The model recovery anti-windup scheme illustrated via control applications

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J. Marcinkovski, S. Podda, V. Vitale, L. Burlion,
F. Forni, F. Morabito, F. Todeschini, C. Barbu

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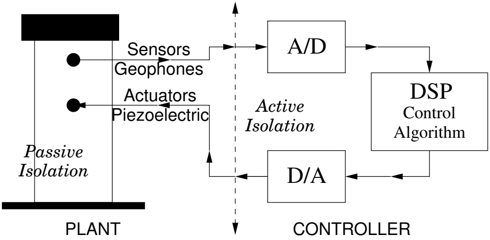
Outline

Active control provides extreme vibration isolation

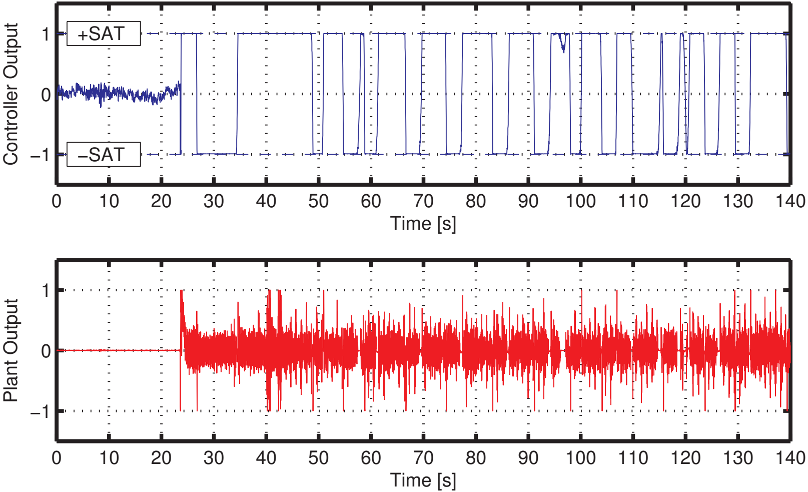
Newport Corporation's Elite 3^{TM} vibration isolation table

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



Input saturation confuses the base control algorithm

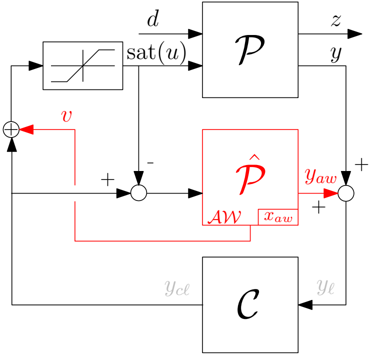
- Extreme vibration suppression (40 dB) up to $t = 23\ s$



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

Linear Model Recovery Anti-Windup main intuition

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



Model Recovery Anti-Windup *(MRAW)*

- 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_ℓ
  - $\Rightarrow \mathcal{C}$ "delivers" linear plant input $y_{c\ell}$

- Unconstrained recovery: **stabilize** x_{aw} to zero using v
- **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)

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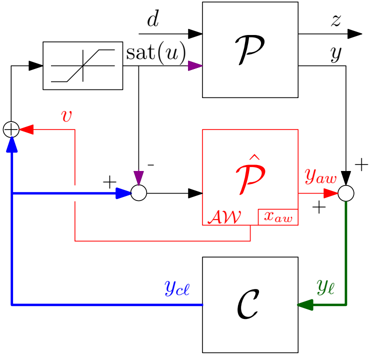

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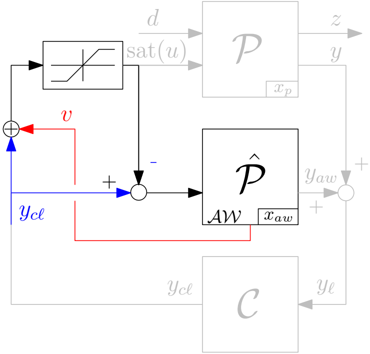

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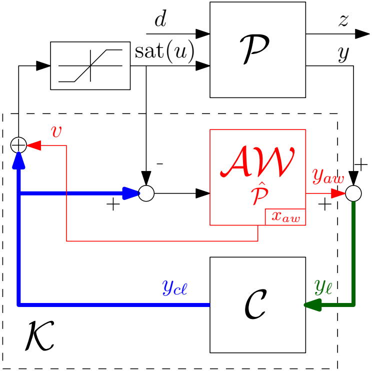
Pagnotta et al. [2007], Zaccarian and Teel [2005], Forni et al. [2012, 2010], Zaccarian et al. [2005]



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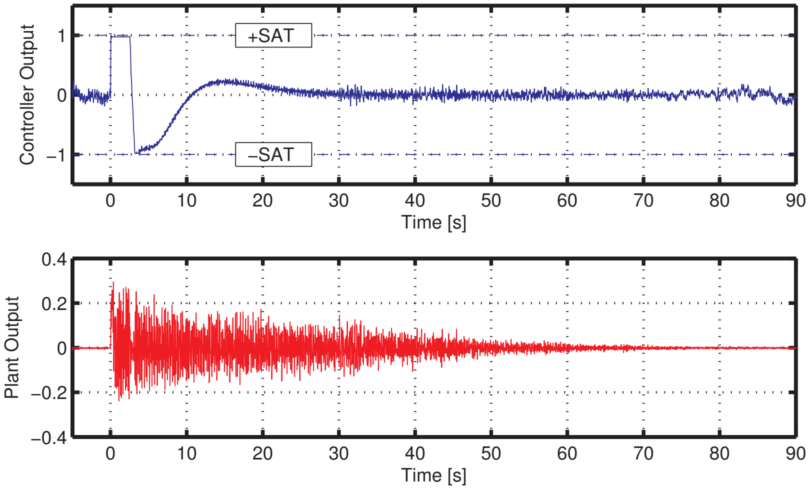
Ad hoc gain adaptation induces very slow isolation recovery

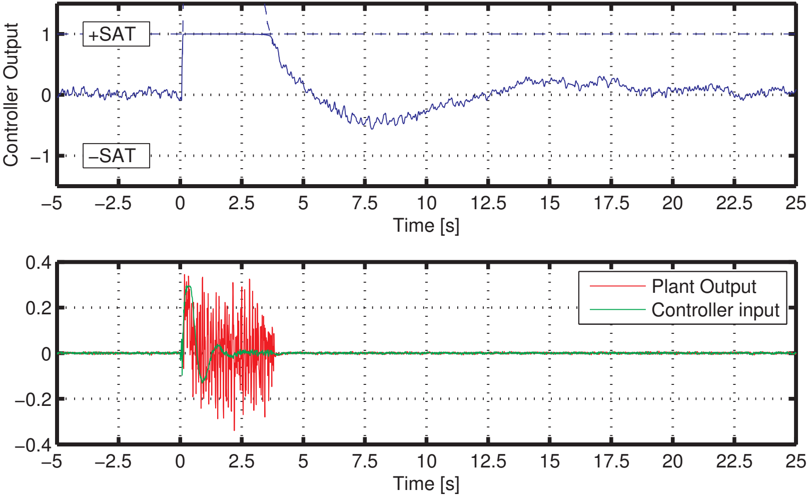
- Effect of a footstep at the side of the table (recovery $>$ 1 minute)



MRAW dramatically reduces isolation recovery time

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

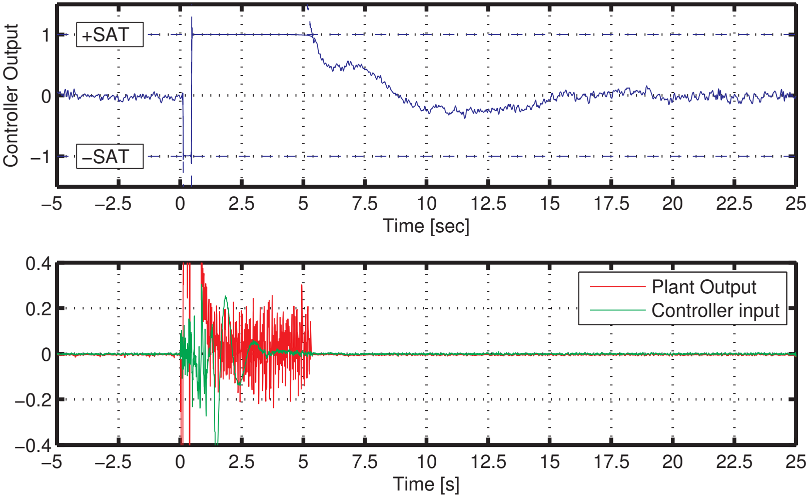
- Effect of a footstep at the side of the table (recovery $\approx$ 4 s)



Even a bat strike does not confuse the MRAW controller

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

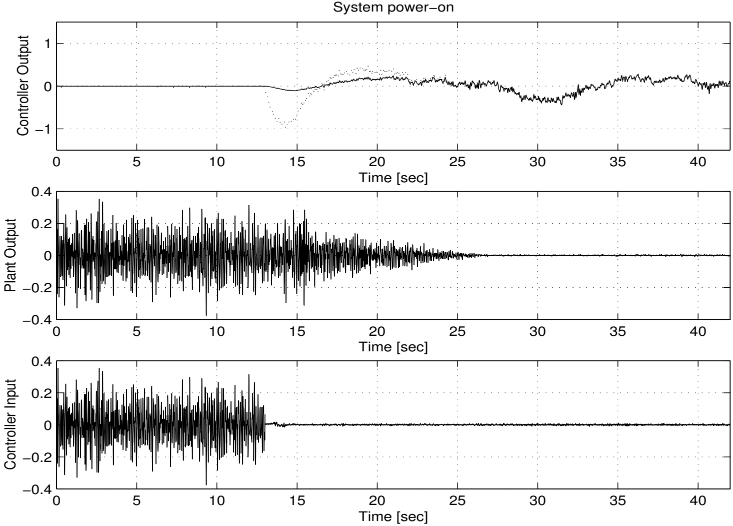
Hitting with a baseball bat the table leg (recovery $\approx$ 5 s)



Bumpless transfer enables smooth controller activation

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

- Controller is gradually activated in bumpless transfer scheme



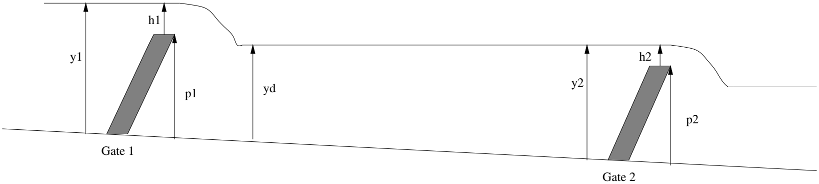
Anti-windup for open-water irrigation channels
Zaccarian et al. [2007]

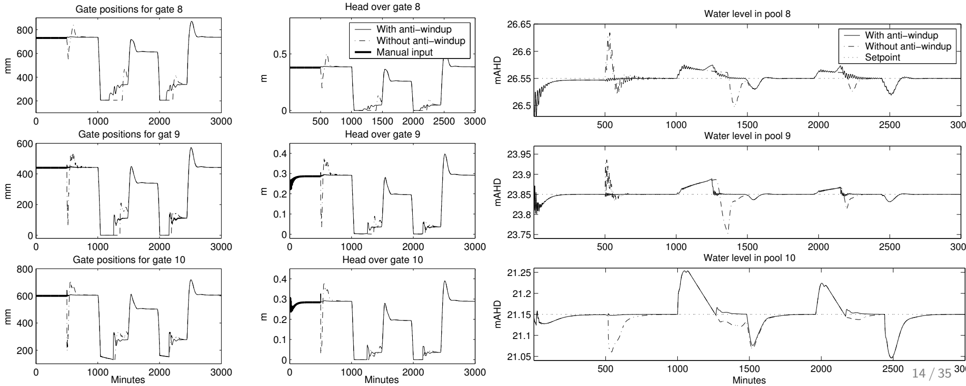
- Open Water Channels: rivers are broken into pools for water saving
- Gate saturation problems:
  - bumpless transfer from manual control to avoid startup transients
  - with small flows in the pools bad lower saturation effects
  - with large disturbances (rain, etc) with overflow to downstream pool
- **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)

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

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

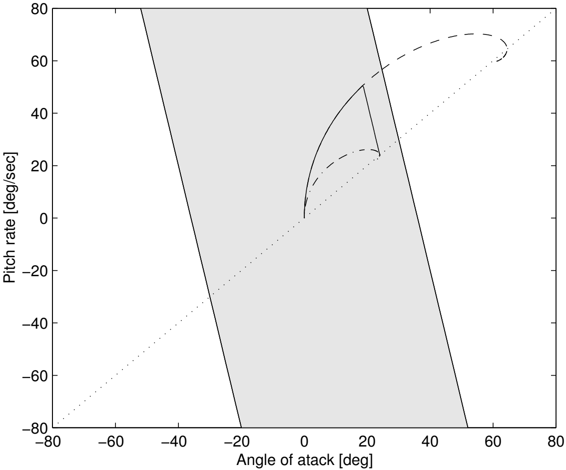
$$\dot{\delta} = R\,\mathrm{sgn}\left[M\,\mathrm{sat}\left(\frac{u}{M}\right) - \delta\right],$$

- Study a flight trim condition with one exp unstable mode

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

Problems due to magnitude saturation

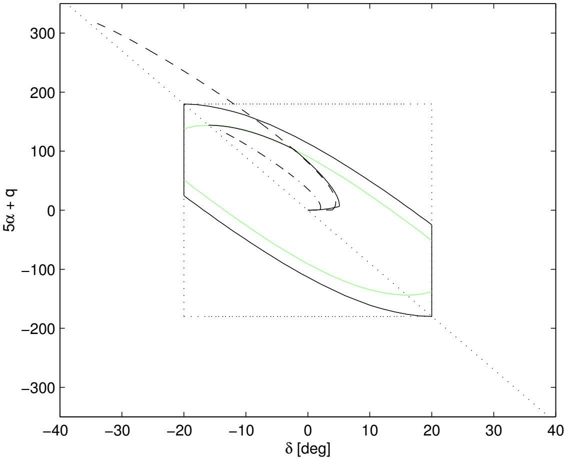
- Unconstrained trajectory may exit the null-controllability region



- Unconstrained ($--$), possible desired trajectories ($-$ and $-\cdot-$)

Problems due to magnitude+rate saturation

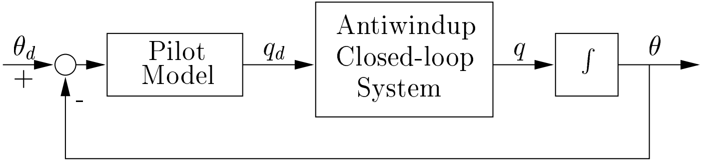
- Unconstrained trajectory may exit the null-controllability region



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

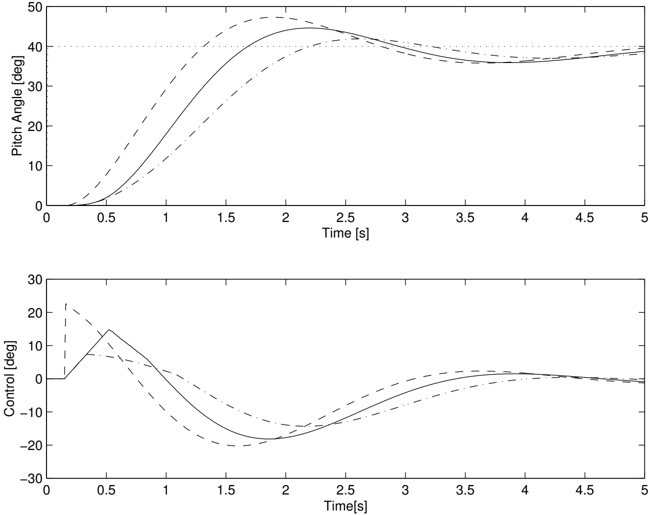
Close the position loop using a pilot model

- Use a simple crossover model



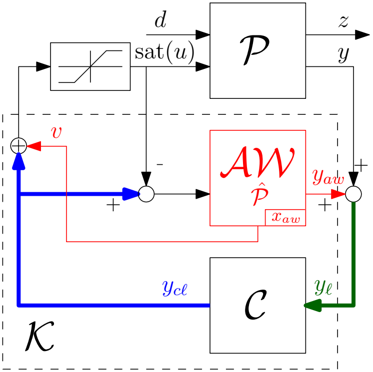
- Study the maneuverability of the aircraft with anti-windup
- Study the possible occurrence of PIOs (Pilot Induced Oscillations)
- Compare the response to the optimal response using static command limiting
- Use a step reference $\theta_d = 40$ *deg*

Piloted flight simulation



(unconstrained −−, anti-windup −, optimal trajectory with static limiting − · −)

Recall the Linear MRAW scheme



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Unconstrained response information (linear case)

- Plant $\mathcal{P}$

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

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

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

- Unconstrained controller $\mathcal{C}$

$$\begin{cases} \dot{x}_c &= A_c\,x_c + B_{cu}\,u_c + B_{cr}\,r \\ y_c &= C_c\,x_c + D_{cu}\,u_c + D_{cr}\,r \end{cases}$$

- Interconnections

$$\begin{cases} u &= y_c + v, \\ u_c &= y + y_{aw} \end{cases}$$

v: to be selected!

- Coordinate transformation: $(x_\ell, x_c, x_{aw}) = (x + x_{aw}, x_c, x_{aw})$
- Unconstrained dynamics $\mathcal{P} + \hat{\mathcal{P}}$: $\begin{cases} \dot{x}_\ell &= A\,x_\ell + B_d\,d + B_u\,y_c \\ y + y_{aw} &= C_y\,x_\ell + D_{dy}\,d + D_{uy}\,y_c \end{cases}$
- $\Rightarrow$ Information about the unconstrained response embedded within the scheme!

The unconstrained response information (nonlinear case)

- Plant $\mathcal{P}$

$$\begin{cases} \dot{x} &= f(x, \mathrm{sat}(u)) \\ z &= h(x, \mathrm{sat}(u)) \end{cases}$$

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

$$\begin{cases} \dot{x}_{aw} &= f(x - x_{aw}, y_c) - f(x, \mathrm{sat}(u)) \\ y_{aw} &= x_{aw} \end{cases}$$

- Unconstrained controller $\mathcal{C}$

$$\begin{cases} \dot{x}_c &= g(x_c, u_c, r) \\ y_c &= k(x_c, u_c, r) \end{cases}$$

- Interconnections

$$\begin{cases} u &= y_c + v, \\ u_c &= x + x_{aw} \end{cases}$$

v: to be selected!

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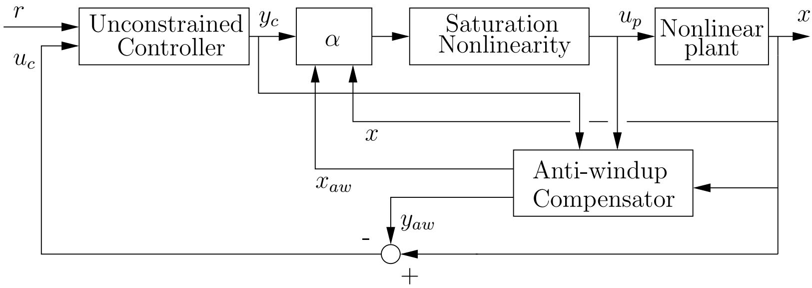
Anti-windup for nonlinear systems: resulting scheme



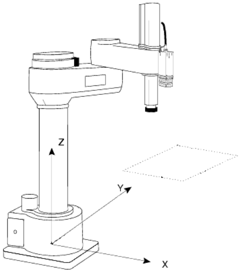
- Need extra plant state measurements
- Recall that $x_{aw} = x_\ell - x$: very useful information
  - worry about stability looking at x
  - worry about performance looking at x_{aw}
- A few application examples:
  - Anti-windup for robot manipulators Morabito et al. [2004]
  - Anti-windup for Brake-by-Wire systems Todeschini et al. [2016]

A SCARA robot manipulator example

Morabito et al. [2004]

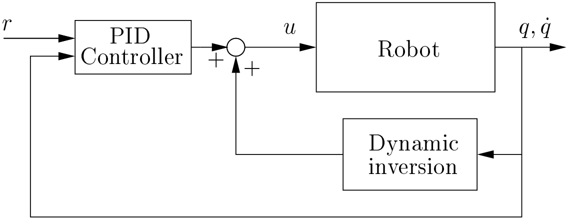
- SCARA robot with limited torque/force inputs

Link	1	2	3	4
m_i	55 Nm	45 Nm	70 N	25 Nm



- General class of systems is:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + h(q) = \mathrm{sat}(u)$$

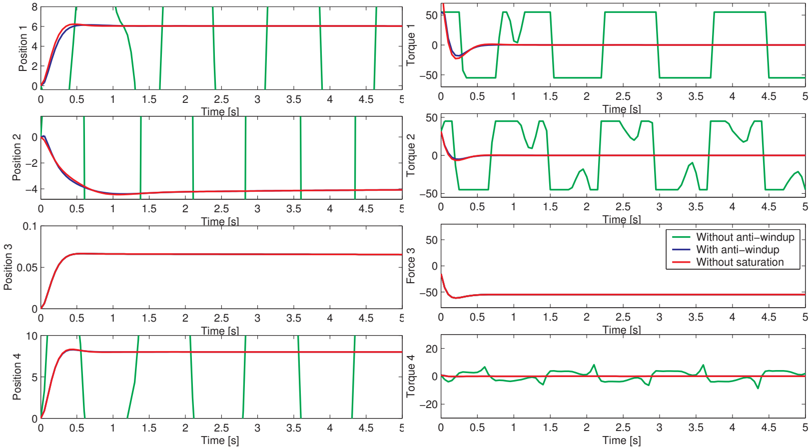


P	I	D
121	7.5	17.8
30	10	8.2
150	1	24.7
150	0.5	20.1

- Feedback linearizing controller+PID action (*computed torque*) induces decoupled linear performance (for small signals)

A slight saturation can be disastrous

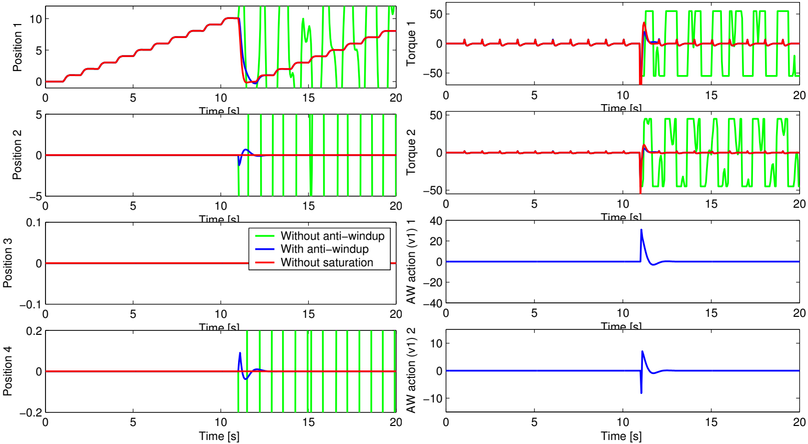
- The reference is $r = [6\ deg,\ -4\ deg,\ 4\ cm,\ 8\ deg]$



- Stability is recovered, performance is almost fully preserved

Anti-windup injects signals and then fades out

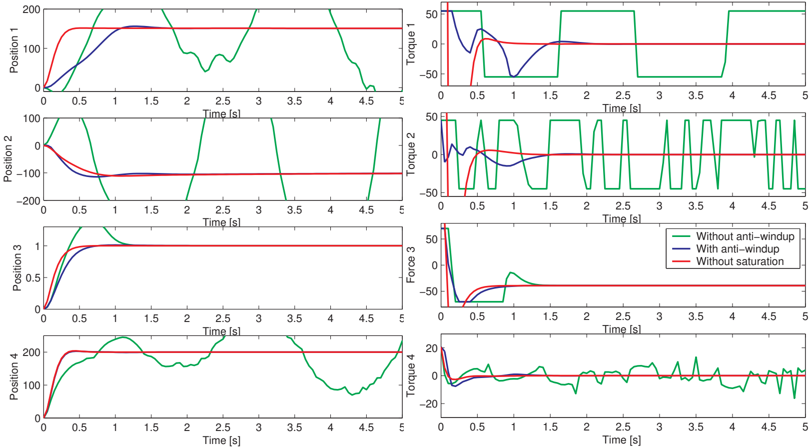
- The reference is a sequence of little step followed by a large step



- The anti-windup action dies away to recover the unconstrained closed-loop

SCARA: large signals (nonlinear stabilizer v)

- The reference is $r = [150\ deg,\ -100\ deg,\ 1\ m,\ 200\ deg]$

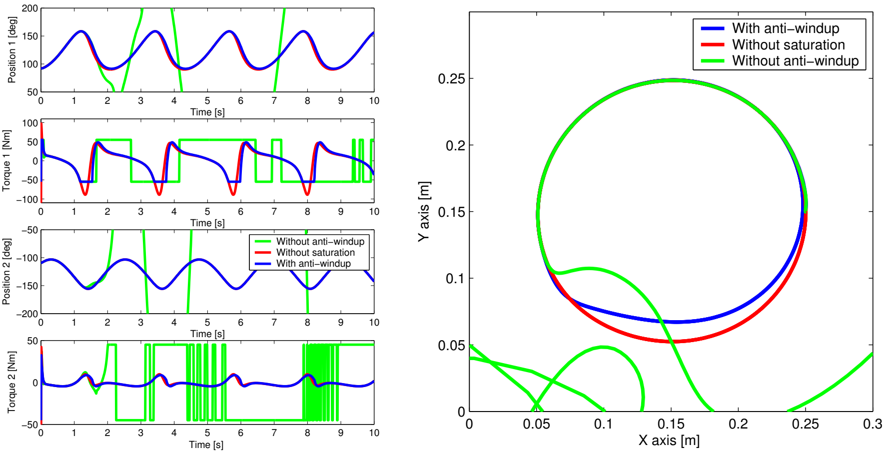


- Performance is dramatically improved (input authority is almost fully explotied)

MRAW intrinsically addresses tracking recovery

Example: a **SCARA robot** (planar robot) following a circular motion

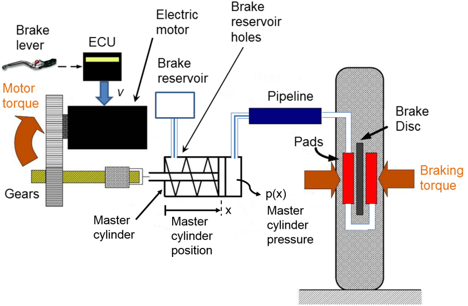
- Saturated "computed torque" controller goes postal (unstable)
- Nonlinear MRAW provides slight performance degradation

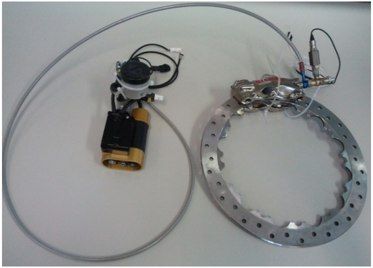


Nonlinear anti-windup for a Brake By Wire System

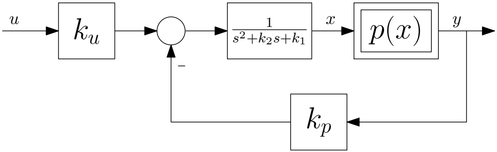
Todeschini et al. [2016]

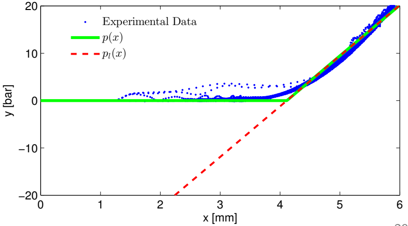
- Brake-by-wire system in motorcycles corresponds to a nonlinear plant





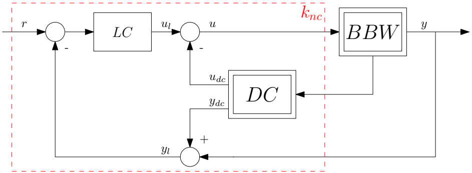
- The main nonlinear effect can be easily isolated in the model:

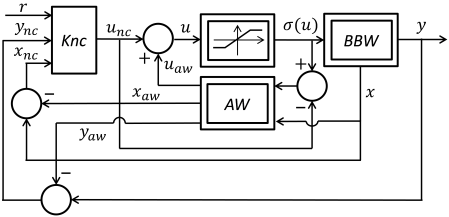


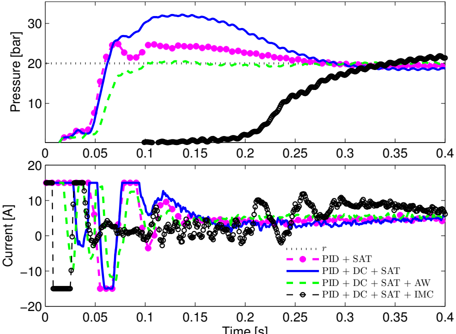


BBW solution uses nonlinear MRAW

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







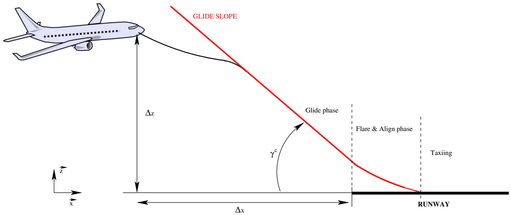
- Step response reveals successful anti-windup action
- Driver would get confused by large overshoots
- Alternative existing solutions (nonlinear IMC-based anti-windup) are unacceptably slow (black)

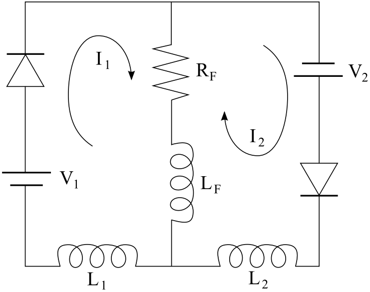
Anti-windup designs apply to additional applications

Vitelli et al. [2010]

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

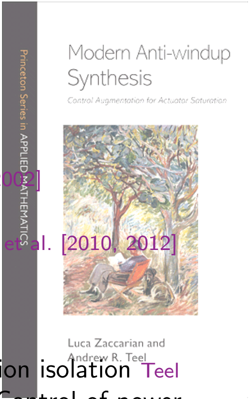
- Thyristors have a min current threshold:
  - below the treshold: circulating current
  - this generates a undesired nonlinearity
  - possibly destabilizing outer feedback
- **Challenge**: reverse anti-windup problem

Conclusions and outlook

- **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]
  - Nonlinear MRAW: Control of Euler-Lagrange systems Morabito et al. [2004], control of Break-by-wire systems Todeschini et al. [2016], Image-based servoing.



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