

Model recovery anti-windup for input-saturated plants illustrated by control applications

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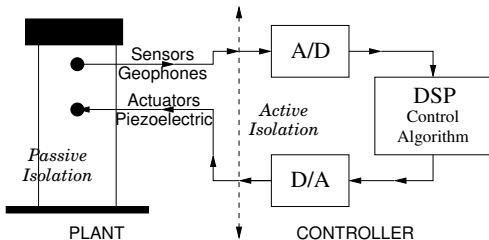
Outline

- 1 Model recovery anti-windup solution
- 2 Applications using Linear Model Recovery Anti-Windup
- 3 Applications using Nonlinear Model Recovery Anti-Windup

Active control provides extreme vibration isolation

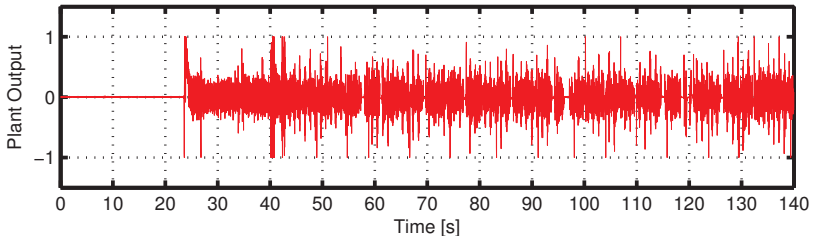
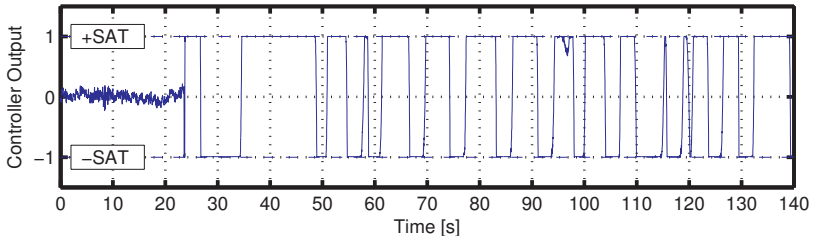
Newport Corporation's Elite 3™ vibration isolation table

- Useful, for example, in
 - high-precision microscopy
 - semiconductor manufacturing
- Actuators: piezoelectric stack
- Sensors: geophones



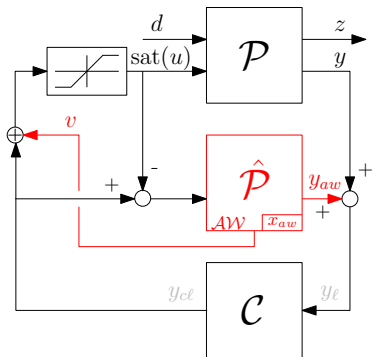
Input saturation confuses the base control algorithm

- Extreme vibration suppression (40 dB) up to $t = 23$ s



- At $t = 23$ s someone walks close to the table

Teel and Kapoor [1997], Zaccarian and Teel [2002, 2011]

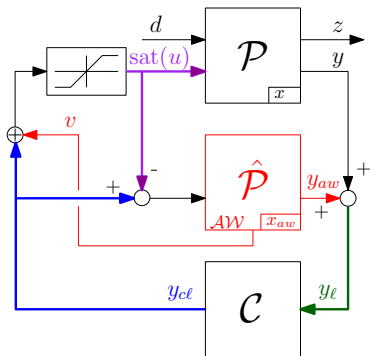


- Framework for **nonlinear** \mathcal{AW} :

- \mathcal{AW} is a model $\hat{\mathcal{P}}$ of \mathcal{P}
- $v = k(x_{aw})$ is a (nonlinear) stabilizer whose construction depends on \mathcal{P}
- \mathcal{AW} is **controller-independent**:
 - any (nonlinear) \mathcal{C} allowed
- Useful feature of MRAW:
 - \mathcal{C} “receives” linear plant output y_e
 - $\Rightarrow \mathcal{C}$ “delivers” linear plant input y_{cl}

Linear Model Recovery Anti-Windup main intuition

Teel and Kapoor [1997], Zaccarian and Teel [2002, 2011]



Model Recovery Anti-Windup (MRAW)

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- Plant \mathcal{P}

$$\begin{cases} \dot{x} &= Ax + B_d d + B_u \text{sat}(u) \\ z &= C_z x + D_{dz} d + D_{uz} \text{sat}(u) \\ y &= C_y x + D_{dy} d + D_{uy} \text{sat}(u) \end{cases}$$

- Anti-windup filter $\hat{\mathcal{P}}$

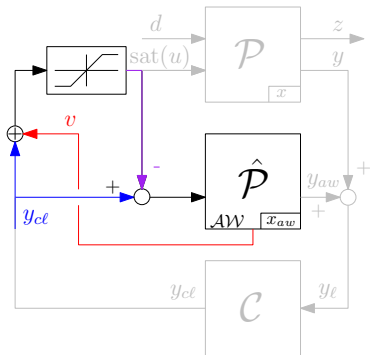
$$\begin{cases} \dot{x}_{aw} &= Ax_{aw} + B_u (y_c - \text{sat}(u)) \\ y_{aw} &= C_y x_{aw} + D_{uy} (y_c - \text{sat}(u)) \end{cases}$$

- Unconstrained dynamics $\mathcal{P} + \hat{\mathcal{P}}$:

$$\begin{cases} \dot{x}_\ell &= Ax_\ell + B_d d + B_u y_c \\ y_\ell &= C_y x_\ell + D_{dy} d + D_{uy} y_c \end{cases}$$

Linear Model Recovery Anti-Windup main intuition

Teel and Kapoor [1997], Zaccarian and Teel [2002, 2011]



Model Recovery Anti-Windup (MRAW)

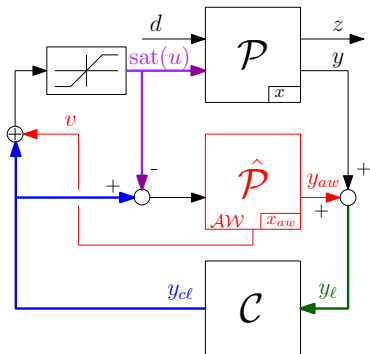
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- Useful feature of MRAW:
 - \mathcal{C} “receives” linear plant output y_ℓ
 - $\Rightarrow \mathcal{C}$ “delivers” linear plant input $y_{c\ell}$

- $x_{aw} = x_\ell - x$ stores useful information about the mismatch response
- Unconstrained recovery: **stabilize** x_{aw} to zero **using** v
- Anti-windup filter $\hat{\mathcal{P}}$ **stabilized by** v through time-varying saturation

$$\begin{cases} \dot{x}_{aw} &= A x_{aw} - B_u (\text{sat}[y_{cl}(t) + k(x_{aw})] - y_{cl}(t)) \\ \dot{z}_{aw} &= C_z x_{aw} - D_{uz} (\text{sat}[y_{cl}(t) + k(x_{aw})] - y_{cl}(t)) \end{cases}$$

Linear Model Recovery Anti-Windup main intuition

Pagnotta et al. [2007], Zaccarian and Teel [2005], Forni et al. [2012, 2010], Zaccarian et al. [2005]



Model Recovery Anti-Windup (MRAW)

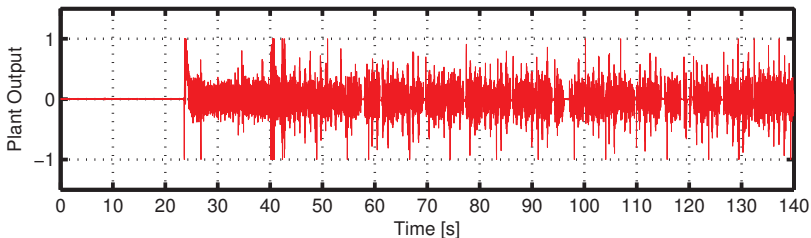
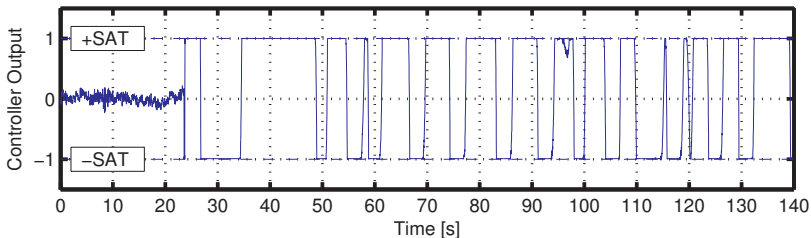
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 - $\Rightarrow \mathcal{C}$ “delivers” linear plant input y_{cl}

Several **extensions** are possible:

- **Reduced order** $\hat{\mathcal{P}}$ possible (tested on adaptive noise suppression)
- MRAW allows for **bumpless transfer** among controllers
- MRAW generalizes to **rate** and **curvature** saturation
- MRAW generalizes to **dead time** plants (Smith predictor)

Base control algorithm confused (recall)

- Extreme vibration suppression (40 dB) up to $t = 23$ s

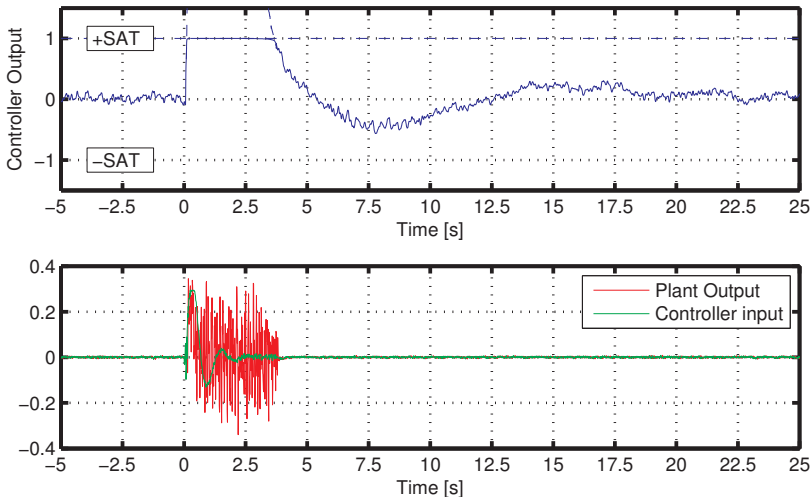


- At $t = 23$ s someone walks close to the table

MRAW dramatically reduces isolation recovery time

Teel et al. [2006], Zaccarian et al. [2000]

- Effect of a footstep at the side of the table (recovery ≈ 4 s)

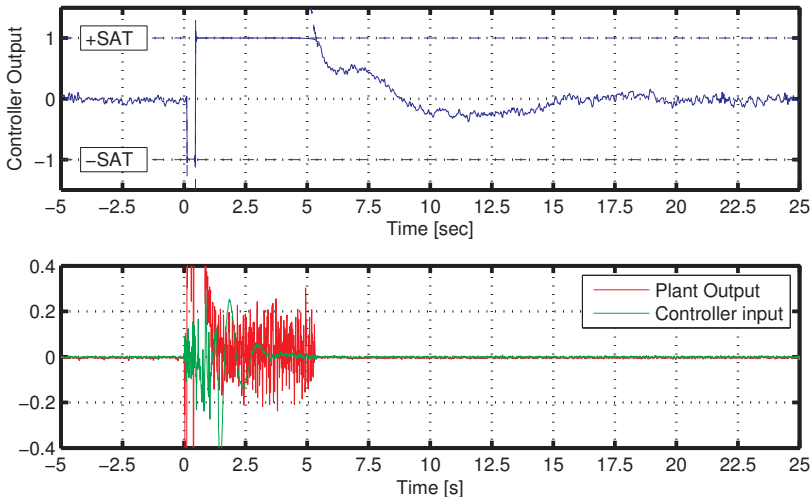


Even a bat strike does not confuse the MRAW controller

Teel et al. [2006], Zaccarian et al. [2000]



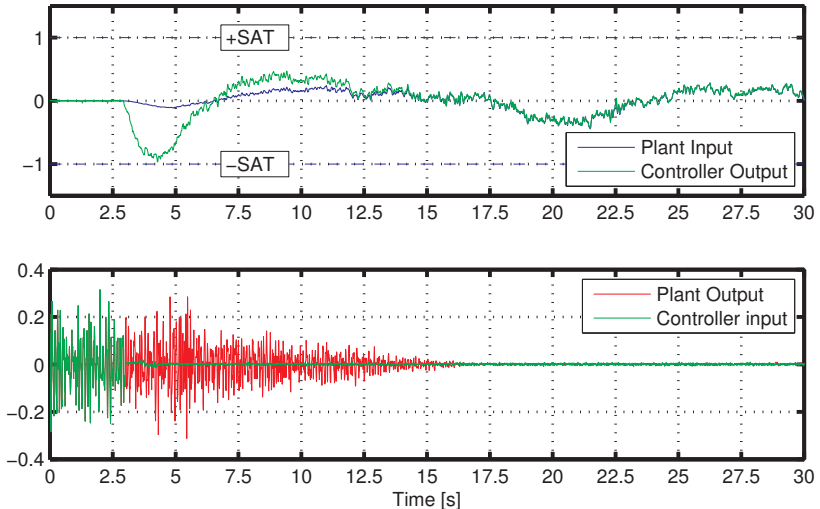
Hitting with a baseball bat the table leg (recovery ≈ 5 s)



Bumpless transfer enables smooth controller activation

Teel et al. [2006], Zaccarian et al. [2000]

- Controller is gradually activated in bumpless transfer scheme



Anti-windup for open-water irrigation channels

Zaccarian et al. [2007]

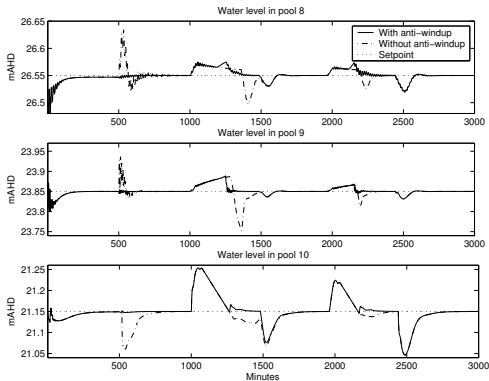
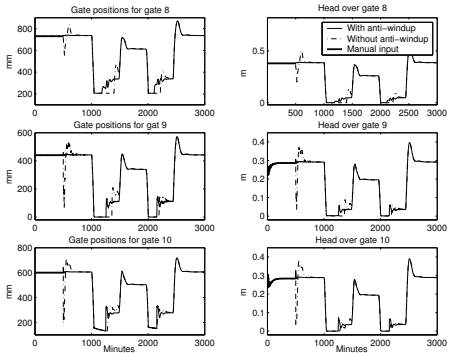
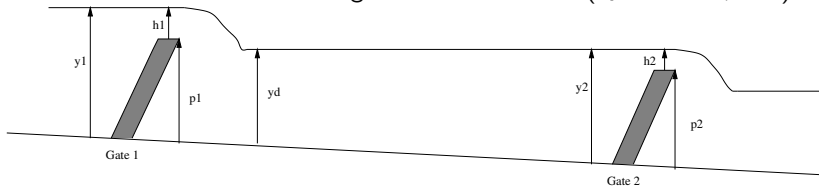
- Open Water Channels: rivers are broken into pools for water saving
- Gate saturation problems:
 - bumpless transfer from manual control to avoid startup transients
 - with small flows in the pools bad lower saturation effects
 - with large disturbances (rain, etc) with overflow to downstream pool
- **Challenge:** plant is not exponentially stable (poles in 0)



Simulations save days of transient response

Zaccarian et al. [2007]

Simulations with model of Haughton Main Channel (Queensland, Aus)



Rate Saturated McDonnell Douglas TAFA dynamics

Barbu et al. [2005]

- Linearized longitudinal dynamics (α =angle of attack; q =pitch rate)

$$\begin{aligned}\dot{z} &:= \begin{bmatrix} \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_{\alpha} & Z_q \\ M_{\alpha} & M_q \end{bmatrix} z + \begin{bmatrix} 0 \\ M_{\delta} \end{bmatrix} \delta \\ &=: A z + B_u \delta\end{aligned}$$

- Saturation: $M = 20 \text{ deg}$, $R = 40 \text{ deg/s}$.

$$\dot{\delta} = R \operatorname{sgn} \left[M_{\text{sat}} \left(\frac{u}{M} \right) - \delta \right],$$



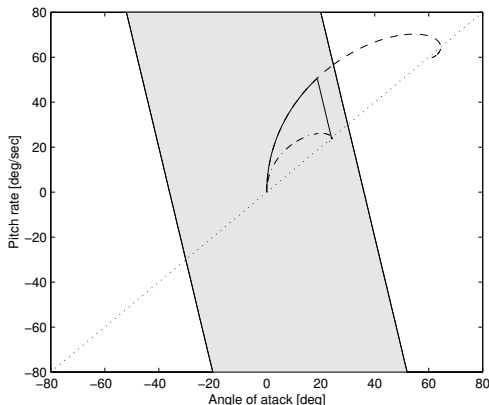
- Study a flight trim condition with one exp unstable mode

$$\dot{x} := \begin{bmatrix} \dot{x}_s \\ \dot{x}_u \end{bmatrix} = \begin{bmatrix} -4 & 0 \\ 0 & 1 \end{bmatrix} x + \begin{bmatrix} b_s \\ b_u \end{bmatrix} \delta$$

Magnitude saturation and exponential instability

Galeani et al. [2007], Teel [1999]

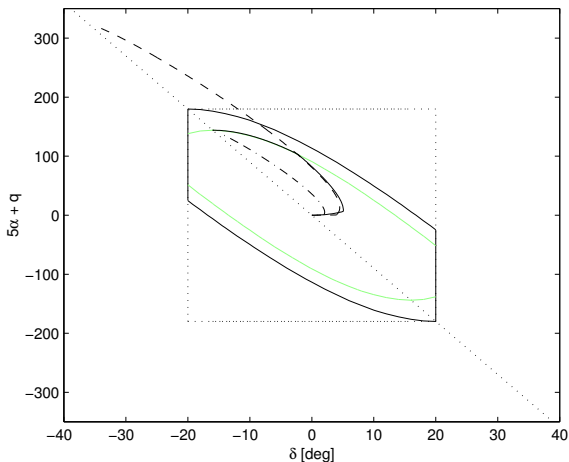
- Unconstrained trajectory may exit the null-controllability region
- To prevent this, AW scheme uses $v = \bar{k}(x_{aw}, x_u)$



- Unconstrained (—), possible desired trajectories (— and — · —)

Problems due to magnitude+rate saturation

- Unconstrained trajectory may exit the null-controllability region

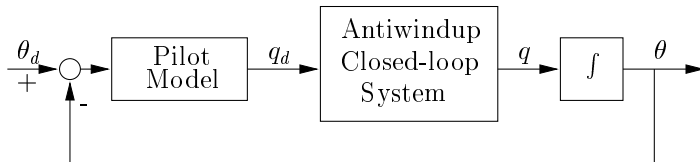


- Unconstrained (---), possible desired trajectories (— and — · —)

Close the position loop using a pilot model

Barbu et al. [2005]

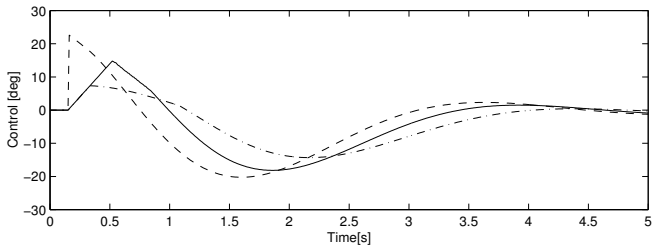
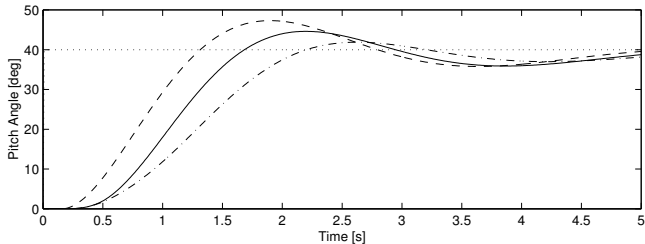
- Use a simple crossover model



- Study the maneuverability of the aircraft with anti-windup
- Study the possible occurrence of PIOs (Pilot Induced Oscillations)
- Compare with static command limiting (saturating q_d)
- Use a step reference $\theta_d = 40 \text{ deg}$

Piloted flight simulation

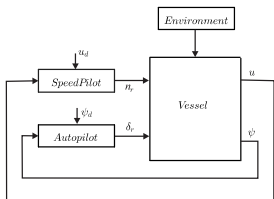
Barbu et al. [2005]



(unconstrained —, anti-windup —, static limiting — · —)

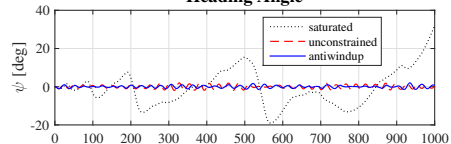
Speed and Heading Control of Ships: approximate models

Donnarumma et al. [2016]

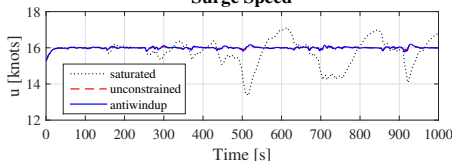


- u = surge speed, n_r = (commanded) shaft speed
- ψ = heading angle, δ_r = rudder angle
- Two independent loops on nonlinearly coupled plant
- Anti-windup model is linear and decentralized
- Robustness of MRAW provides strong improvement

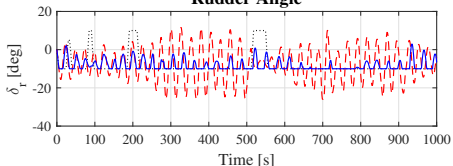
Heading Angle



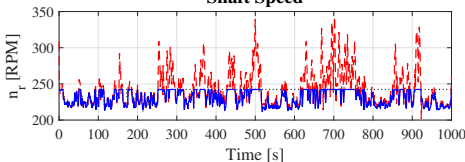
Surge Speed



Rudder Angle



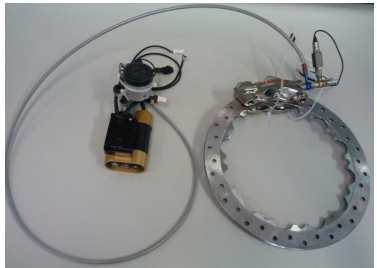
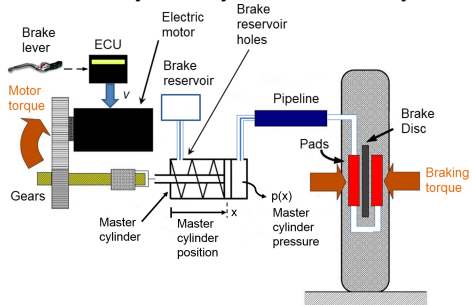
Shaft Speed



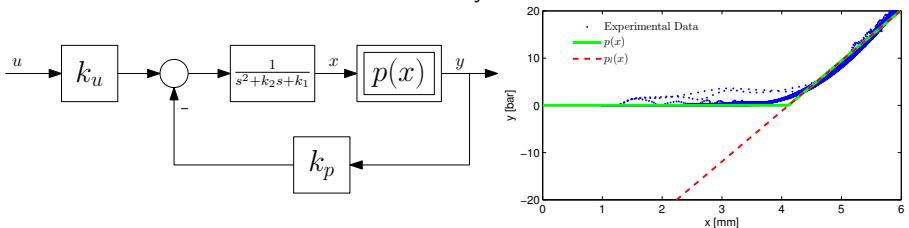
Nonlinear anti-windup for a Brake By Wire System

Todeschini et al. [2016]

- Brake-by-wire system in motorcycles corresponds to a nonlinear plant

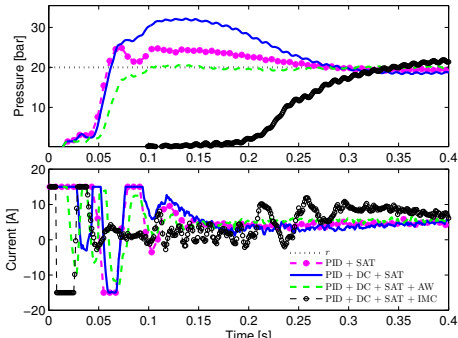
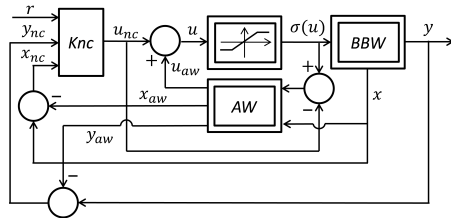
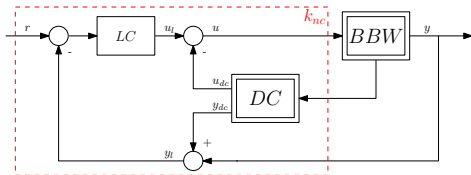


- The main nonlinear effect can be easily isolated in the model:



BBW solution uses nonlinear MRAW

- “Deadzone compensation” scheme provides **nonlinear** baseline controller
- **Fully Nonlinear anti-windup** addresses saturation with **nonlinear plant** and **nonlinear controller**



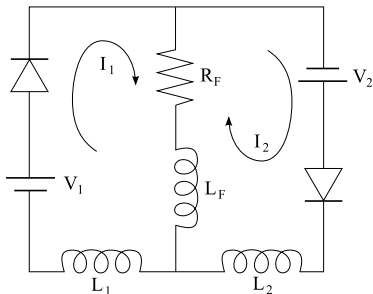
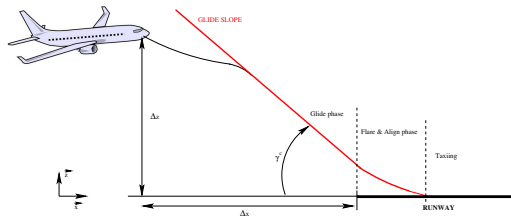
- Step response reveals successful anti-windup action
- Driver would get confused by large overshoots
- Alternative existing solutions (nonlinear IMC-based anti-windup) are unacceptably slow (black)

Anti-windup designs apply to additional applications

Vitelli et al. [2010], Burlion et al. [2019]

Image-based visual servoing

- Relevant for plane landing
 - follow reference glide slope
 - position measurement scaled by unknown factor
- **Challenge:** plant is uncertain (need robust approach)



Small signal nonlinearity compensation in high-power circulating current amps

- Thyristors have a min current threshold:
 - below the treshold: circulating current
 - this generates a undesired nonlinearity
 - possibly destabilizing outer feedback
- **Challenge:** reverse anti-windup problem

References

- ▷ **Summary** of the proposed Model Recovery Anti-Windup in Galeani et al. [2009], Zaccarian and Teel [2011]
- ▷ **Model-Recovery anti-windup** schemes
 - Baseline ideas Teel and Kapoor [1997], Zaccarian and Teel [2002]
 - Bumpless transfer extensions Zaccarian and Teel [2005]
 - Generalizations to rate and curvature saturations Forni et al. [2010, 2012]
 - Dead-time plants (input delays) Zaccarian et al. [2005]
- ▷ **MRAW Applications** discussed in this talk:
 - Linear MRAW: Flight Control Barbu et al. [2005], Vibration isolation Teel et al. [2006], Open Water Channels Zaccarian et al. [2007], Control of power converters Vitelli et al. [2010], Ship control Donnarumma et al. [2016].
 - Nonlinear MRAW: Control of Euler-Lagrange systems Morabito et al. [2004], control of Break-by-wire systems Todeschini et al. [2016], Image-based servoing Burlion et al. [2019].

Modern Anti-windup Synthesis

Control Augmentation for Actuator Saturation



Luca Zaccarian and
Andrew R. Teel

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