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Nonlinear Control and Observer Problems in Fuel Cell Technology

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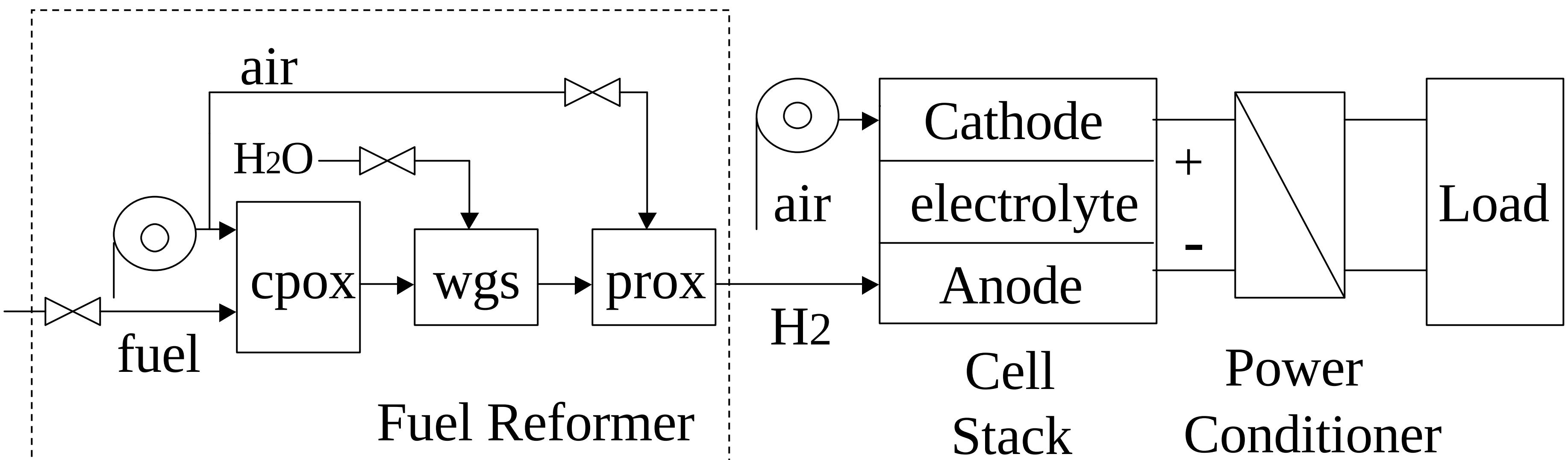
Design Problems

Controls:

- Stringent requirements for regulation of CO, H2, temperatures, etc.
- Quick start-up and load-following

Observers:

- Sensors not designed to operate in reformate gas streams
- Key ingredients in fault detection and isolation algorithms



Main Challenges

Nonlinearity:

- Turbulent flow pressure dynamics
- Control variables (air and fuel flows) multiplied by state variables (concentrations)
- Kinetic equations

Complexity:

- Large and stiff differential equations
- Strong interconnections between subsystems

Uncertainty:

- Kinetic parameters
- Pressure drop characteristics
- Air composition (varying humidity)

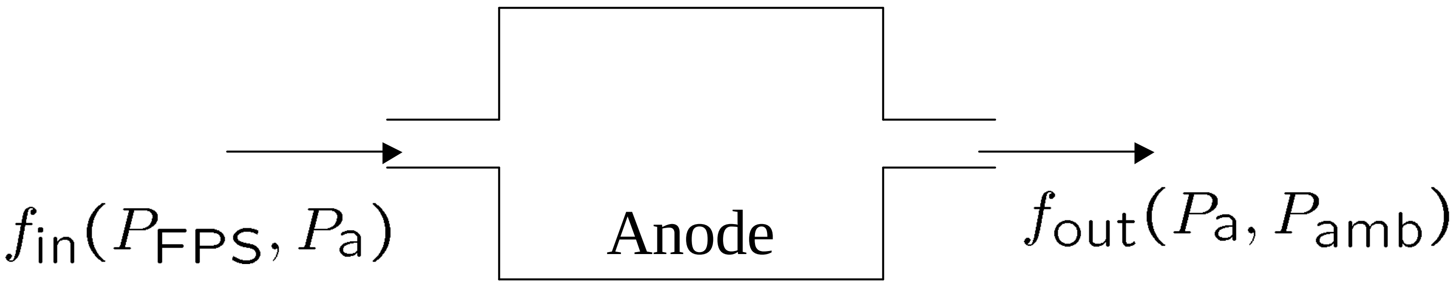
Current Work: Hydrogen Observers

Shortcomings of available hydrogen sensors:

- Not designed to operate in fuel stream
- Cost ($500-$2000)
- Response time (10-100 sec.)
- Lifetime (6 months to 3 years)
- Accuracy (1% - 10%)

OUR TASK: Estimate, rather than measure, hydrogen with a model-based observer

Estimating Hydrogen in the Anode



P_{H_2} : exit partial pressure

θ : inlet partial pressure

$$\dot{P}_{H_2} = f_{\text{in}}(P_{\text{FPS}}, P_{\text{a}})\frac{\theta}{P_{\text{FPS}}} - f_{\text{out}}(P_{\text{a}}, P_{\text{amb}})\frac{P_{H_2}}{P_{\text{a}}} - k\, I$$

θ evolves according to FPS dynamics. We treat it as a slowly-varying parameter.

Task: Estimate P_{H_2} and θ from voltage measurement

$$V = h(P_{H_2}^{\mathsf{av}}, P_{O_2}^{\mathsf{av}}, I) \qquad \text{(Nernst eq'n)}$$

$$P_{H_2}^{\mathsf{av}} = \frac{1}{2}(P_{H_2} + \theta)$$

Our observer exploits the monotone increasing property: $\partial V / \partial P_{H_2} > 0$

$$\begin{aligned} \dot{\hat{P}}_{H_2} &= f_{\mathsf{in}}(P_{\mathsf{FPS}}, P_{\mathsf{a}}) \frac{\hat{\theta}}{P_{\mathsf{FPS}}} - f_{\mathsf{out}}(P_{\mathsf{a}}, P_{\mathsf{amb}}) \frac{\hat{P}_{H_2}}{P_{\mathsf{a}}} - kI \\ \dot{\hat{\theta}} &= -\gamma[\phi(\hat{V}) - \phi(V)] \qquad \gamma > 0 \end{aligned}$$

Error system $e := \hat{P}_{H_2} - P_{H_2} \quad \tilde{\theta} := \hat{\theta} - \theta$

$$\begin{aligned} \dot{e} &= f_{\mathsf{in}}(P_{\mathsf{FPS}}, P_{\mathsf{a}}) \frac{\tilde{\theta}}{P_{\mathsf{FPS}}} - f_{\mathsf{out}}(P_{\mathsf{a}}, P_{\mathsf{amb}}) \frac{e}{P_{\mathsf{a}}} \\ \dot{\tilde{\theta}} &= -\gamma[\phi(\hat{V}) - \phi(V)] \end{aligned}$$

same sign as $e + \tilde{\theta}$

Main Result

Suppose the adaptive observer is implemented with measurement error $V_o = V + d$ and θ varies with bounded derivative $\dot{\theta}$. If $\phi(\cdot)$ is designed s.t.

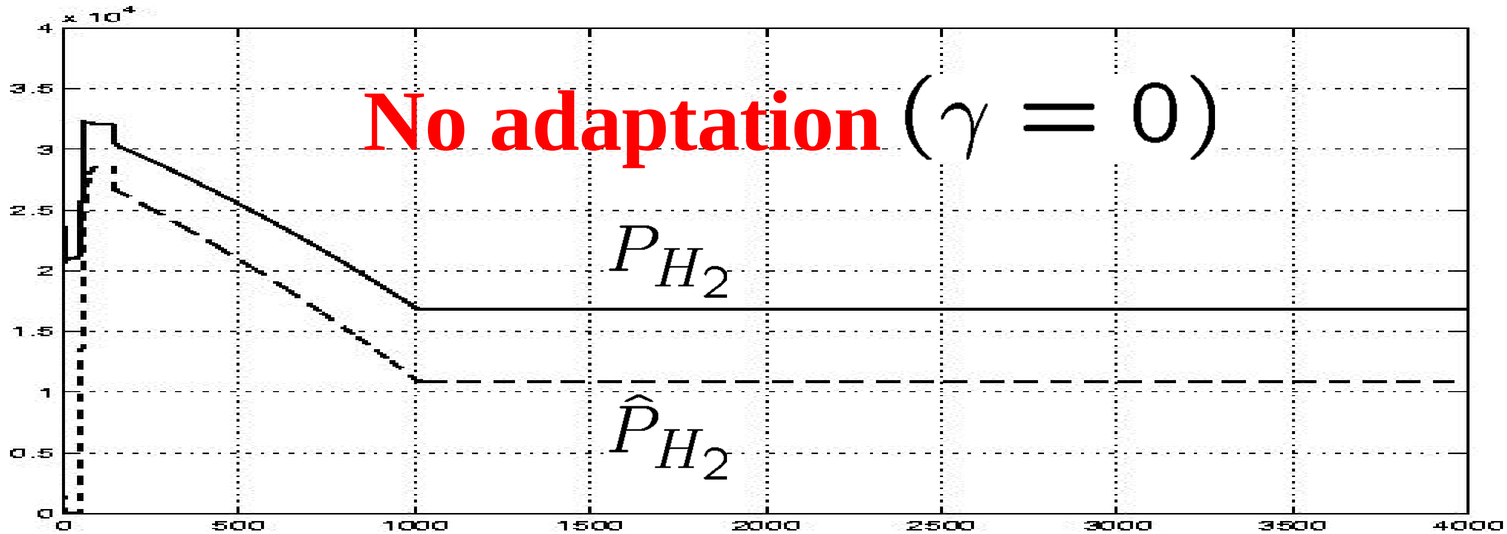
$$\frac{\partial}{\partial P_{H_2}^{\mathrm{av}}}\phi(h(P_{H_2}^{\mathrm{av}}, P_{O_2}^{\mathrm{av}}, I)) \geq 1$$

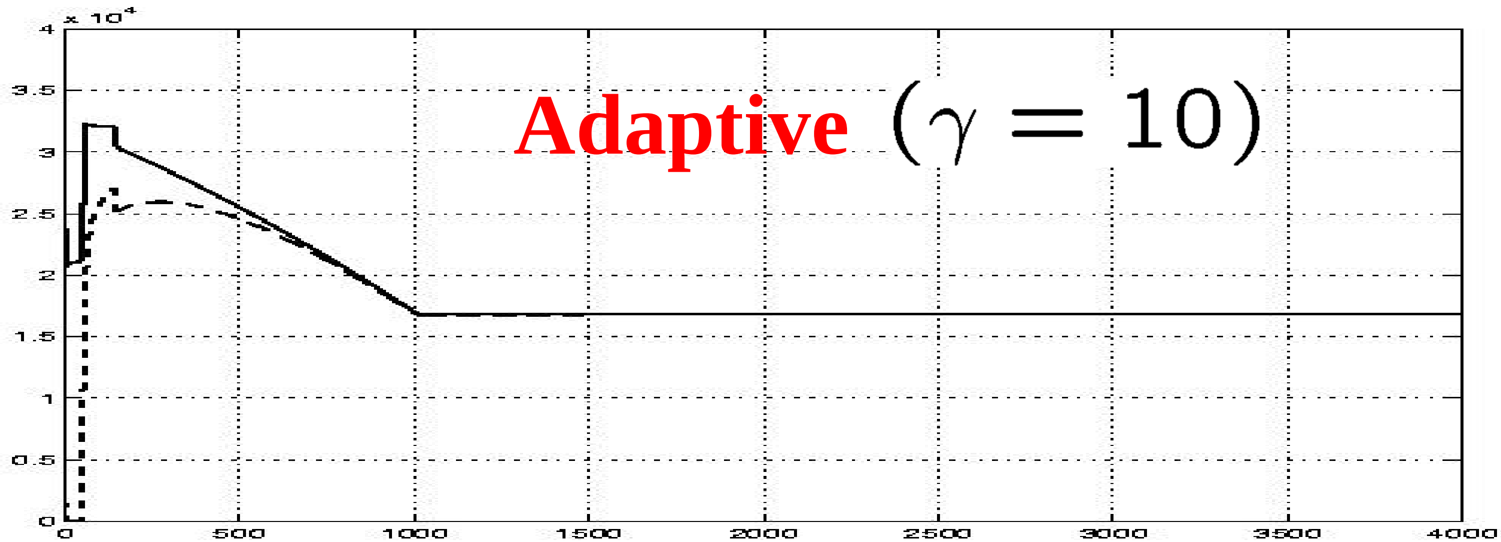
then, for $\gamma > \gamma^*$, the observer guarantees

$$\begin{aligned} |(e(t), \tilde{\theta}(t))| &\leq b|(e(t_0), \tilde{\theta}(t_0))| + \frac{g}{\gamma} \sup_{t_0 \leq \tau \leq t} |\dot{\theta}(\tau)| \\ &\quad + g \sup_{t_0 \leq \tau \leq t} |\phi(V) - \phi(V + d(\tau))| \end{aligned}$$

$$\begin{aligned} \limsup_{t \to \infty} |(e(t), \tilde{\theta}(t))| &\leq \frac{g}{\gamma} \limsup_{t \to \infty} |\dot{\theta}(t)| \\ &\quad + g \limsup_{t \to \infty} |\phi(V) - \phi(V + d(t))| \end{aligned}$$

Simulations with a High-Order Model





Conclusions & Continuing Work:

- This observer is sensitive to measurement disturbances for large values of P_{H_2}

$\Rightarrow$ Alternative adaptive designs that do not rely on voltage

- Detection of common sensor and actuator faults with observer-based algorithms

- Simplified models that capture essential dynamics: Tools from singular perturbations, nonlinear dynamics, and large-scale systems for model-reduction

- Robustness to unmodeled dynamics and uncertain parameters