Experiences on the use of reset control in low-level feedback loops for the automotive industry

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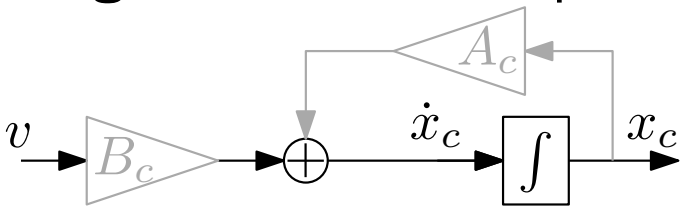
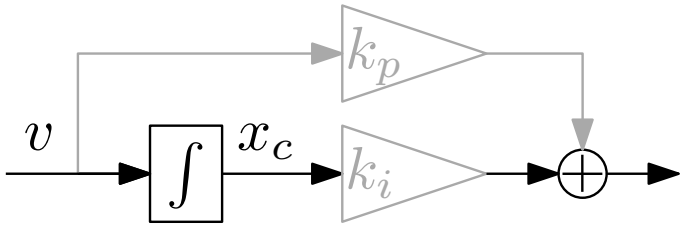
An analog integrator and its Clegg extension Clegg [1958]

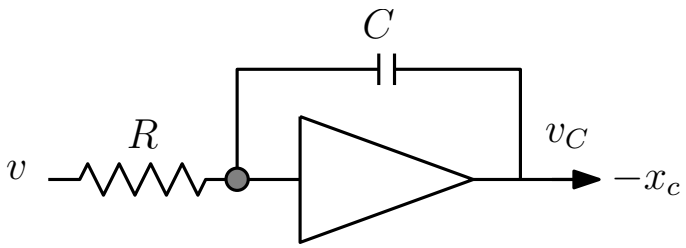
Integrators: core components of dynamical control systems



$$\dot{x}_c = A_c x_c + B_c v$$

Example: PI controller



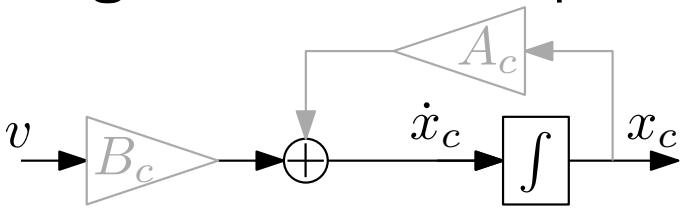


$$\dot{x}_c = \frac{1}{RC} v$$

- In an analog integrator, the state information is stored in a capacitor:

An analog integrator and its Clegg extension Clegg [1958]

Integrators: core components of dynamical control systems



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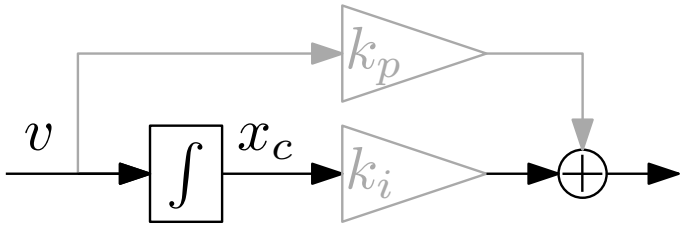
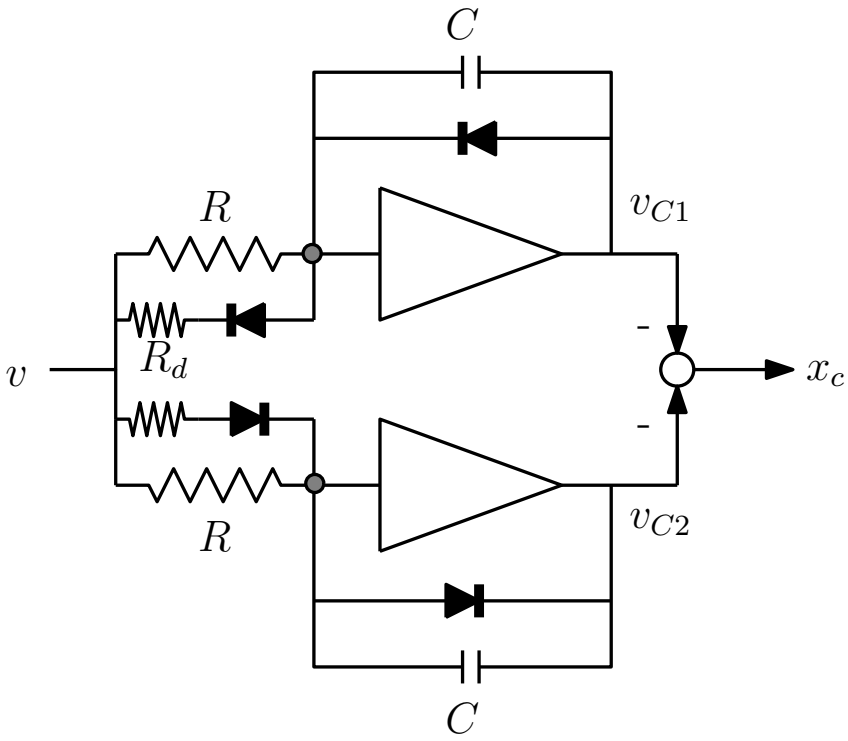


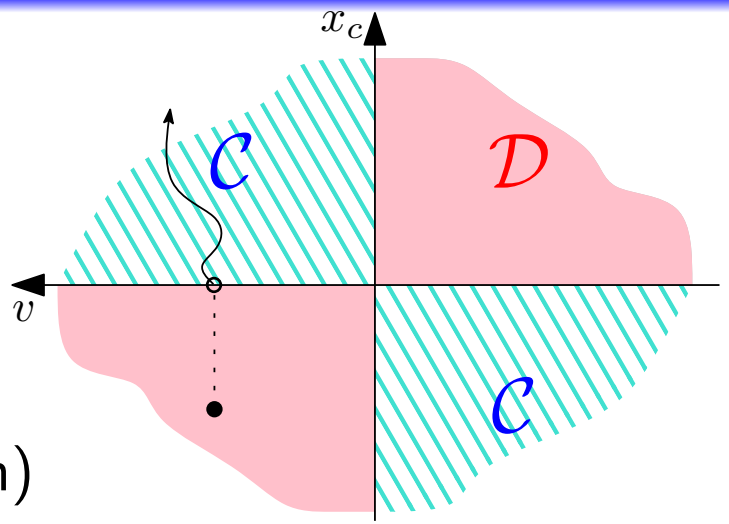


- Clegg's integrator Clegg [1958]:
  - *feedback diodes*: the **positive** part of x_c is all and only coming from the **upper** capacitor (and viceversa)
  - *input diodes*: when $v \leq 0$ the upper capacitor is reset and the lower one integrates (and viceversa) [$R_d \ll 1$]
- As a consequence $\Rightarrow$ v and x_c **never have opposite signs**

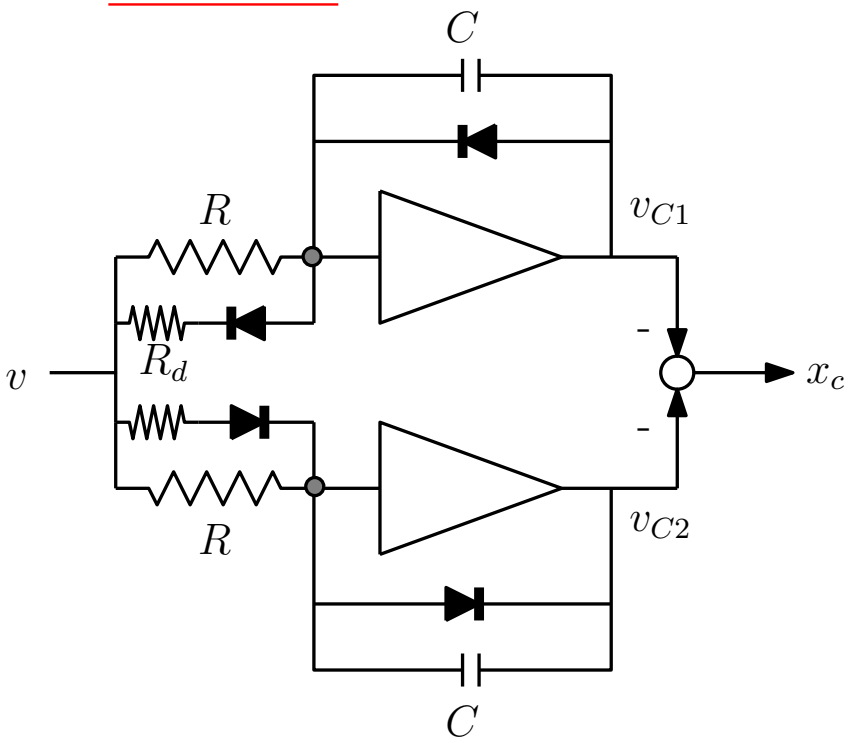
Hybrid dynamics rule flowing or jumping of solutions

Hybrid Clegg integrator:

$$\dot{x}_c = \frac{1}{RC} v, \qquad \text{allowed when } x_c v \geq 0,$$
$$x_c^+ = 0, \qquad \text{allowed when } x_c v \leq 0,$$



- Flow set $\mathcal{C}$: where x_c may flow (1st eq'n)
- Jump set $\mathcal{D}$: where x_c may jump (2nd eq'n)



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Stabilization using hybrid jumps to zero

First Order Reset Element Nešić et al. [2011], Loquen et al. [2007]:

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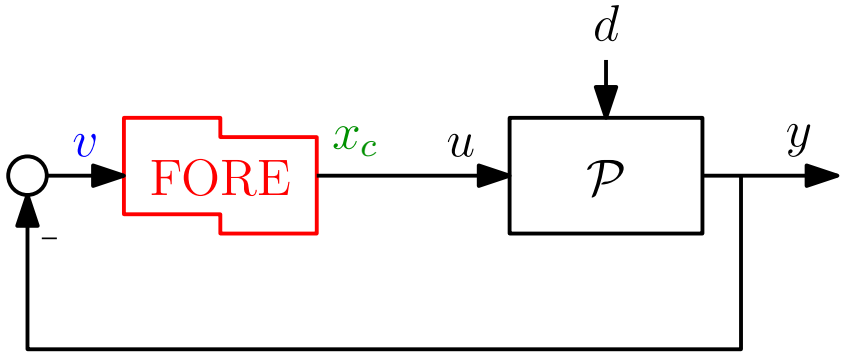


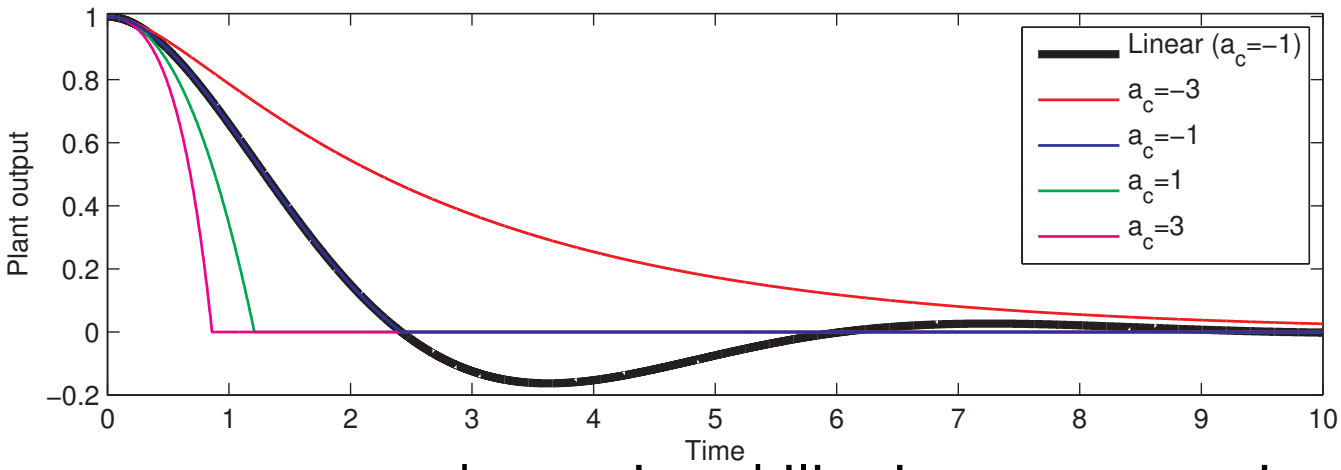
Theorem If $\mathcal{P}$ is linear, minimum phase and relative degree one, **then** a_c, b_c or (a_c, b_c) large enough $\Rightarrow$ global exponential stability

Theorem In the planar case, γ_{dy} shrinks to zero as parameters grow

Simulation uses:

$$\mathcal{P} = \frac{1}{s}$$

$$b_c = 1$$



Interpretation: Resets remove overshoots, instability improves transient

Piecewise quadratic Lyapunov function construction

- Proposed in Zaccarian et al. [2011], Loquen [2010], Aangenent et al. [2010]
- Given $N \geq 2$ (number of sectors)
- Patching angles:

$$-\theta_\epsilon = \theta_0 < \theta_1 < \cdots < \theta_N = \frac{\pi}{2} + \theta_\epsilon$$

- Patching hyperplanes ($C_p = [0 \ \cdots \ 0 \ 1]$)

$$\Theta_i = \begin{bmatrix} 0_{1\times(n-2)} & \sin(\theta_i) & \cos(\theta_i) \end{bmatrix}^T$$

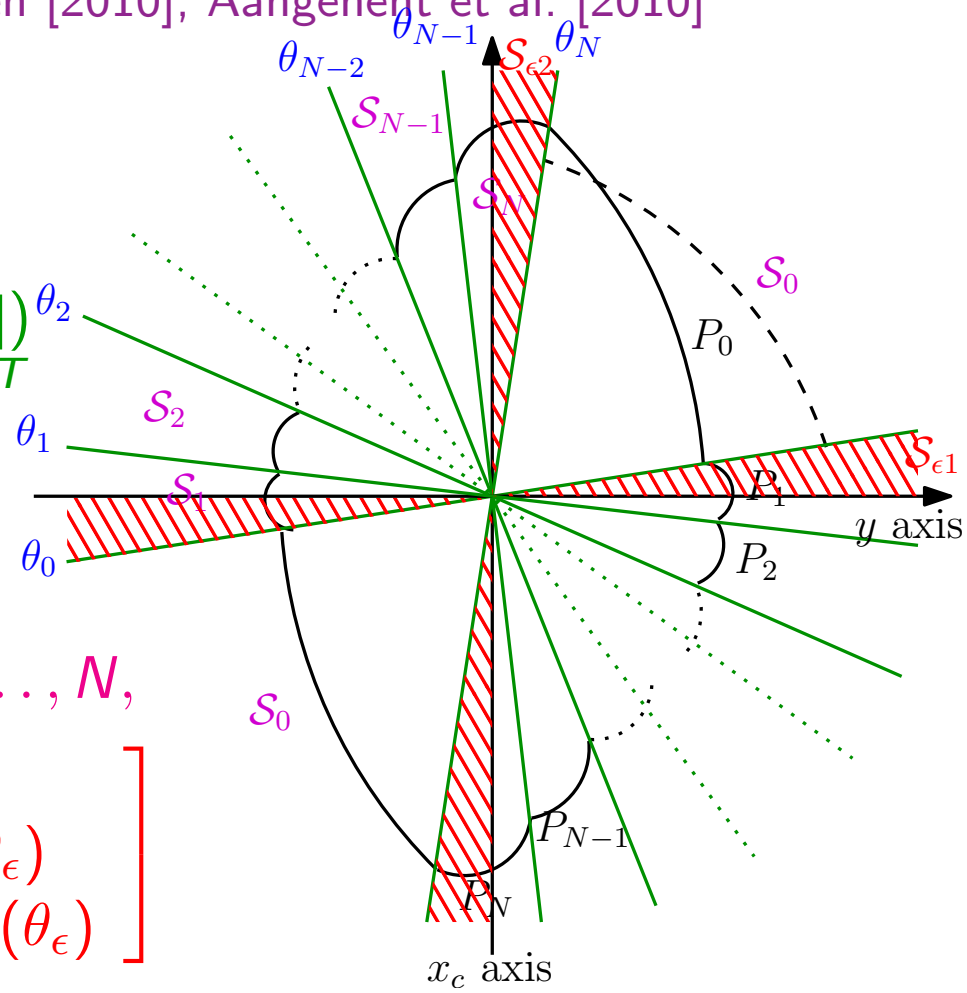
- Sector matrices:

$$S_0 := \Theta_0\Theta_N^T + \Theta_N\Theta_0^T$$

$$S_i := -(\Theta_i\Theta_{i-1}^T + \Theta_{i-1}\Theta_i^T), \quad i = 1, \ldots, N,$$

$$S_{\epsilon 1} := \begin{bmatrix} 0_{(n-2)\times(n-2)} & 0 & 0 \\ 0 & 0 & \sin(\theta_\epsilon) \\ 0 & \sin(\theta_\epsilon) & -2\cos(\theta_\epsilon) \end{bmatrix}$$

$$S_{\epsilon 2} := \begin{bmatrix} 0_{(n-2)\times(n-2)} & 0 & 0 \\ 0 & -2\cos(\theta_\epsilon) & \sin(\theta_\epsilon) \\ 0 & \sin(\theta_\epsilon) & 0 \end{bmatrix}$$



Hybrid closed-loop:

$$\begin{aligned} \dot{x} &= A_F x + B_d d, & x \in \mathcal{C} \\ x^+ &= A_J x, & x \in \mathcal{D} \end{aligned}$$

Piecewise quadratic Lyapunov theorem

Theorem Zaccarian et al. [2011], Loquen [2010]: If the following LMIs in the green unknowns (where $Z = [I_{n-2}\ 0_{(n-2)\times 2}]$) are feasible:

$$(Flow)\quad \begin{bmatrix} A_F^T P_i + P_i A_F + \tau_{Fi} S_i & P_i B_d & C^T \\ \star & -\gamma_{dy} I & 0 \\ \star & \star & -\gamma_{dy} I \end{bmatrix} < 0, i = 1, \ldots, N,$$

$$(Jump)\quad A_J^T P_1 A_J - P_0 + \tau_J S_0 \leq 0$$

$$(Cont'ty)\quad \Theta_{i\perp}^T (P_i - P_{i+1}) \Theta_{i\perp} = 0, \quad i = 0, \ldots, N-1,$$

$$(Cont'ty)\quad \Theta_{N\perp}^T (P_N - P_0) \Theta_{N\perp} = 0$$

$$(Overlap)\quad A_J^T P_1 A_J - P_1 + \tau_{\epsilon 1} S_{\epsilon 1} \leq 0$$

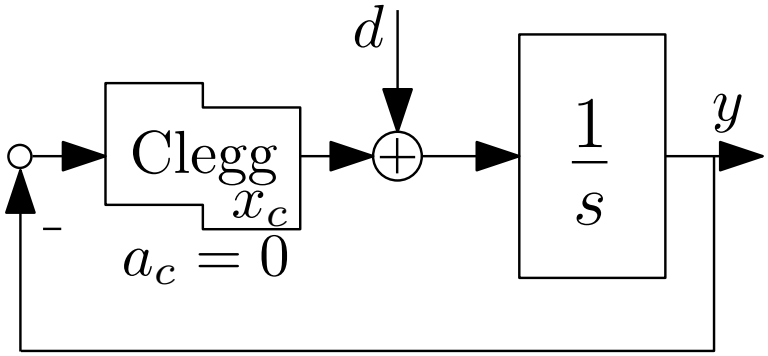
$$(Overlap)\quad A_J^T P_1 A_J - P_N + \tau_{\epsilon 2} S_{\epsilon 2} \leq 0$$

$$(Origin)\quad \begin{bmatrix} Z(A_F^T P_0 + P_0 A_F) Z^T & Z P_0 B_d & Z C^T \\ \star & -\gamma_{dy} I & 0 \\ \star & \star & -\gamma_{dy} I \end{bmatrix} < 0,$$

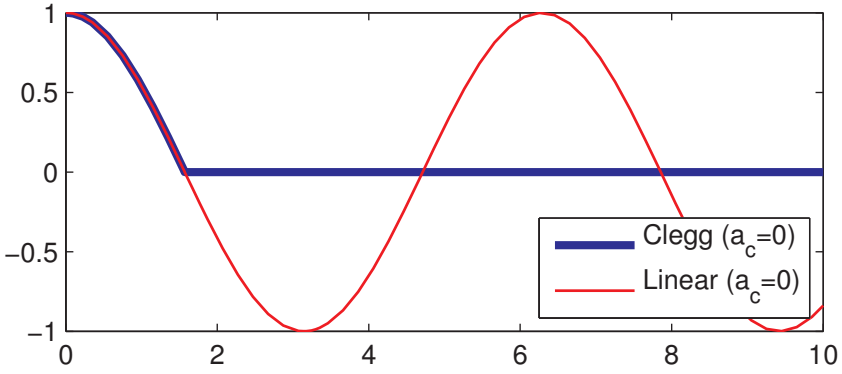
then global exponential stability + finite $\mathcal{L}_2$ gain γ_{dy} from d to y

Example 1: Clegg ($a_c = 0$) connected to an integrator

- Block diagram:



- Output response (overcomes linear systems limitations)



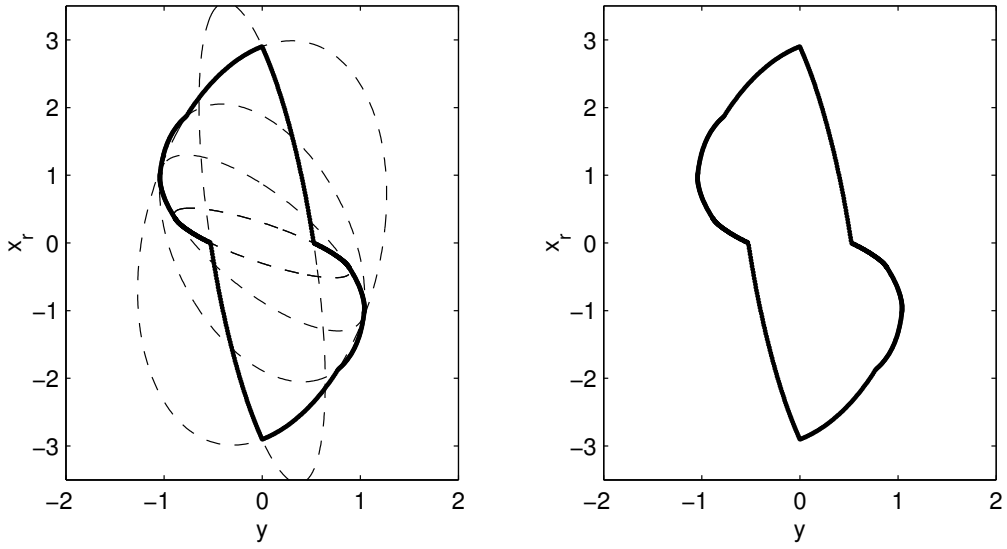
- Quadratic Lyapunov functions are unsuitable

- Gain γ_{dy} estimates ($N = \#$ of sectors)

N	2	4	8	50
gain γ_{dy}	2.834	1.377	0.914	0.87

- A lower bound: $\sqrt{\frac{\pi}{8}} \approx 0.626$

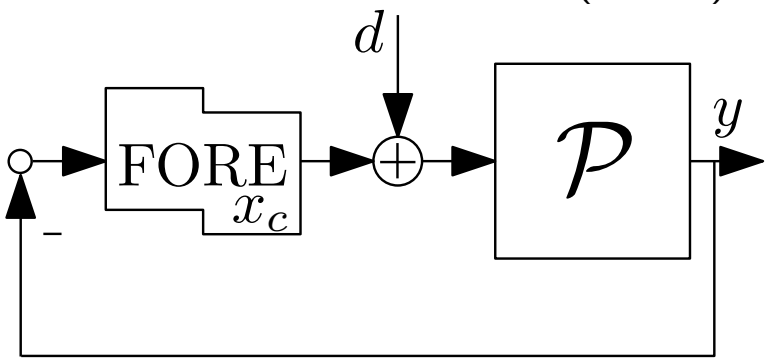
- Lyapunov func'n level sets for $N = 4$



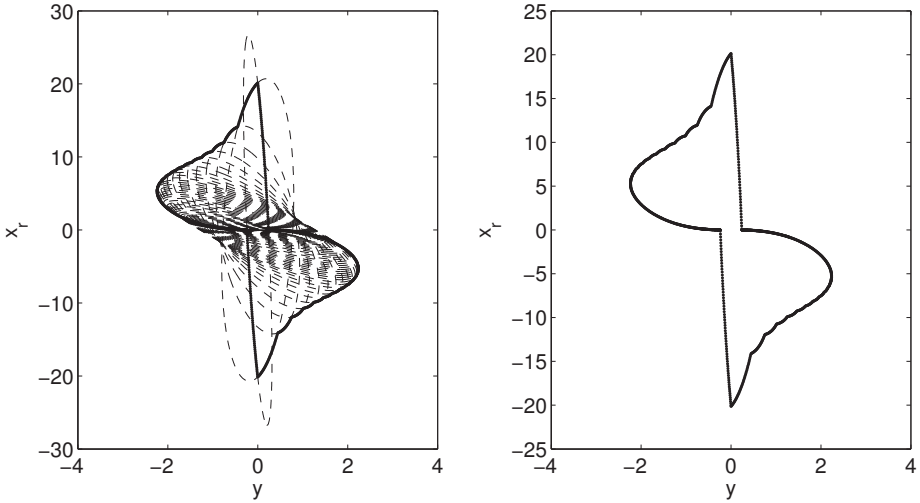
- $P_1, \ldots, P_4$ cover 2nd/4th quadrants
- P_0 covers 1st/3rd quadrants

Example 2: FORE (any a_c) and linear plant (Hollot et al.)

- Block diagram ($\mathcal{P} = \frac{s+1}{s(s+0.2)}$)



- $a_c = 1$: level set with $N = 50$



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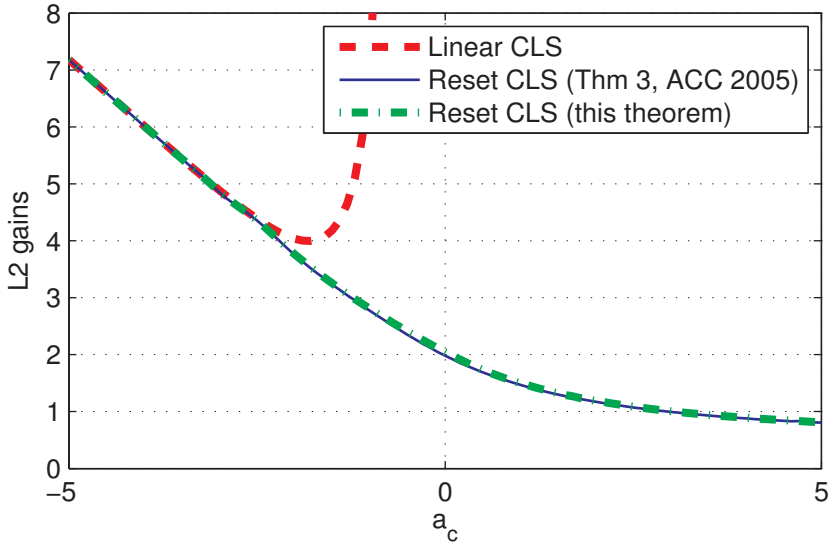
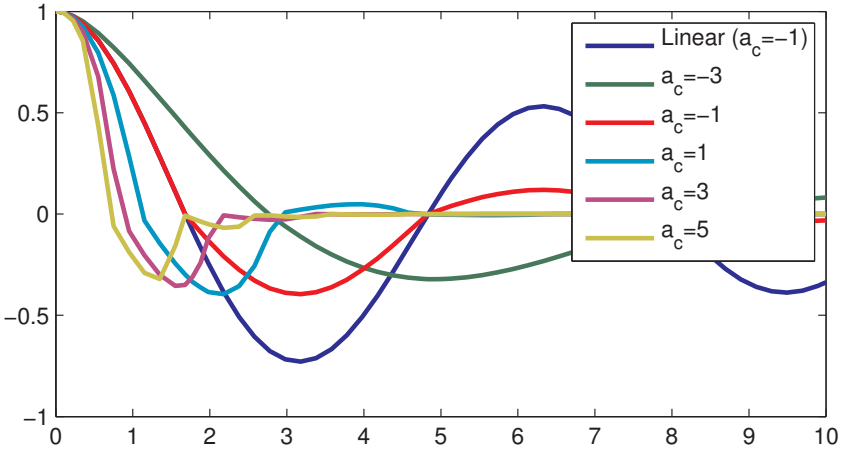


- Time responses



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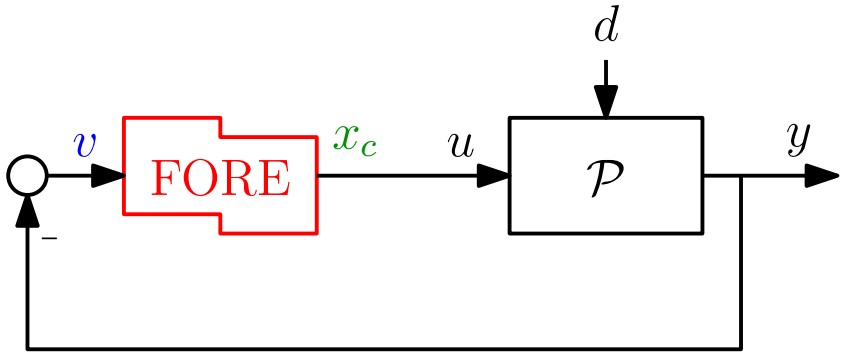

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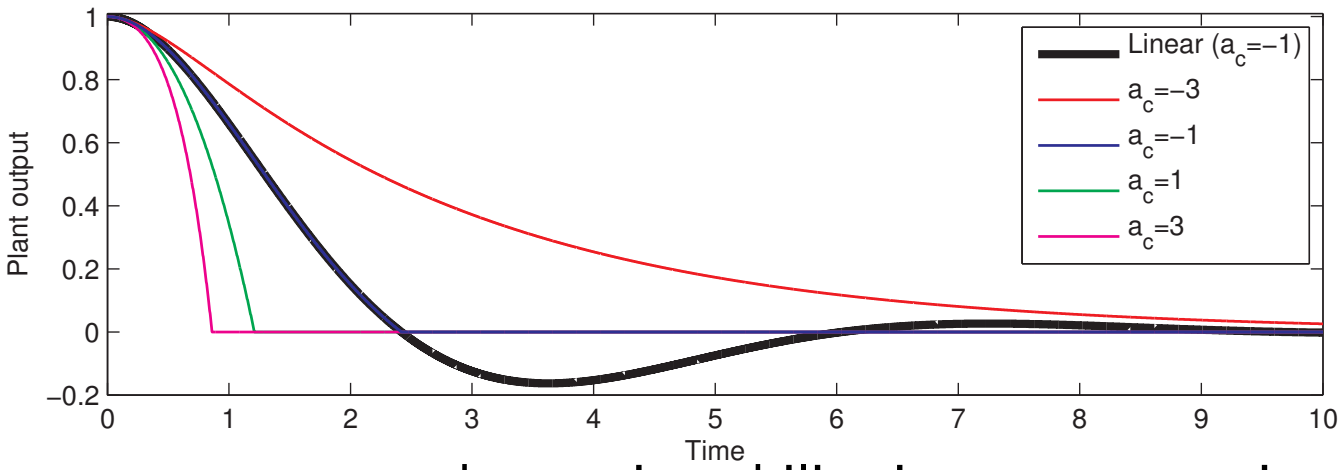

Interpretation: Resets remove overshoots, instability improves transient

Set point adaptive **regulation** using hybrid jumps to zero

- Relevant works Panni et al. [2014], Loquen et al. [2008]
- Parametric feedforward $u_{ff} = \Psi(r)^T \alpha$

$$\begin{cases} \dot{x}_c = a_c x_c + b_c v, \\ \dot{\alpha} = 0, \end{cases} \qquad x_c v \geq 0,$$

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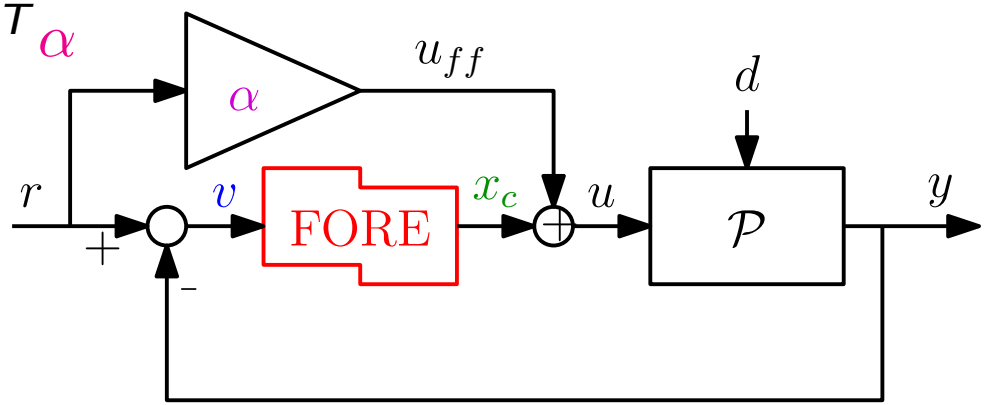
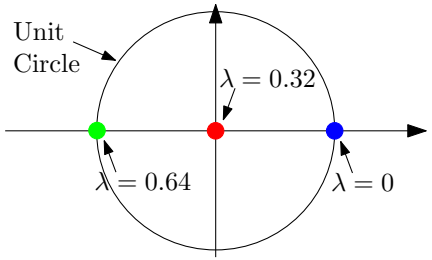
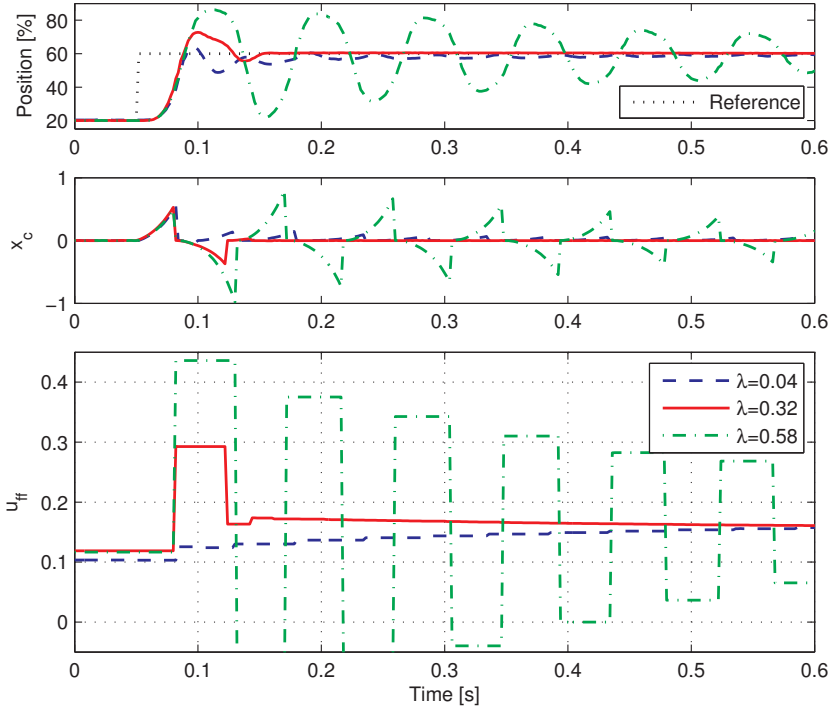


Theorem: If FORE stabilizes with $r = 0$, then for constant r, $y \to r$

Lemma: Tuning of λ using discrete-time rules (Ziegler-Nichols)

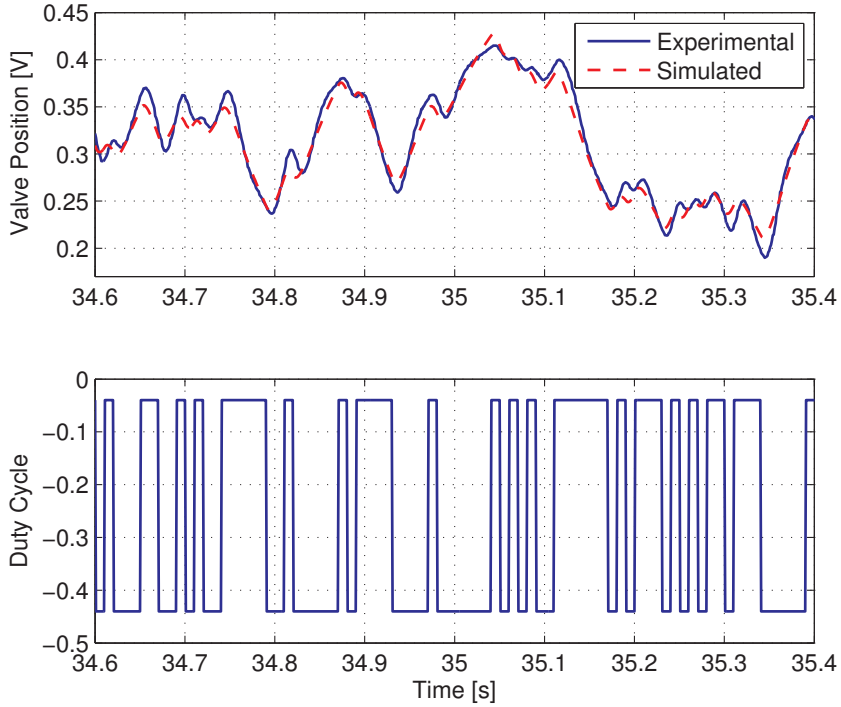


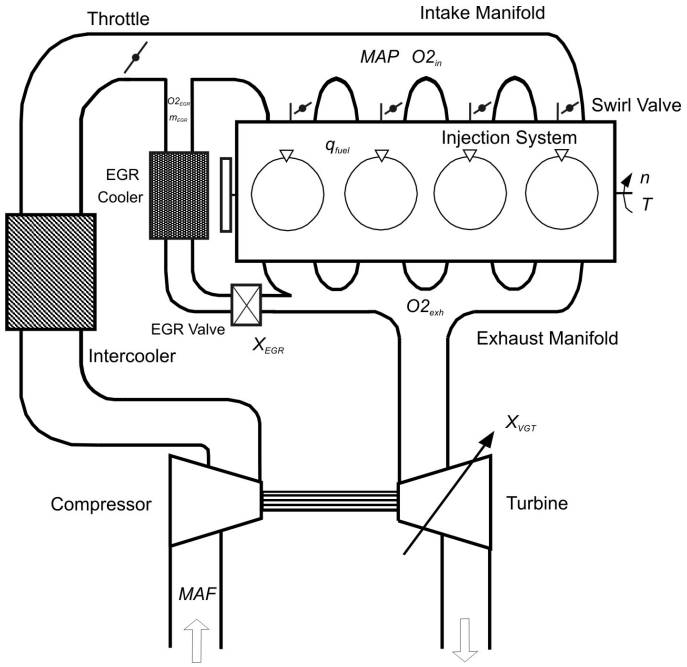
Example: EGR Experiment (next slide)



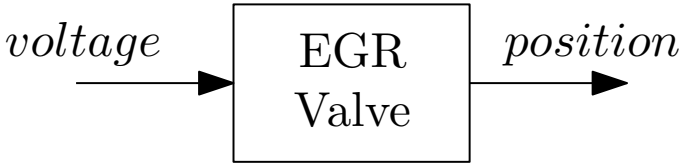
Fast regulation of EGR valve position in Diesel engines

- Reported in Panni et al. [2014]
- EGR: Recirculates Exhaust Gas in Diesel engines
- Subject to strong disturbances $\Rightarrow$ need aggressive controllers (recall exp. unstable transients)



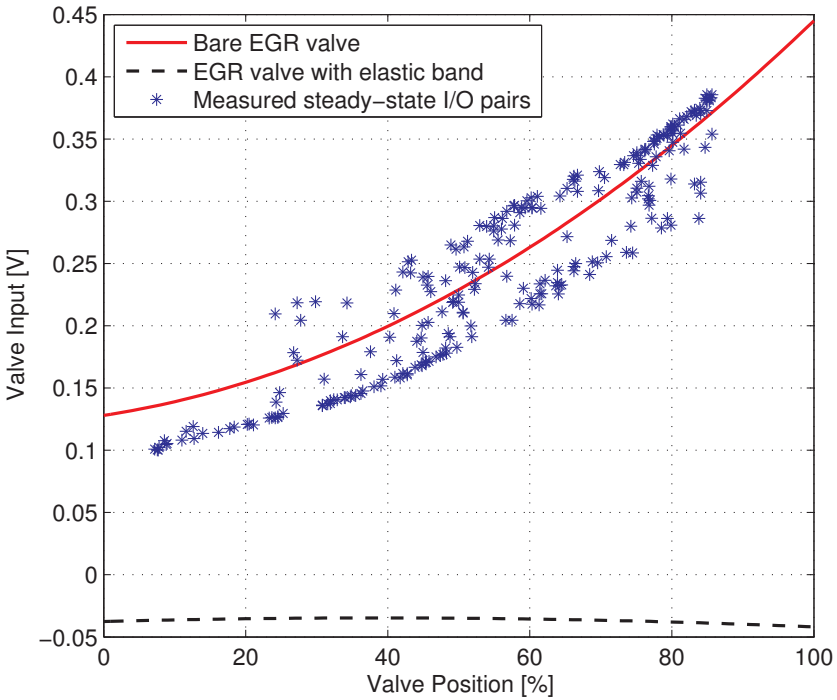


- Identified valve transfer function:

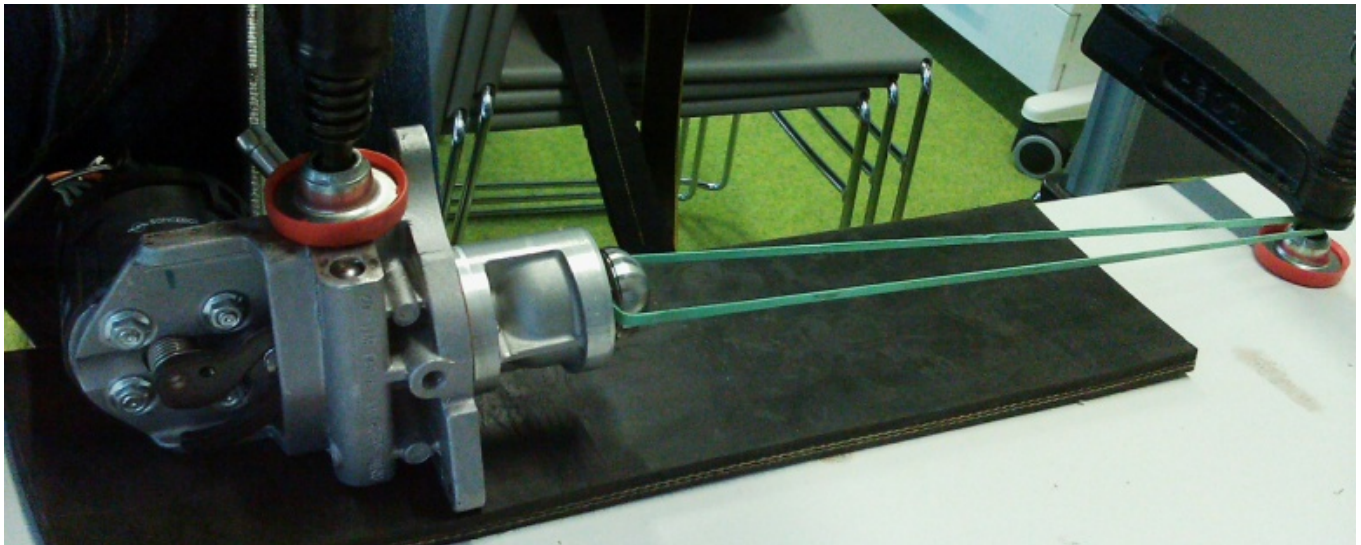


$$P(s) = \frac{2200}{(s+164.4)(s+10.69)}.$$

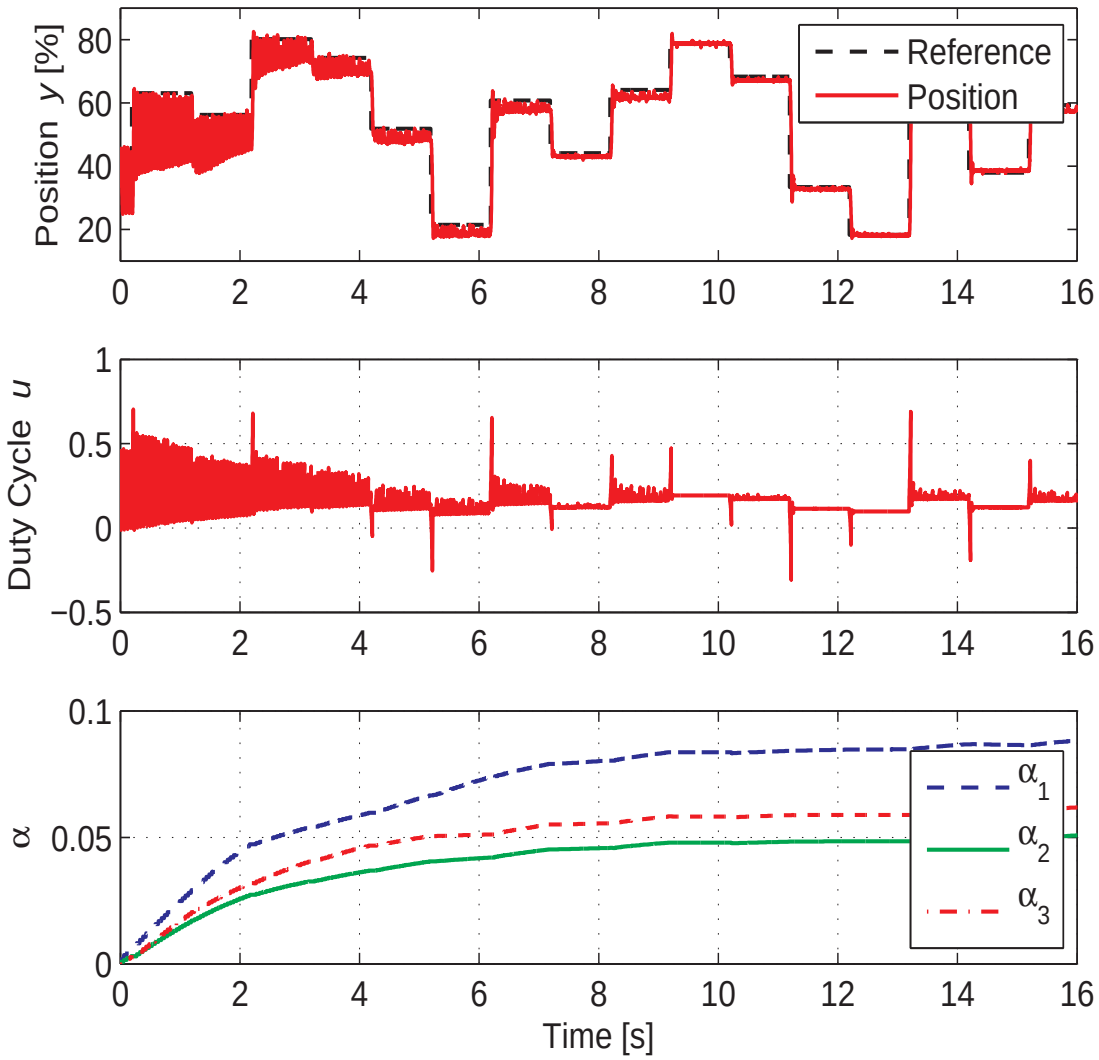
Feedforward: α converges to suitable parametrization



- $\star$: steady-state input/output pairs (stiction!!)
- Red Solid: $u_{ff} = \Psi^T(r)\alpha^*$, with α^* steady-state for α
- Black dashed: $u_{ff} = \Psi^T(r)\bar{\alpha}^*$ when pulling the valve with an elastic band

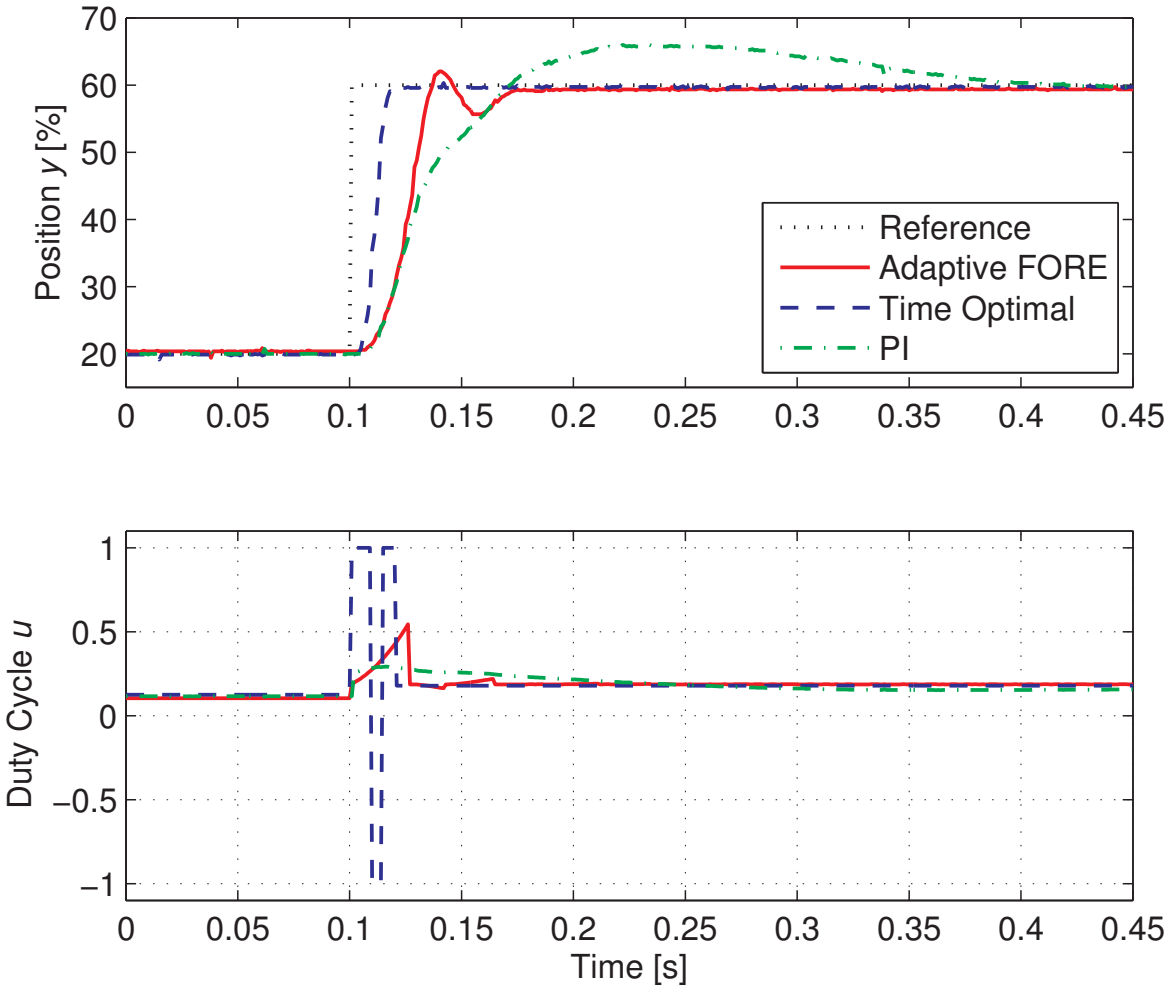


Experimental adaptation of feedforward in lab setup



- **Random sequence** of position reference steps
- Adaptation gain λ intentionally selected small and α initialized at zero to **appreciate transient**
- Initial transient shows **typical oscillations** arising with inaccurate feedforward
- As $\alpha \to \alpha^*$, the step responses become **increasingly desirable**

Laboratory experiments close to time-optimal

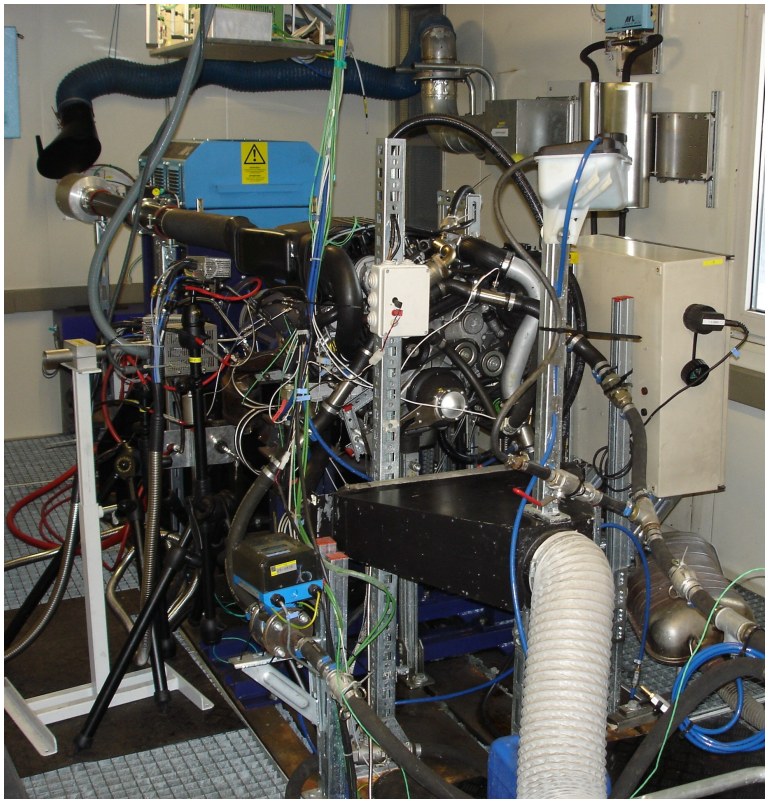


- Time-optimal: unrobust, obtained via trial and error
- PI: Tuned using standard MATLAB tools
- Adaptive FORE: Response after $\alpha \to \alpha^* = (0.128,\ 0.087,\ 0.115)$

- Note the exponentially diverging voltage: aggressive action for disturbance rejection on the real engine

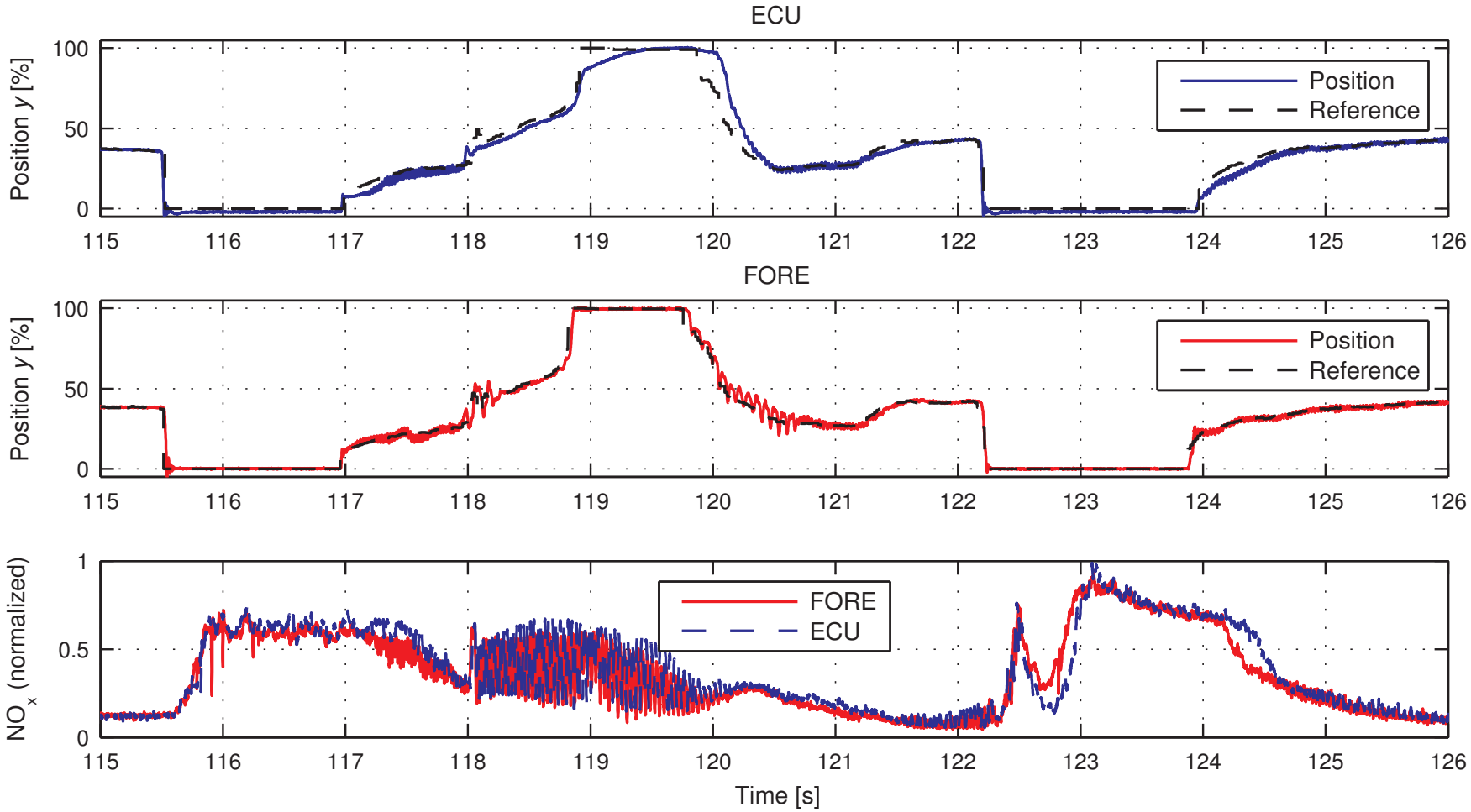
Experiments on Diesel engine testbench (JKU)

Experimental testbench at the Johannes Kepler Universitet (Linz, Austria)



- **Specs**: 2 liter, 4 cylinder passenger car turbocharged Diesel engine
- **Compared**: to factory EGR valve controller coded in ECU (gain scheduled PI with feedforward)
- **Test cycle**: Urban part of *New European Driving Cycle*
- **Relevance**: Faster EGR positioning $\Rightarrow$ Reduced NO_x emissions

Adaptive FORE provides substantial performance increase



- Mean squared error: ECU $= 6.68$ (100%), FORE $= 1.53$ (23 %)
- Improvement most important with EGR almost closed ($t \approx 117,\ 124$)
- Recent results promise time-varying reference tracking

Set-point Regulation using hybrid jumps to zero (recall)

- Parametric feedforward $u_{ff} = \Psi(r)^T \alpha$

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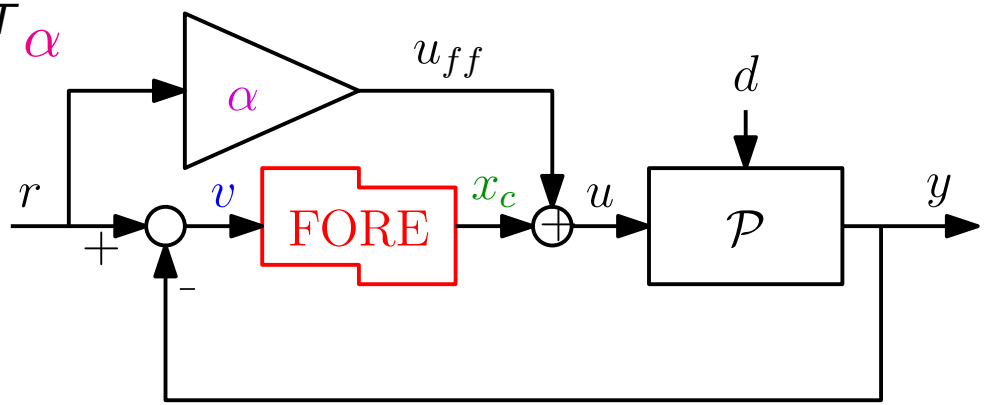

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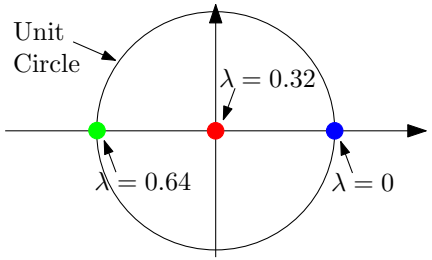
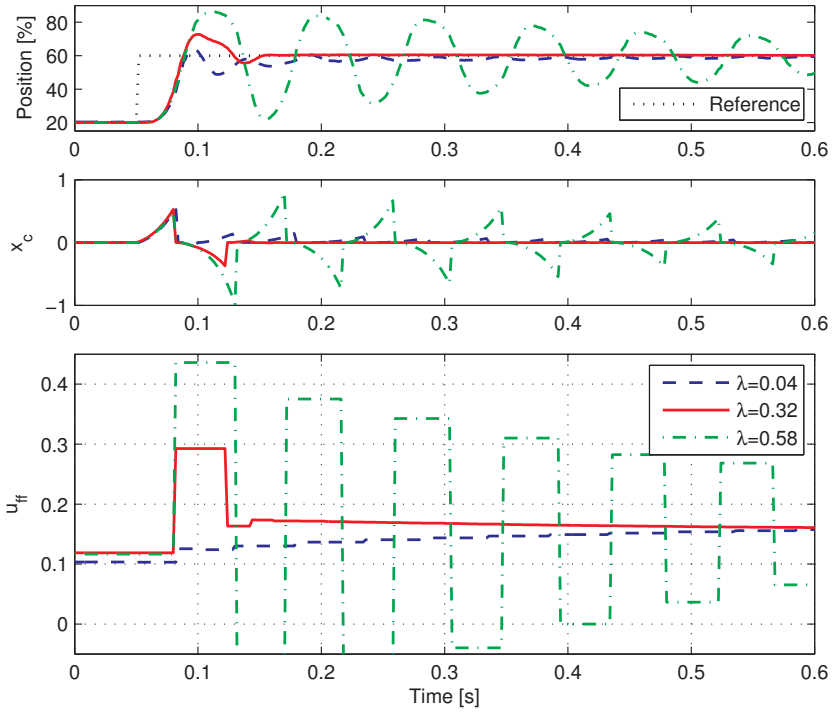
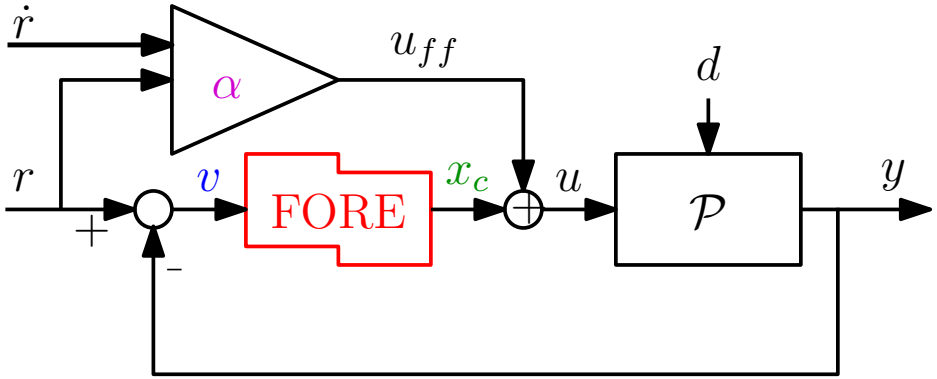


Example: EGR Experiment (next slide)



Adaptive **Reference tracking** using hybrid jumps to zero

- NEW Parametric feedforward:
  $u_{ff} = \Psi(r)^T \alpha \;\Rightarrow\; \Psi(r,\dot{r})^T \alpha$
- Proposed in Cordioli et al. [2015]
- Feedback/Feedforward equations:



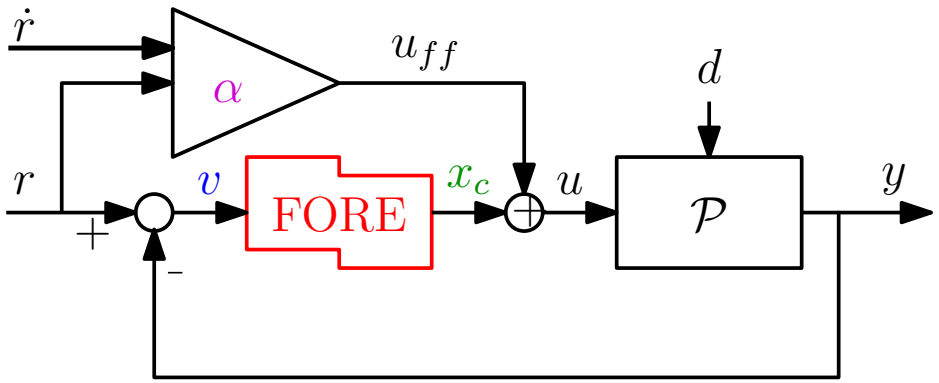
$$\begin{cases} \dot{x}_c = a_c x_c + b_c v, \\ \dot{\alpha} = 0,\ \dot{\tau} = 1 \\ \dot{\Xi} = \mathrm{e}^{-A_f \tau} B \Psi^T(r,\dot{r}), \end{cases} \quad x_c v \geq 0, \qquad \begin{cases} x_c^+ = 0, \\ \alpha^+ = \alpha + \lambda \frac{(C\exp(A_f\tau)\Xi)^T}{\max\{1, |C\exp(A_f\tau)\Xi|^2\}} x_c \\ \tau^+ = 0,\ \Xi^+ = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \end{cases} \quad x_c v \leq 0,$$

Theorem: If FORE stabilizes, then for any $\lambda \in (0,1)$ the parameter estimation error $|\alpha - \alpha^*|$ is **non-increasing**.
If $\alpha(0,0) = \alpha^*$, then any reference $r \in C^1$ is tracked.
Under *persistence of excitation* property, $|\alpha - \alpha^*|$ converges to zero and **asymptotic tracking** of any $r \in C^1$ holds.

Note: this is a simplified exposition without temporal regularization

Reference tracking with **approximate adaptation**

- NEW Parametric feedforward:
  $u_{ff} = \Psi(r)^T \alpha \;\Rightarrow\; \Psi(r, \dot{r})^T \alpha$
- Proposed in Cordioli et al. [2015]
- Feedback/Feedforward equations:

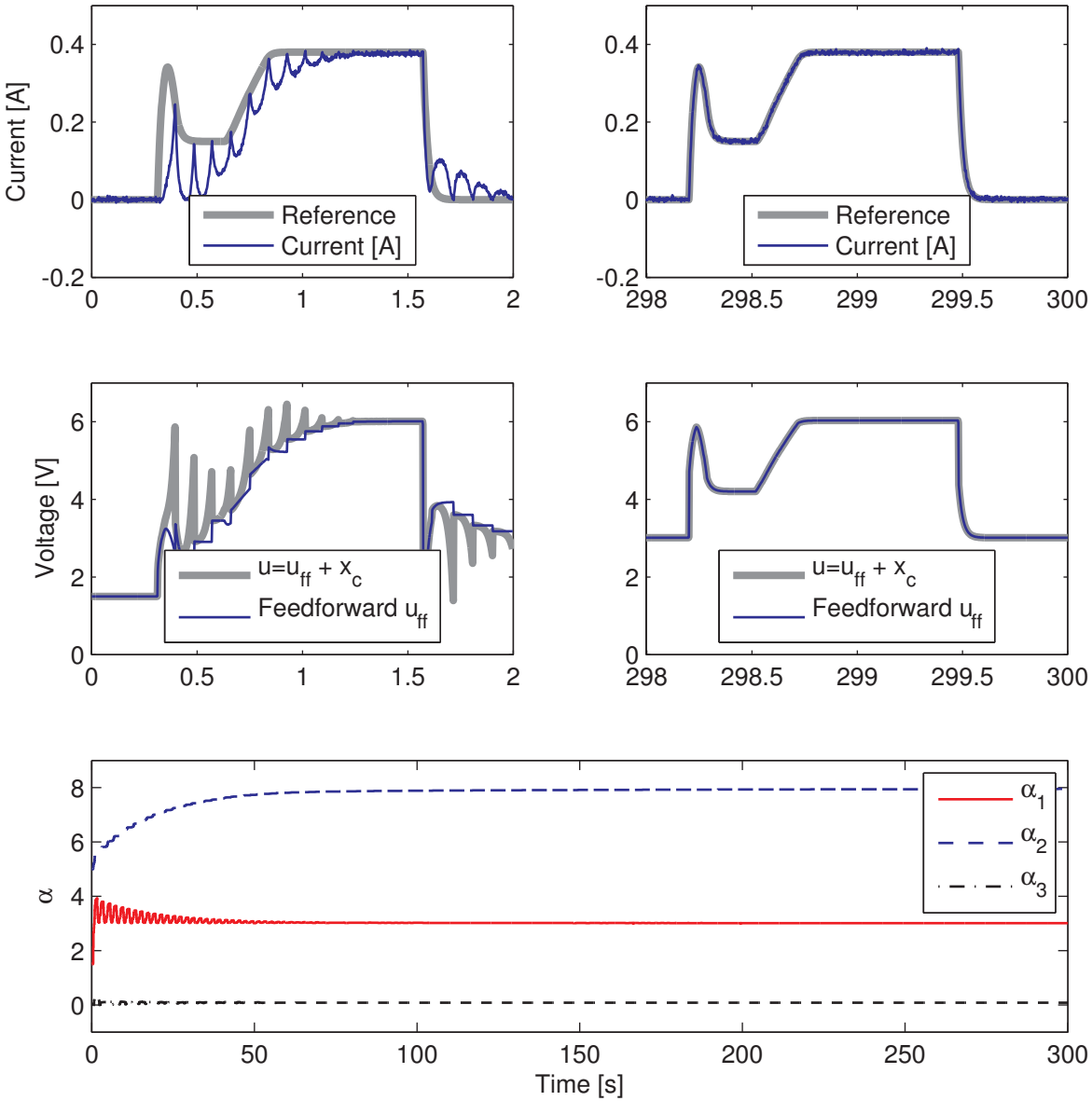


$$\begin{cases} \dot{x}_c = a_c x_c + b_c v, \\ \dot{\alpha} = 0, \; \dot{\tau} = 1 \end{cases} \quad x_c v \geq 0, \qquad \begin{cases} x_c^+ = 0, \\ \alpha^+ = \alpha + \lambda \frac{\varphi(\tau)}{\max\{1, |\varphi(\tau)|^2\}} \Psi(r, \dot{r}) x_c \\ \tau^+ = 0, \end{cases} \quad x_c v \leq 0,$$

Theorem: If FORE stabilizes, then for any $\lambda \in (0, 1)$ the parameter estimation error $|\alpha - \alpha^*|$ is **non-increasing**.
If $\alpha(0, 0) = \alpha^*$, then any reference $r \in C^1$ is tracked.
Under *persistence of excitation* property, $|\alpha - \alpha^*|$ converges to zero and **asymptotic tracking** of any $r \in C^1$ holds.

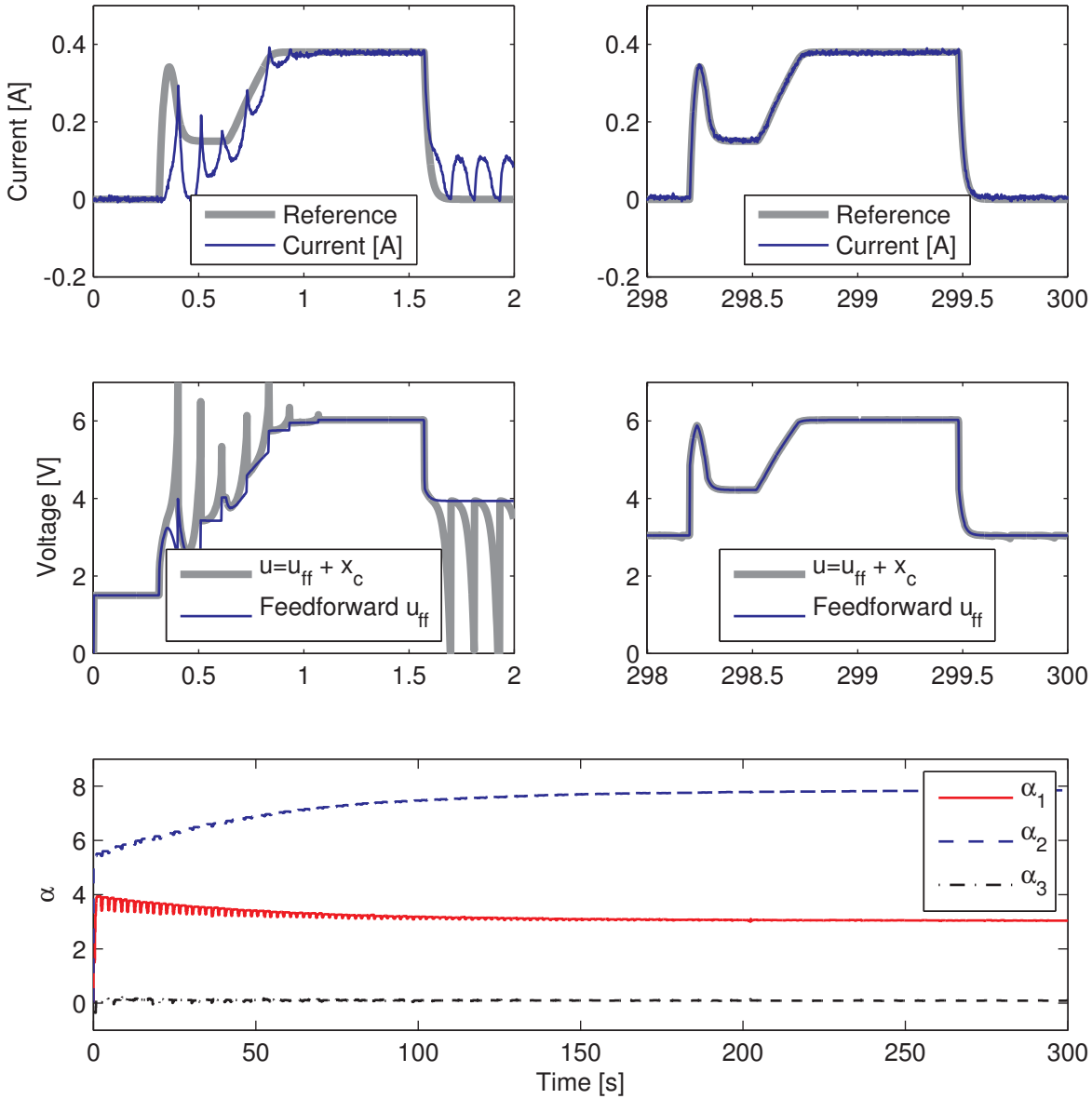
Note: this is a simplified exposition without temporal regularization

Continuous-time simulations predict desirable behavior

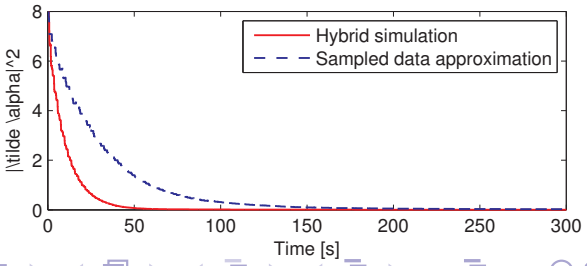


- Hybrid dynamics simulated in MATLAB using dedicated Toolbox (HyEQ from R. Sanfelice)
- Reference is repeated multiple times
- Parameters show desirable convergence (lower plot)

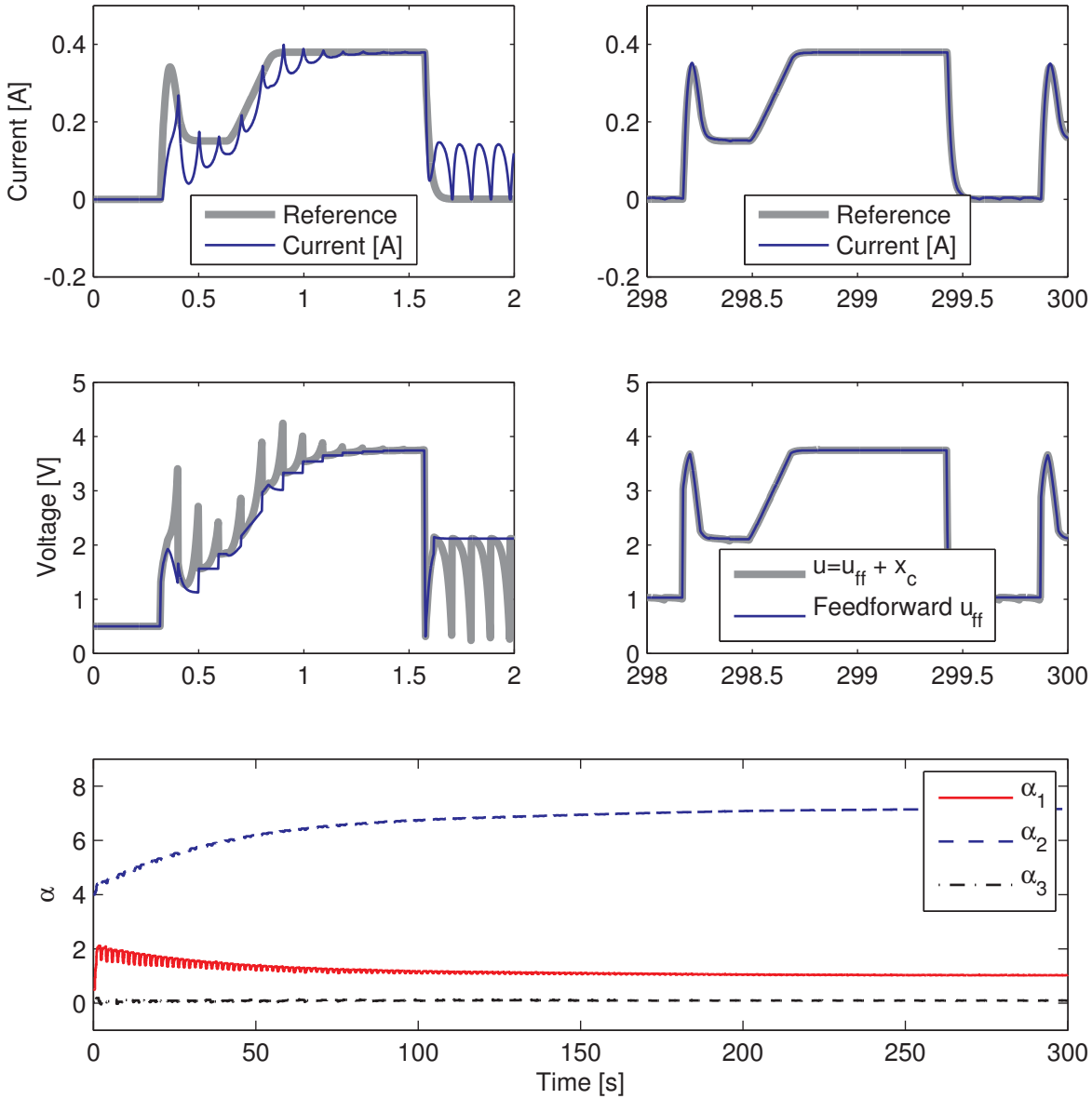
Discretized simulation with PWM ⇒ slight deterioration



- Sampled-data controller and PWM voltage: **simulation is not** hybrid
- **Intrinsic robustness** of scheme leads to slightly deteriorated behavior
- **Slower convergence** to zero of estimation error $|\alpha - \alpha^*|^2$

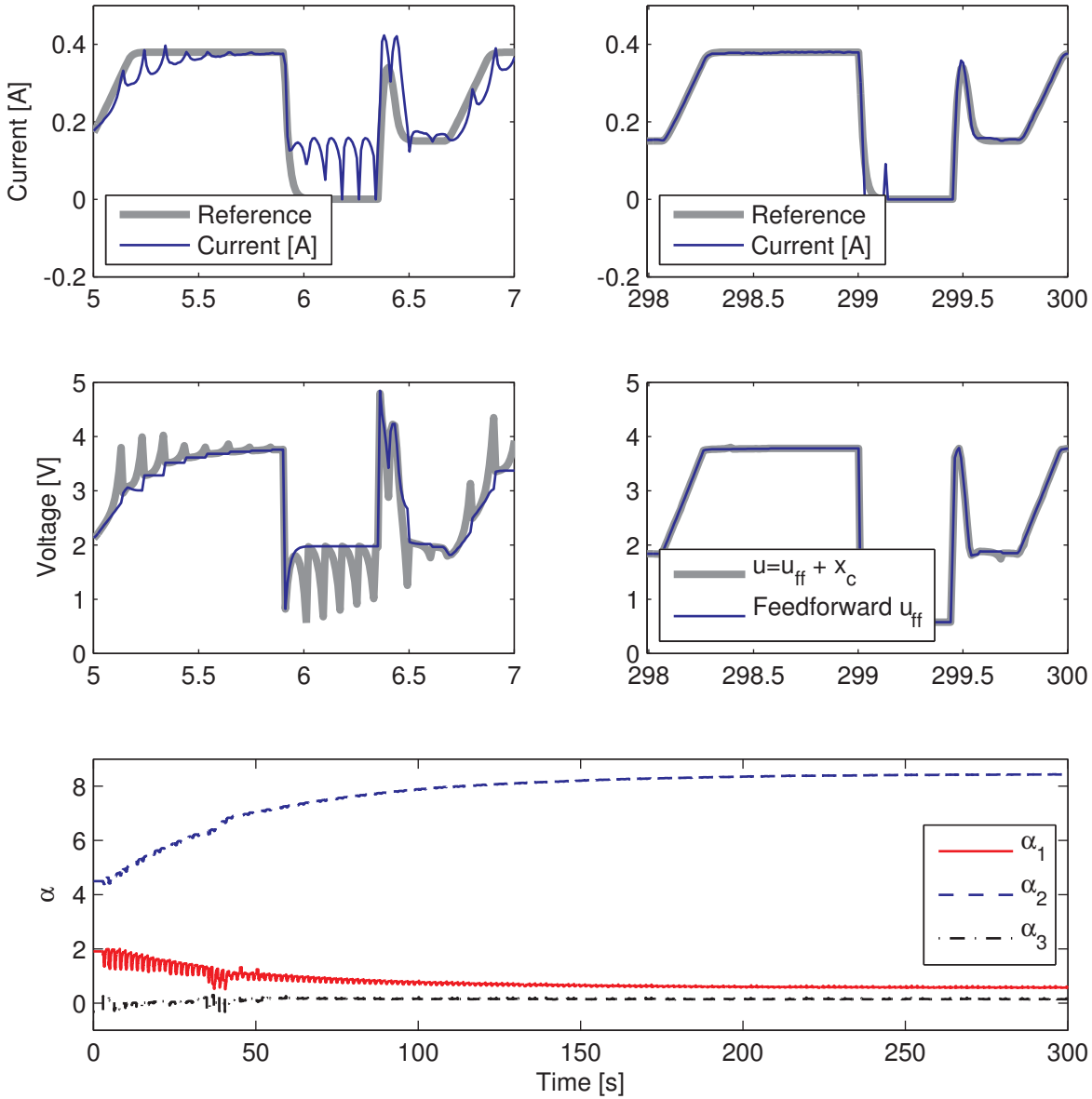


Software in the loop simulation requires accuracy



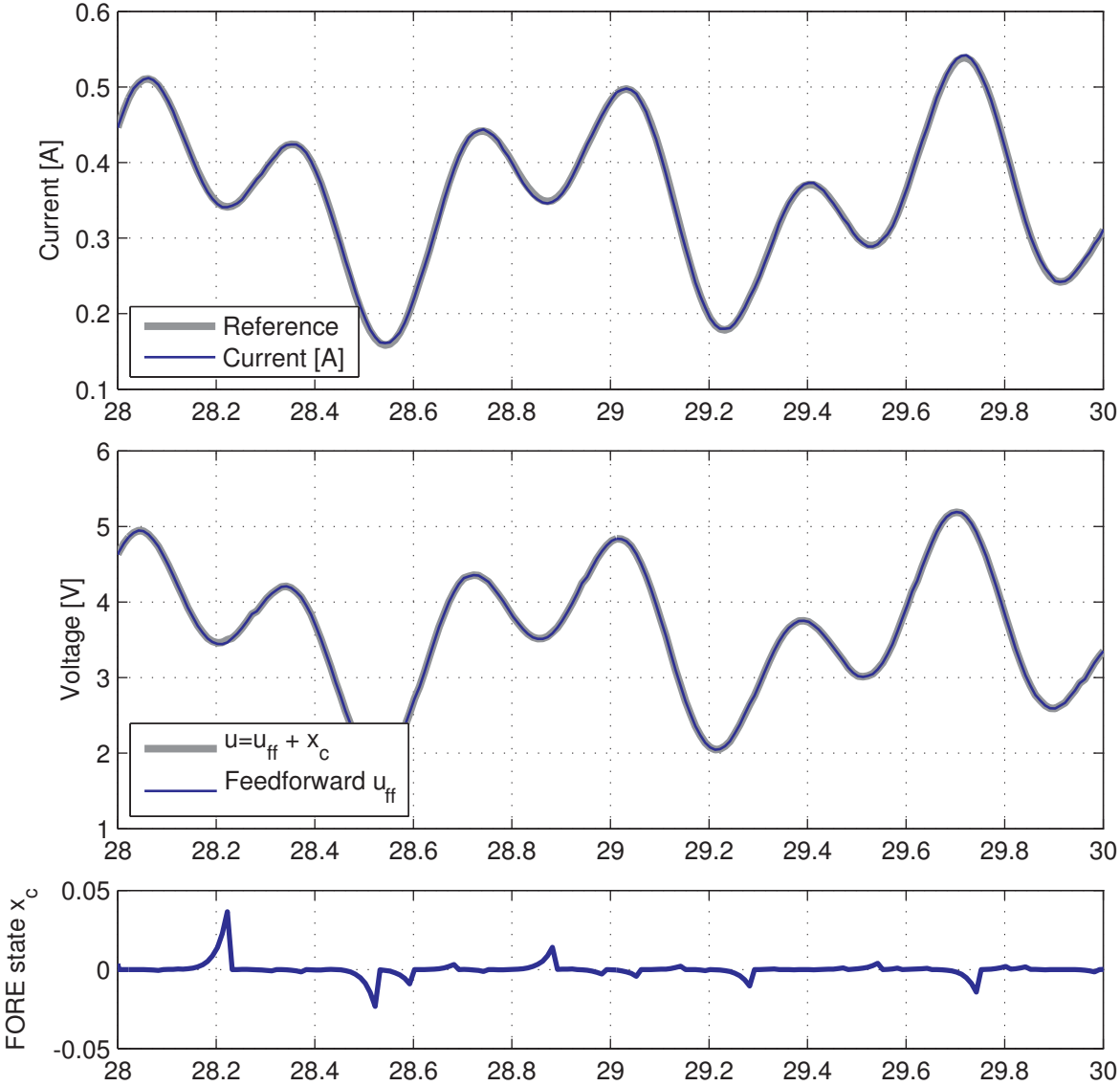
- SIL: control law is **flashed into ECU** and simulated against MATLAB model
- To prevent freezing of parameter estimates α a **32 bit accuracy** was necessary in some variables
- Arising results **essentially coincide** with discrete-time simulation

Experiments on the real valve are satisfactory



- Expected results from SIL **confirmed by the experiment**
- **Small spike** during the zero current phase could be removed by suitable logic
- **Convergence of parameters is perturbed** during some phases (disturbances?)

Experiment: a different (richer) sinusoidal reference



- A close look reveals **anticipatory action** of the dependence on $\dot{r}$
- Feedback correction action reveals presence of **exponentially diverging control bursts**
- **Homogeneous** hybrid dynamics with unstable continuous-time component

Conclusions and future work

Conclusions

- Recent hybrid systems techniques allow to understand better Clegg integrators and FOREs (after 50 years)
- Reset control allows for aggressive control action (exponentially diverging input bursts)
- Resets destroy internal model property: special feedforward is needed
- The proposed feedforward provides convenient adaptation (memory of past transients)
- Experimental results keep confirming technological advantages

Future work

- Use alternative adaptation laws with weaker assumptions
- Extend to higher order plants (but still FOREs)
- Validate on additional experimental challenges

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