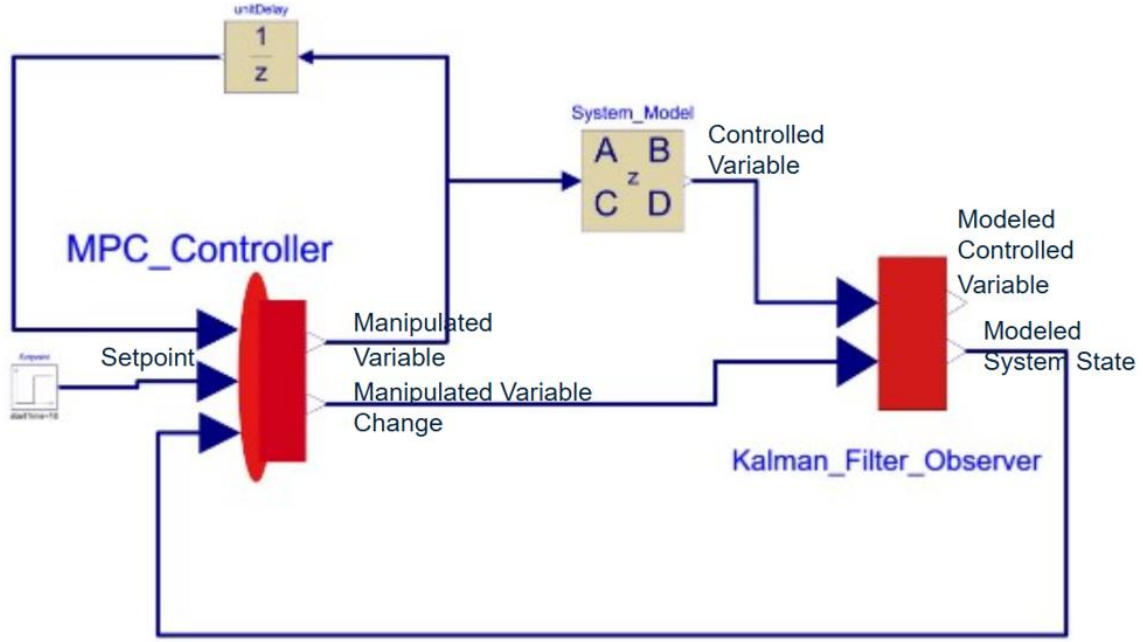
- Prior work used FMU export to MATLAB/Simulink -> co-simulation challenges (latency, solver sync)
- Goal: unified environment for plant + controller -> fair PID vs. MPC comparison

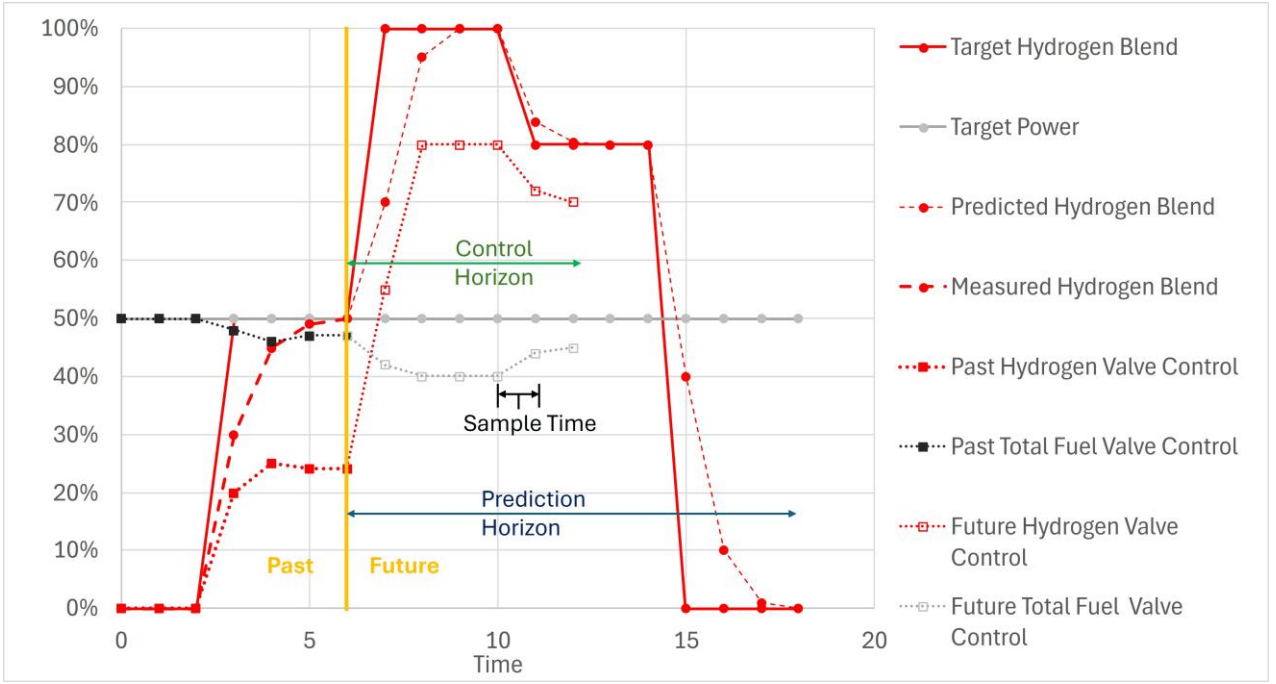


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MPC Architecture Overview

- Three components all in native Modelica MPC:
  - Kalman Filter Observer - state estimation from noisy measurements MPC Controller - receding-horizon QP optimization (cost function J)
  - QP Solver - active-set method for constraint handling





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Motivation

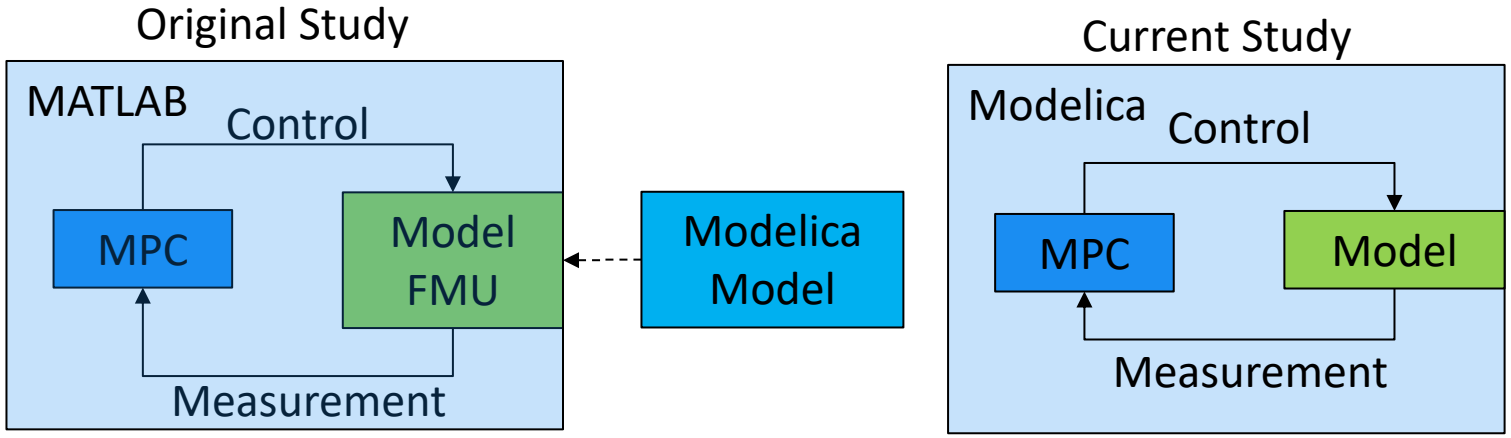
- Hydrogen blending in gas turbines introduces multi-variable coupling: fuel composition <-> combustion dynamics <-> emissions <-> power output
- Hydrogen's lower volumetric energy density, wider flammability, and faster flame speed alter combustion tuning
- EPRI hydrogen blending testing revealed criticality of time lag between actual and reported blend

Can we build a native Modelica MPC that handles these challenges in a unified simulation environment?

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Why Modelica? Why Native MPC?

- Modelica: declarative, a-causal, equation-based, multi-domain physical modeling language
- No publicly available native Modelica MPC existed for general use
- Physical Systems modeling via a-causal paradigm in Modelica
  - Declarative Equation based models allow for robust physical system simulation
- Native MPC in Modelica
  - Challenge: Not readily available in general open modern form
  - Allows for Modelica physical system model and Control in one common environment

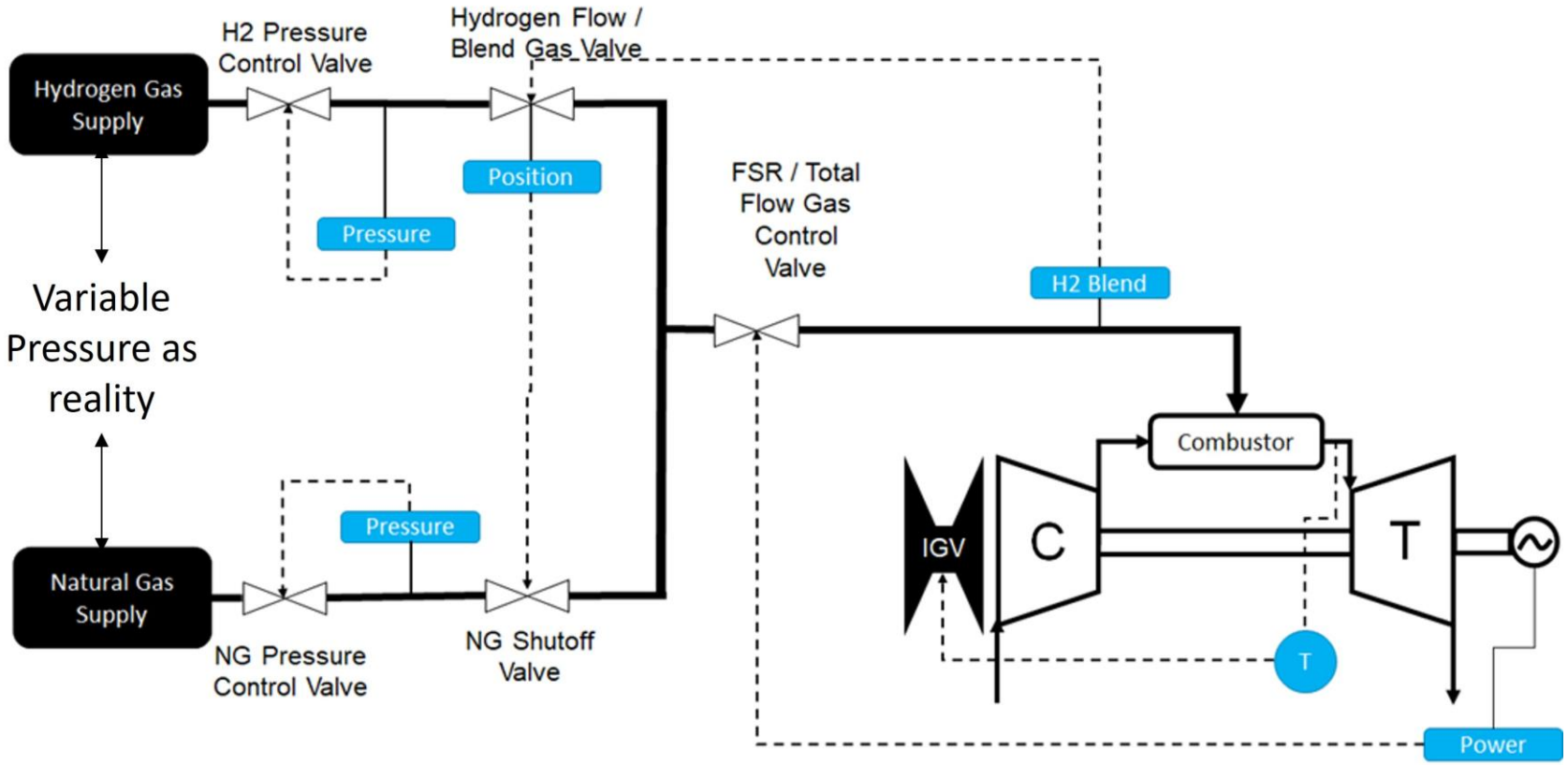


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Gas Turbine System Model

- Built in Modelon Impact using the Thermal Power Library
- 4 actuators: H_2 FCV, FSR (total fuel), PCV (pressure), NG SOV

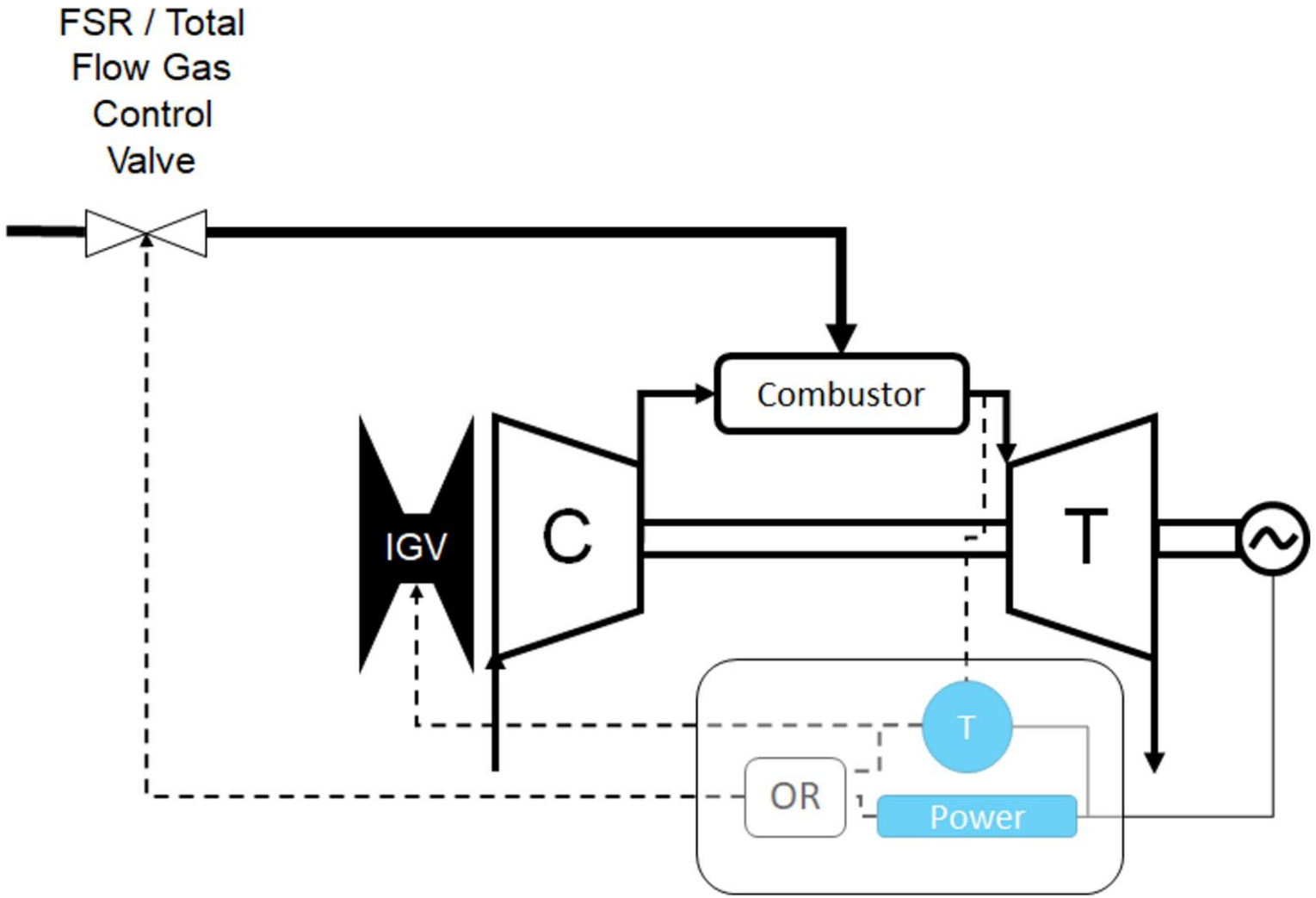
- 3 controlled variables: Hydrogen blend ratio, Generator power, Turbine firing temperature
  Calibrated with EPRI gas turbine testing data



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Updated Baseload and Partload Control Logic

- Added Separate Base and Part load Control Method
- Partload
  - IGV controls to Temperature
  - Fuel Controls to Power
- Baseload
  - Fuel Controls to Temperature
  - IGV at max



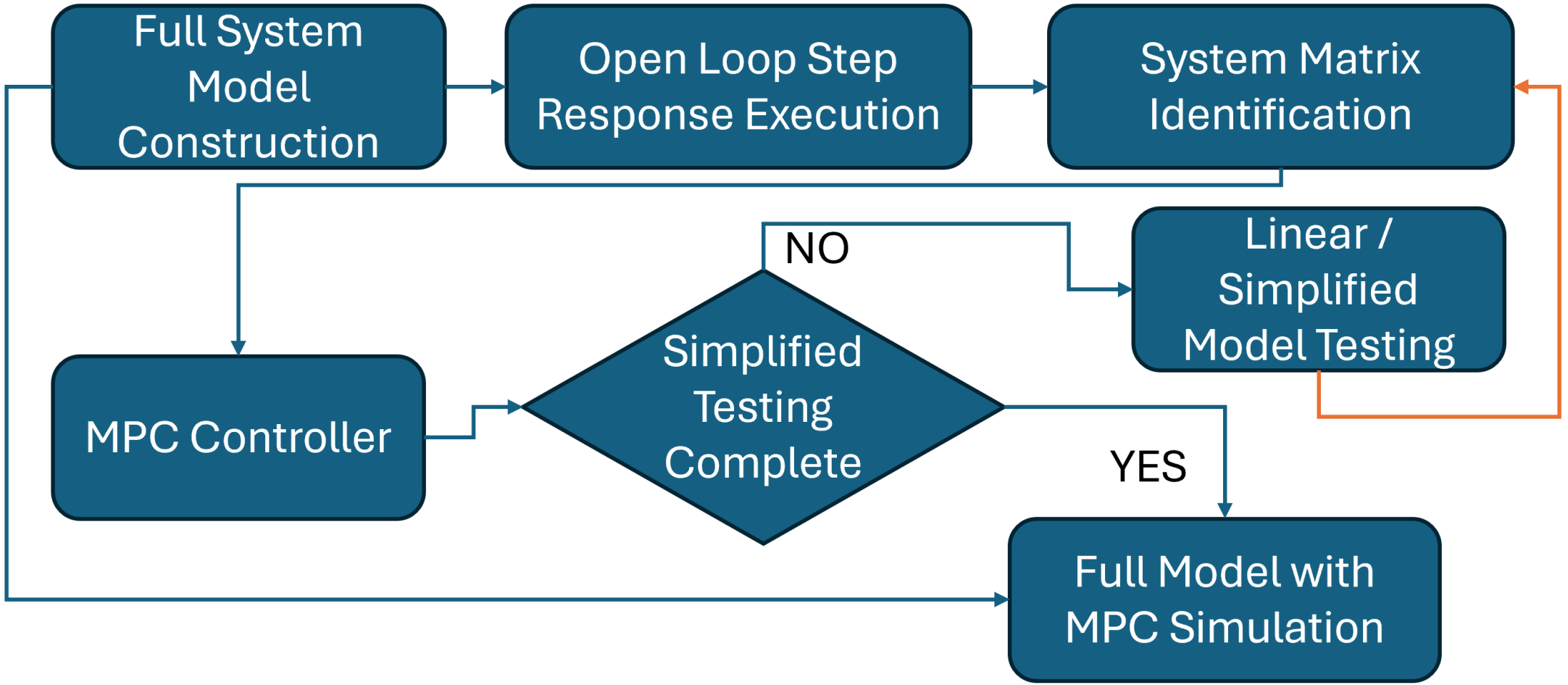
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Incremental MPC Development

Variant	Inputs × Outputs	Horizon	Constraints	Key Feature
SISO MPC v1	1×1	1 step	Basic	Initial Matlab+ Modelica system
SISO MPC v2	1×1	1 step	Active-set QP + KKT	Hard bounds on inputs & states, delay states
MIMO MPC	3×3	1 to N steps	Full MIMO QP	Prediction horizon, reference trajectory

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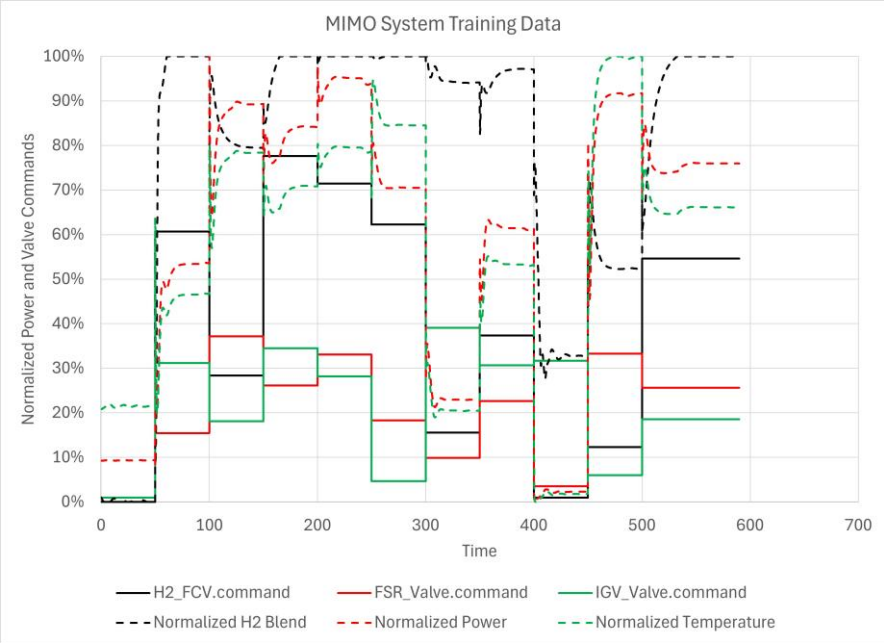
Development Process

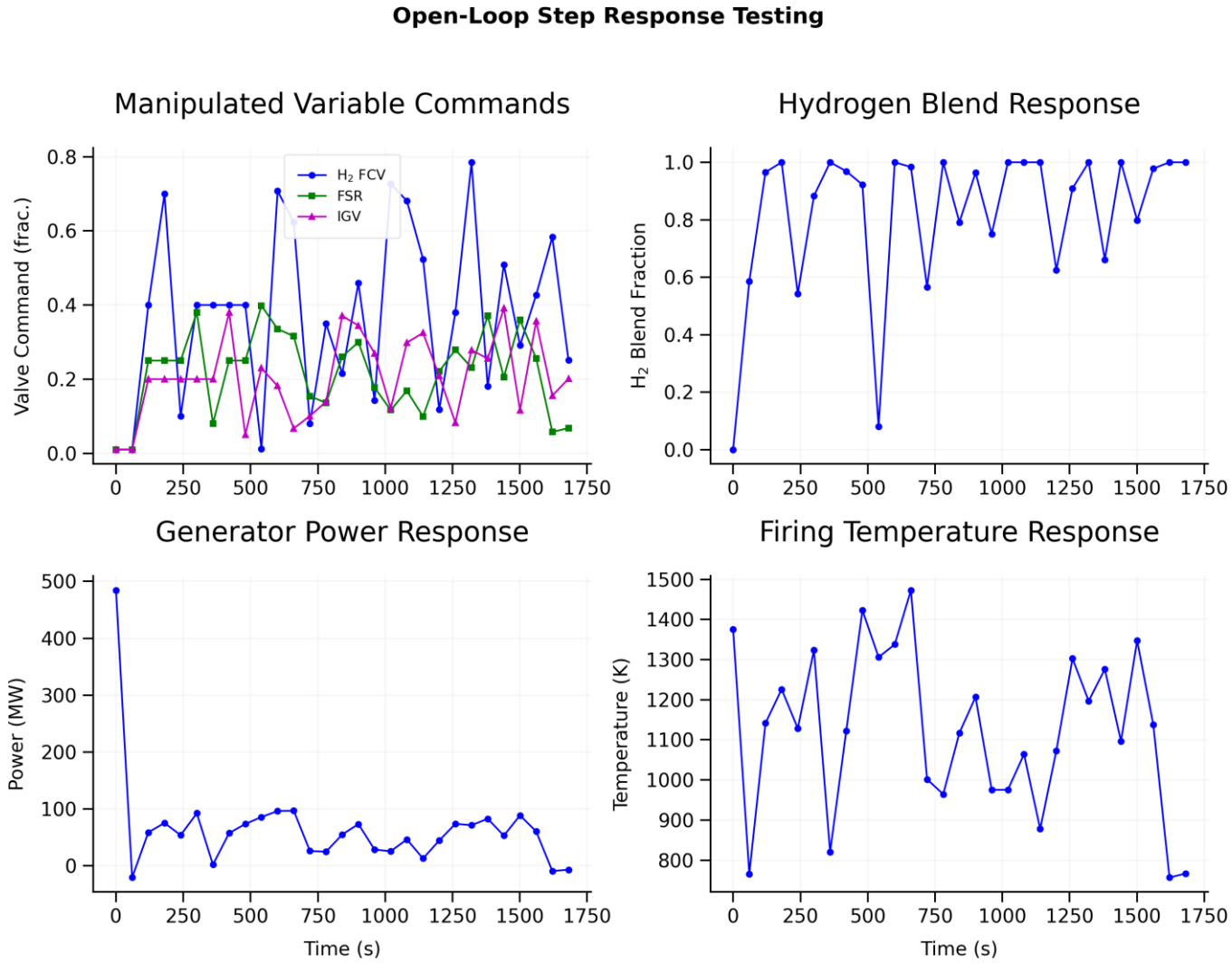


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Open Loop Test Data

- Open Loop Testing Conducted with Full System model
- At range of operational conditions





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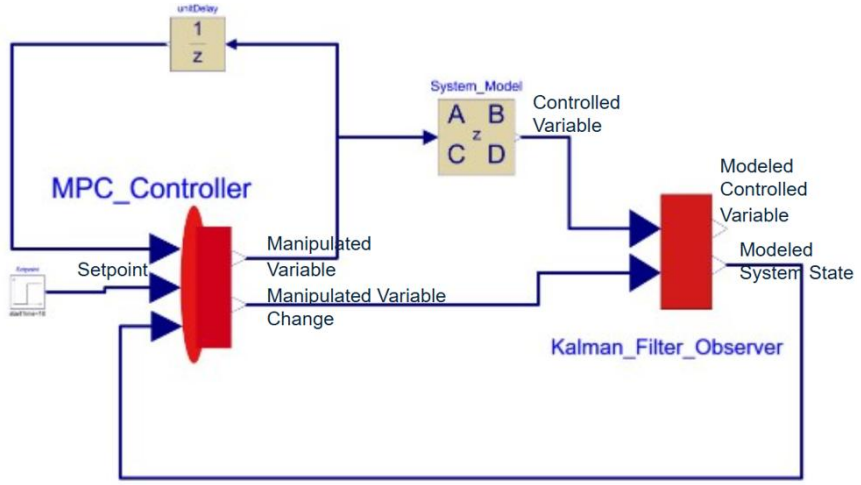
System Identification Process for MPC

- Open-Loop Data Ingestion
  - Dimensional time-series data (from Open Loop testing) is loaded for 3 inputs (H_2 FCV, FSR valve, IGV) and 3 outputs (H_2 blend, power, firing temperature).
- Non-Dimensionalization
  - Each channel is scaled to [0, 1] using known physical ranges
- Ridge Regression System ID
  - A discrete-time MIMO state-space model is identified directly from the non-dimensionalized data using regularized least-squares
- Re-Discretization
  - The identified model is converted from the training timestep to the MPC control interval MPC Prediction Matrices
  - Prediction matrices are constructed from the re-discretized (A, B, C)

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Simplified / Linear Model Testing

- Linear State Space Model Used For System Testing
  - Used To Identify System Performance and refinement needs



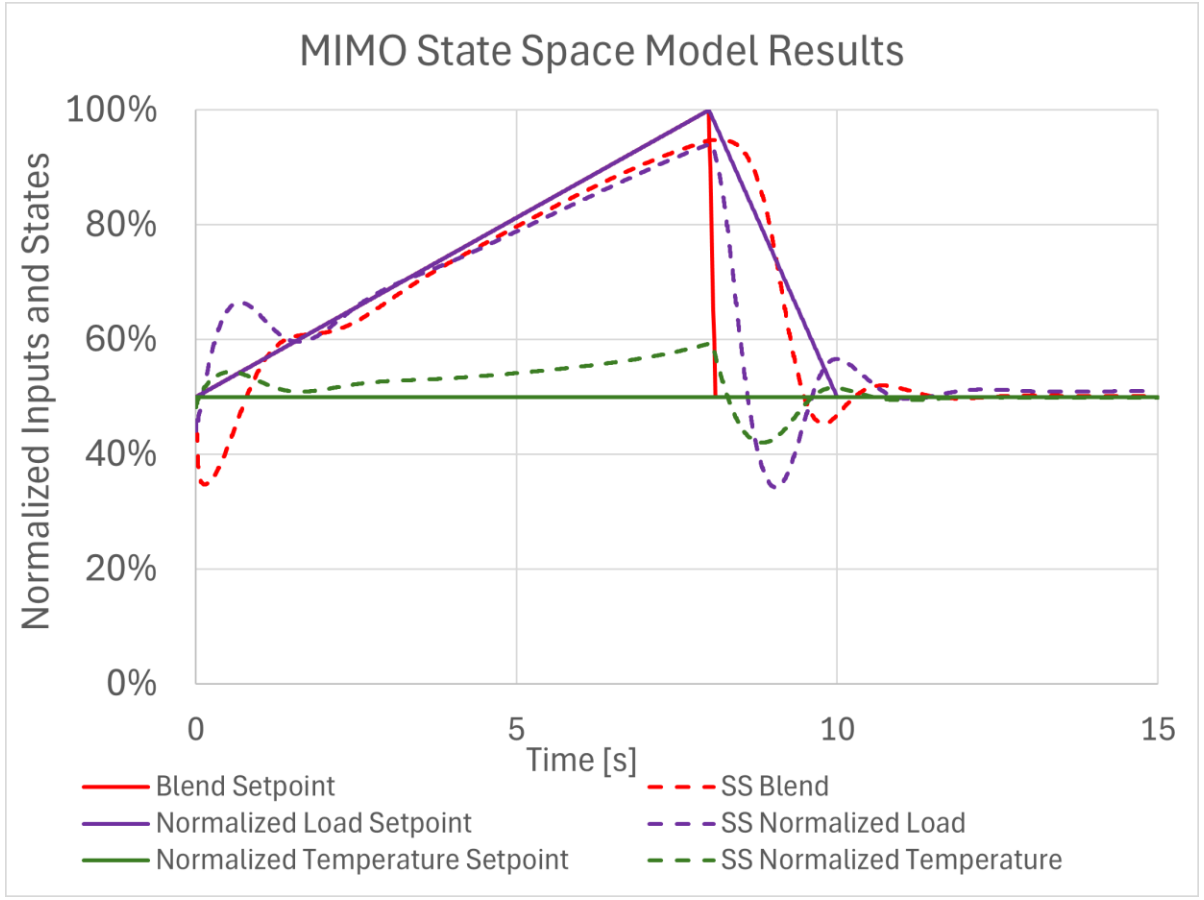
- Sigmoid Function used on process output prediction
  - Wrapper allows for non-linearity in system response

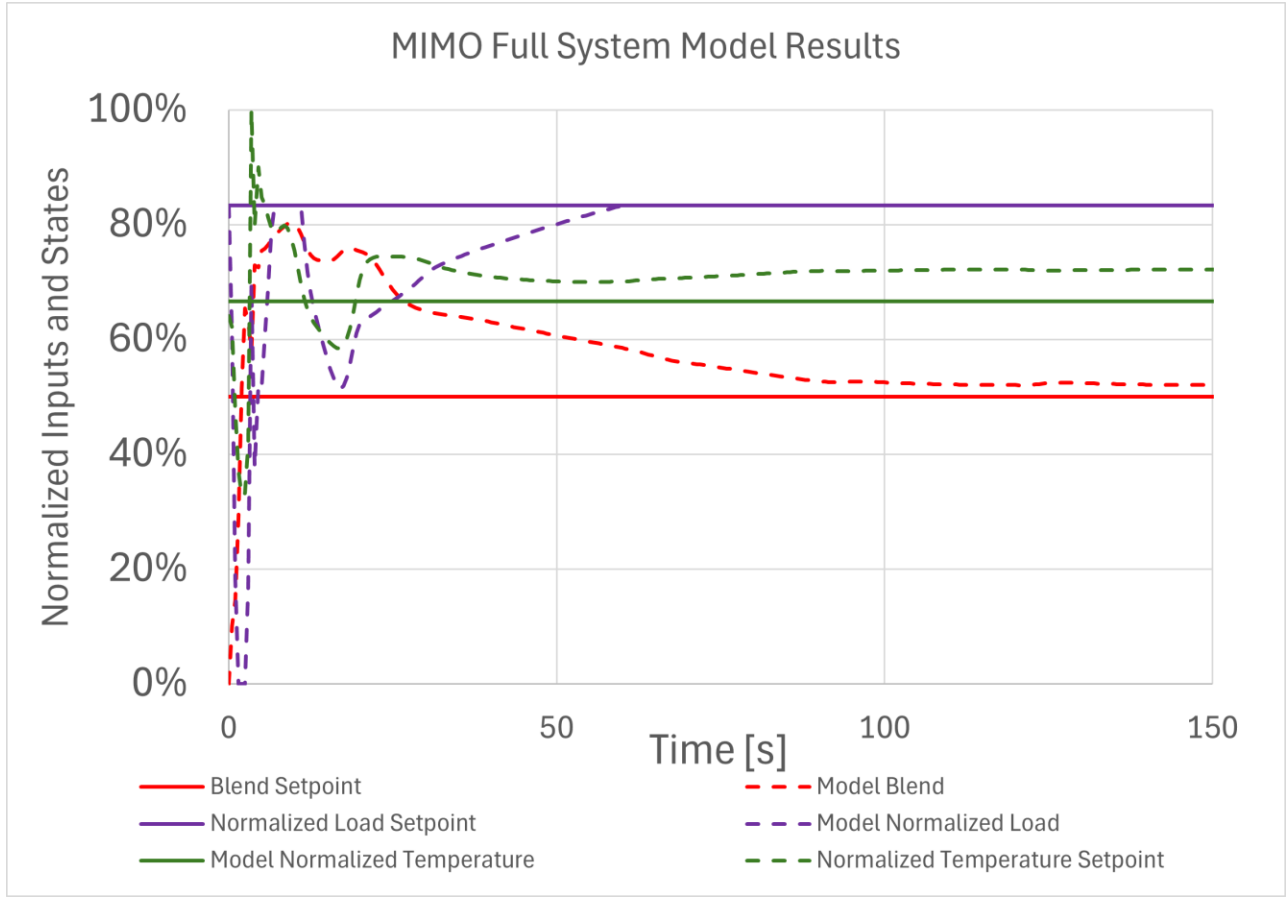
$$\mathbf{x}[k] = \mathbf{A}\,\mathbf{x}[k-1] + \mathbf{B}\,\mathbf{u}[k],$$
$$\mathbf{y}[k] = \sigma\big(\mathbf{C}\,\mathbf{x}[k-1] + \mathbf{D}\,\mathbf{u}[k]\big),$$
$$\text{where } \sigma(z) = \frac{1}{1+e^{-z}}.$$

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Initial Feasibility Results

GT Model Validation	State-space Model	Physics-based Model
Settling Time	MW=10s, H_2=15s, TIT=10s	MW=60s, H_2=80s, TIT=70s
Steady-State Error	0% all	MW=0%, H_2=0.1%, TIT=0.3%





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Future Study Refinement Campaign

- Two parallel tracks:
  - Updated system ID, Hessian regularization, system and MPC alignment
  - QP solver reformulation (S1 -> S2)
- Experiment matrix: S1 (baseline) -> S2 (refined), with progressive corrections

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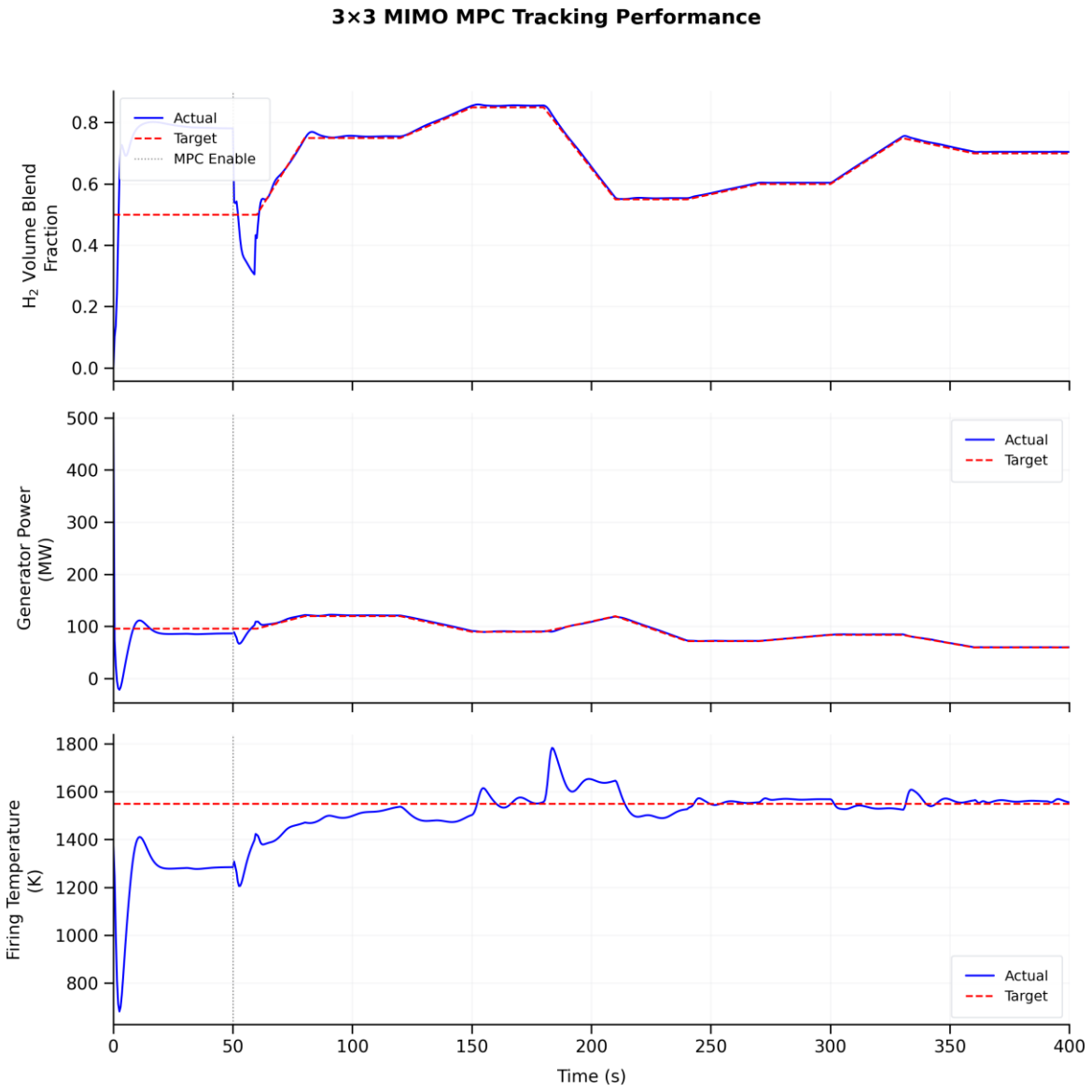
QP Solver Refinement

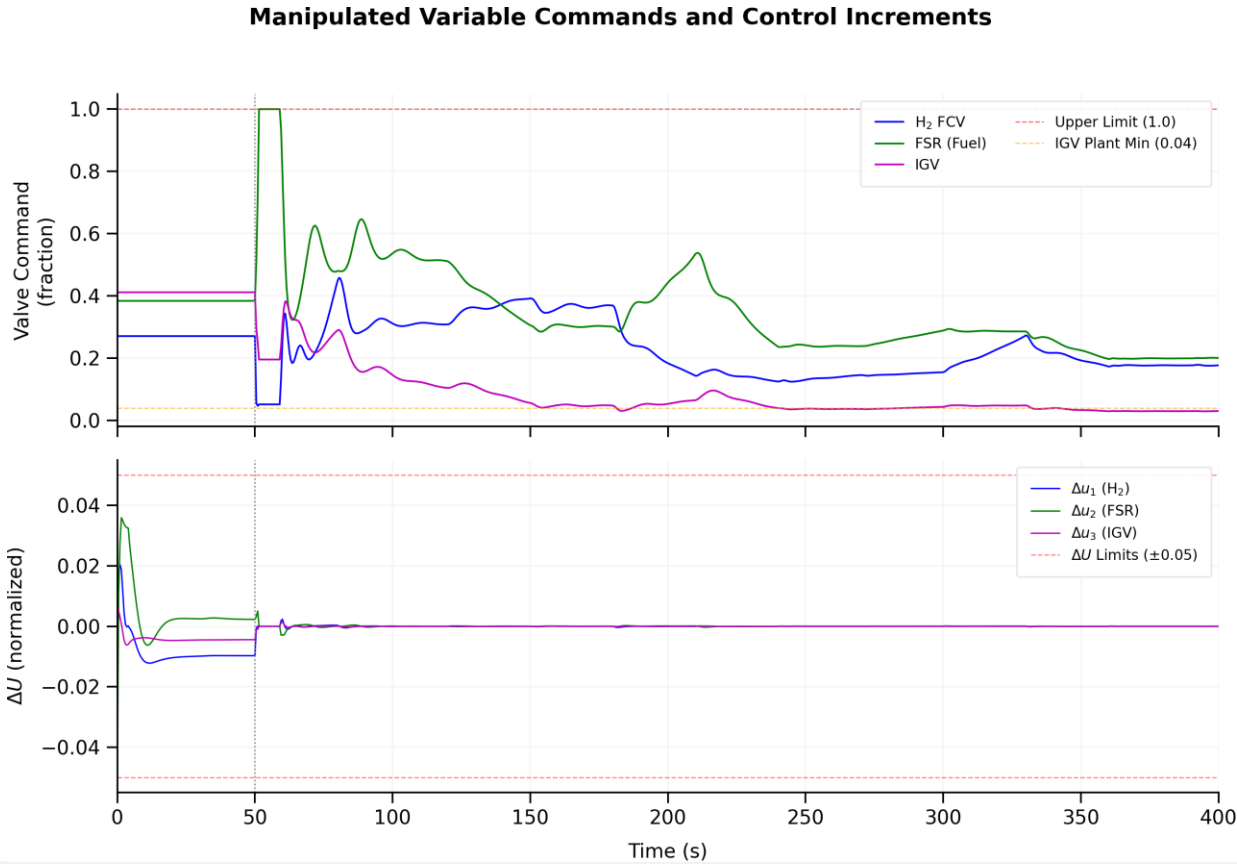
- S1 Limitations:
  - Implicit constraint handling (no explicit Lagrange multipliers in MIMO)
  - Full-step updates -> constraint boundary violations
  - Singular KKT matrix with near-parallel constraint normals
- S2 Improvements:
  - Explicit KKT saddle-point system (min primal x, max Lagrange constraint ʎ)
  - Hessian regularization: $\varepsilon_H = 10^{-6}$
    - ensures that H_{reg} is strictly positive definite even when H has small eigenvalues
  - (2,2)-block regularization: $\varepsilon_KKT = 10^{-8}$
    - Prevents normal active constraints which occur when MPC time << Plant time
  - Step-length line search
  - Active-set safety limits (max 50, 200 iterations)

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Refinement Improved Results

- Final steady-state:
  - H_2 blend: 0.705 vs. 0.700 target (0.70% error)
  - Load: 60.53 vs. 60.0 MW (0.53 MW error)
  - T_fire: 1556 vs. 1550 K (6 K offset)
- H_2 FCV operates within [0.047, 0.458] - no saturation
- Settling times: H_2 at 182.5s, Load at 331.5s, T_fire at 337.5s





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Practical Lessons for MPC in Modelica

- Debugging symptom (PV divergence) separated from root cause by multiple layers (plant -> Kalman -> prediction matrices -> QP -> constraints)
- Sample time vs. horizon trade-off: Ts = 0.01s gives accuracy but negligible look-ahead; Ts = 1.0s gives meaningful prediction but amplifies model mismatch
- Modelica's equation-based paradigm makes procedural MPC logic challenging but feasible via algorithm sections

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Conclusions

- Native Modelica MPC is feasible and functional - SISO through 3×3 MIMO with Kalman filter and QP solver
- Explicit KKT with dual regularization eliminates numerical singularities
- Constraint alignment is critical - mismatch caused persistent tracking failure
- Robust multi-variable tracking achieved - H_2 within 0.70%, load within 0.53 MW, temperature within 6 K
- Architecture scales to sample periods commensurate with plant dynamics
- All models and algorithms to be made publicly available for community use
- **Interested in learning others experiences or insights in Modelica Models for physical systems and controls**

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