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

\[
\begin{align*}
\dot{x}_c &= A_c x_c + B_c v \\
\dot{x}_c &= 1 \frac{v}{RC}
\end{align*}
\]

- In an analog integrator, the state information is stored in a capacitor.
An analog integrator and its Clegg extension \cite{Clegg1958}

**Integrators**: core components of dynamical control systems

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

**Example**: PI controller

- **Clegg’s integrator** \cite{Clegg1958}:
  - *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:

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

- **Flow set** \( C \): where \( x_c \) may flow (1st eq’n)
- **Jump set** \( D \): where \( x_c \) may jump (2nd eq’n)

- 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
Stabilization using hybrid jumps to zero

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

\[ \dot{x}_c = a_c x_c + b_c v, \quad x_c v \geq 0, \]
\[ x_c^+ = 0, \quad x_c v \leq 0, \]

**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, \( \gamma_{dy} \) 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:
  \[-\theta_\varepsilon = \theta_0 < \theta_1 < \cdots < \theta_N = \frac{\pi}{2} + \theta_\varepsilon\]
- 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:
  \[S_0 := \Theta_0 \Theta_N^T + \Theta_N \Theta_0^T\]
  \[S_i := -(\Theta_i \Theta_{i-1}^T + \Theta_{i-1} \Theta_i^T), \quad i = 1, \ldots, N,\]
  \[S_{\varepsilon 1} := \begin{bmatrix} 0_{(n-2) \times (n-2)} & 0 & 0 \\ 0 & 0 & \sin(\theta_\varepsilon) \\ 0 & \sin(\theta_\varepsilon) & -2 \cos(\theta_\varepsilon) \end{bmatrix}\]
  \[S_{\varepsilon 2} := \begin{bmatrix} 0_{(n-2) \times (n-2)} & 0 & 0 \\ 0 & -2 \cos(\theta_\varepsilon) & \sin(\theta_\varepsilon) \\ 0 & \sin(\theta_\varepsilon) & 0 \end{bmatrix}\]

Hybrid closed-loop:
\[
\dot{x} = A_F x + B_d d, \quad x \in \mathcal{C} \\
x^+ = A_J x, \quad x \in \mathcal{D}
\]
### 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:

\[
(Flow) \quad \begin{bmatrix}
A_F^T P_i + P_i A_F + \tau F_i S_i & P_i B_d & C^T \\
* & -\gamma_{dy} I & 0 \\
* & * & -\gamma_{dy} I
\end{bmatrix} < 0, \ i = 1, \ldots, N,
\]

\[
(Jump) \quad A_J^T P_1 A_J - P_0 + \tau J S_0 \leq 0
\]

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

\[
(Cont’ty) \quad \Theta_{N \perp}^T (P_N - P_0) \Theta_{N \perp} = 0
\]

\[
(Overlap) \quad A_J^T P_1 A_J - P_1 + \tau_{\epsilon_1} S_{\epsilon_1} \leq 0
\]

\[
(Overlap) \quad A_J^T P_1 A_J - P_N + \tau_{\epsilon_2} S_{\epsilon_2} \leq 0
\]

\[
(Origin) \quad \begin{bmatrix}
Z(A_F^T P_0 + P_0 A_F) Z^T & ZP_0 B_d & ZC^T \\
* & -\gamma_{dy} I & 0 \\
* & * & -\gamma_{dy} I
\end{bmatrix} < 0,
\]

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

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Clegg and FORE are hybrid

Exponential Stability

Set-point Regulation

Reference Tracking

Conclusions

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

- **Block diagram:**

- **Output response (overcomes linear systems limitations)**

- **Gain \(\gamma_{dy}\) estimates \((N = \# \text{ of sectors})\)**

- **A lower bound:** \(\sqrt{\frac{\pi}{8}} \approx 0.626\)

- **Lyapunov func’n level sets for \(N = 4\)**

- **Quadratic Lyapunov functions are unsuitable**

- **\(P_1, \ldots, P_4\) cover 2nd/4th quadrants**

- **\(P_0\) covers 1st/3rd quadrants**
Example 2: FORE (any $a_c$) and linear plant (Hollot et al.)

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

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

- Gain $\gamma_{dy}$ estimates

- Time responses
Stabilization using hybrid jumps to zero (recall)

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

\[
\dot{x}_c = a_c x_c + b_c v, \quad x_c v \geq 0, \\
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**Theorem** If \( \mathcal{P} \) is linear, minimum phase and relative degree one, then 
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**Simulation**

uses:
\[
\mathcal{P} = \frac{1}{s} \\
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\]

**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 $u_{ff} = \Psi(r)^T \alpha$

$$\begin{align*}
\dot{x}_c &= a_c x_c + b_c v, \\
\dot{\alpha} &= 0, \\
x_c v &\geq 0, \\
\begin{cases} 
  x_c^+ = 0, \\
  \alpha^+ = \alpha + \lambda \frac{\Psi(r)}{|\Psi(r)|^2} x_c,
\end{cases} \\
x_c v &\leq 0,
\end{align*}$$

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

**Lemma:** Tuning of $\lambda$ 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 ⇒ need aggressive controllers (recall exp. unstable transients)

Identified valve transfer function:

\[ P(s) = \frac{2200}{(s + 164.4)(s + 10.69)}. \]
Feedforward: $\alpha$ converges to suitable parametrization

- $\star$: steady-state input/output pairs (stiction!!)
- Red Solid: $u_{ff} = \Psi^T(r)\alpha^*$, with $\alpha^*$ steady-state for $\alpha$
- 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 $\lambda$ intentionally selected small and $\alpha$ 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 $u_{ff} = \Psi(r)^T \alpha$

\[
\begin{align*}
\dot{x}_c &= a_c x_c + b_c v, \\
\dot{\alpha} &= 0, \\
x_c^+ &= 0, \\
\alpha^+ &= \alpha + \lambda \frac{\Psi(r)}{|\Psi(r)|^2} x_c,
\end{align*}
\]

$x_c v \geq 0$, $x_c v \leq 0$,

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

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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:**

\[
\begin{align*}
\dot{x}_c &= a_c x_c + b_c v, \\
\dot{\alpha} &= 0, \quad \dot{\tau} = 1 \\
\dot{\Xi} &= e^{-A_f \tau} B \Psi^T (r, \dot{r}), \\
\end{align*}
\]

\[
\begin{cases}
  x_c^+ = 0, \\
  \alpha^+ = \alpha + \lambda \frac{(C \exp(A_f \tau) \Xi)^T}{\max\{1, |C \exp(A_f \tau) \Xi|^2\}} x_c, \\
  \tau^+ = 0, \quad \Xi^+ = [0 \ 0 \ 0], \\
  x_c v \leq 0, \\
\end{cases}
\]

**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

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- Feedback/Feedforward equations:

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\begin{align*}
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\]
\[
\begin{align*}
x_c^+ &= 0, \\
\alpha^+ &= \alpha + \lambda \frac{\varphi(\tau)}{\max\{1, |\varphi(\tau)|^2\}} \Psi(r, \dot{r}) x_c \\
\tau^+ &= 0, \\
x_c v &\leq 0,
\end{align*}
\]

**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 $\Rightarrow$ 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 $\alpha$, 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?)
Clegg and FORE are hybrid

Exponential Stability  Set-point Regulation  Reference Tracking  Conclusions  References

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


