Architectural Issues in Control System Design

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Presented at the Nordic Process Control Workshop
26-27 August, 2010

Control has been an incredibly rewarding and exciting journey for me!

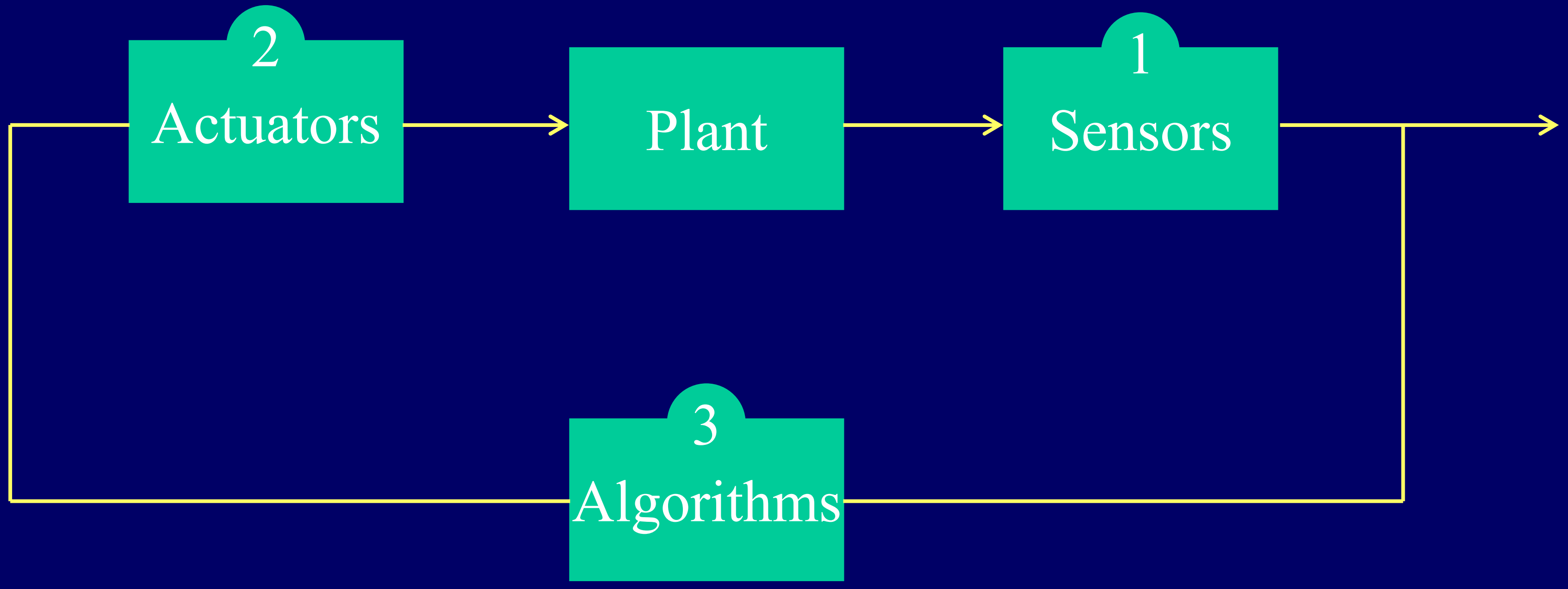
Why Architecture?

Analogy: Civil Engineering

- What form should the bridge take?

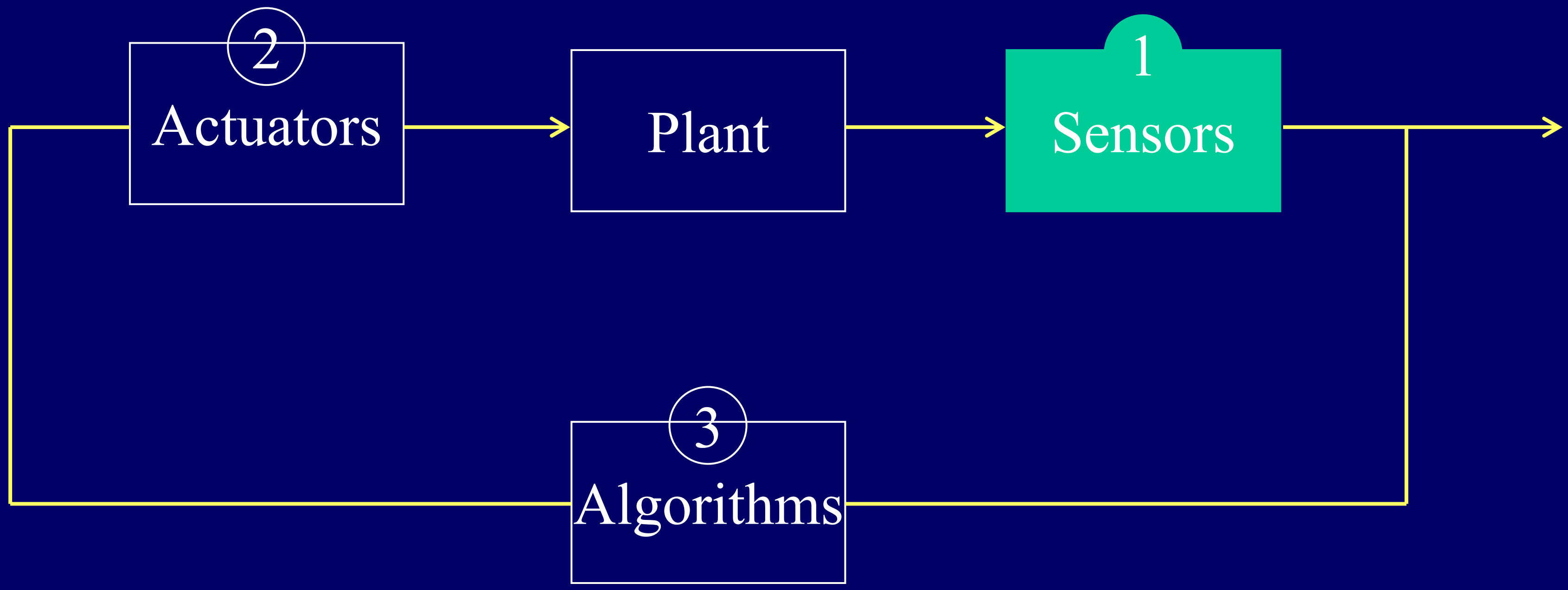
- What materials?
- Should we build a bridge or tunnel?
- Finally: Optimize cables, beams, etc.

Architectural Issues in Control



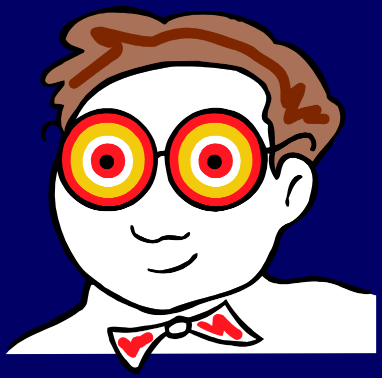
Illustrate by five *Real World Examples*

Architectural Issues in Control



1. Sensors

Sensors are the eyes of control.



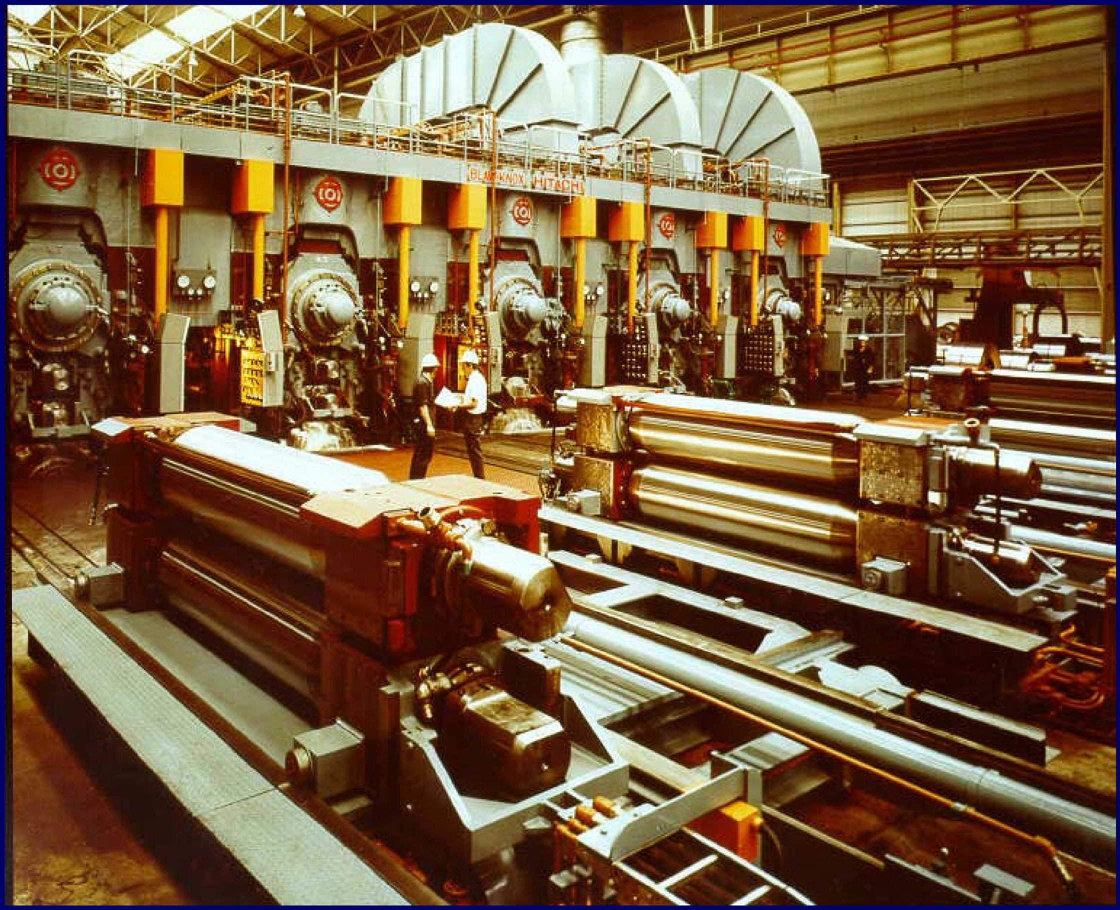
Poor eye-sight → Poor Control!

1. Sensors

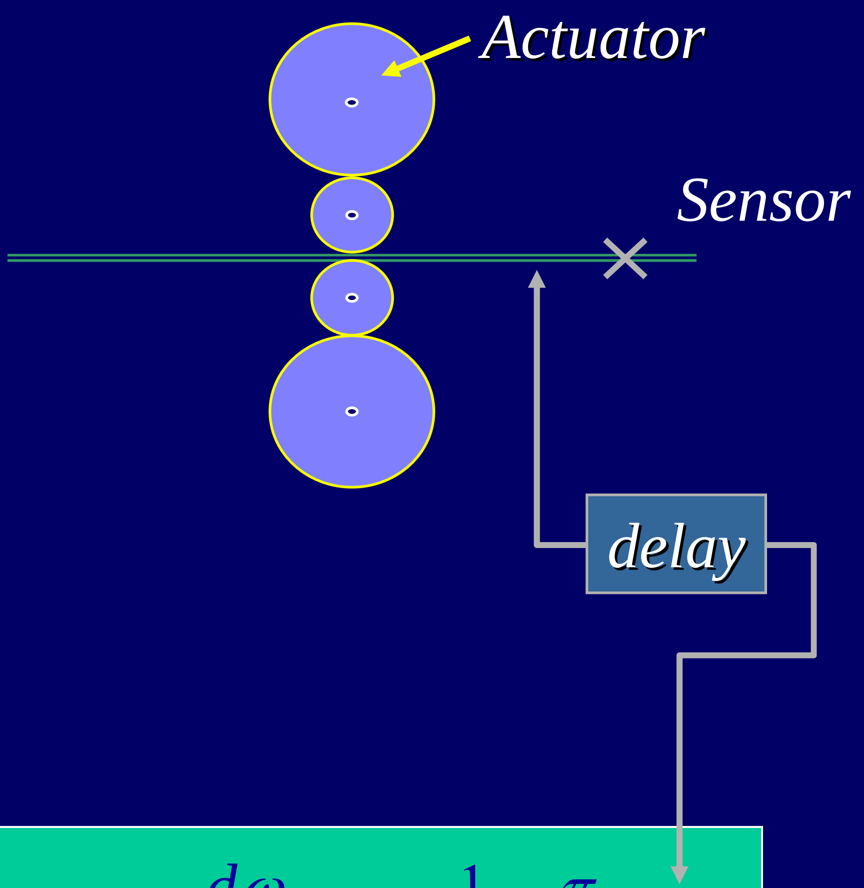
(Example 1) Soft Sensors

Example 1:

Rolling Mill Centre Line Gauge Control



Schematic of Centre Line Gauge Control



Bode:

$$\int \log T \frac{d\omega}{\omega^2} = \pi \sum \frac{1}{z_i} + \frac{\pi}{2} \quad \tau$$

How to avoid fundamental limit?

Change the architecture by using alternate *sensors*

BISRA Gauge (1954)

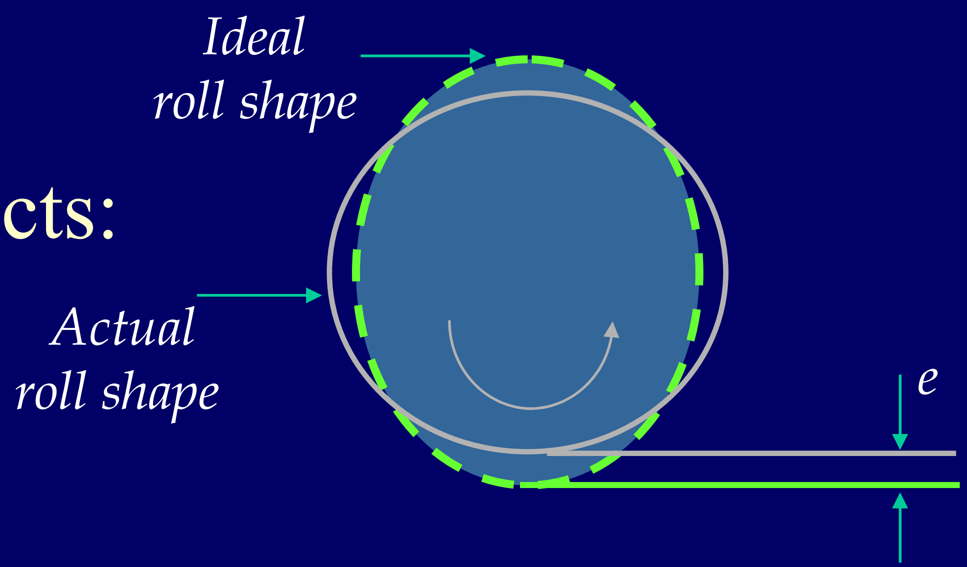
$$F = M(s - h)$$

$$\hat{h} = \frac{F}{M} + s$$

Removes delay

Deterministic Disturbances

Roll Eccentricity Effects:



Roll Eccentricity (slightly exaggerated)

The effect of the roll eccentricity illustrated above is to add an eccentricity term, *e*, to the BISRA gauge equation:

$$F = M(h - s + e)$$

Problem

- Eccentricity acts as measurement error
- Uncontrolled mill gives natural attenuation ($^1/_3$)
- Controlled mill

$$S + T = 1$$

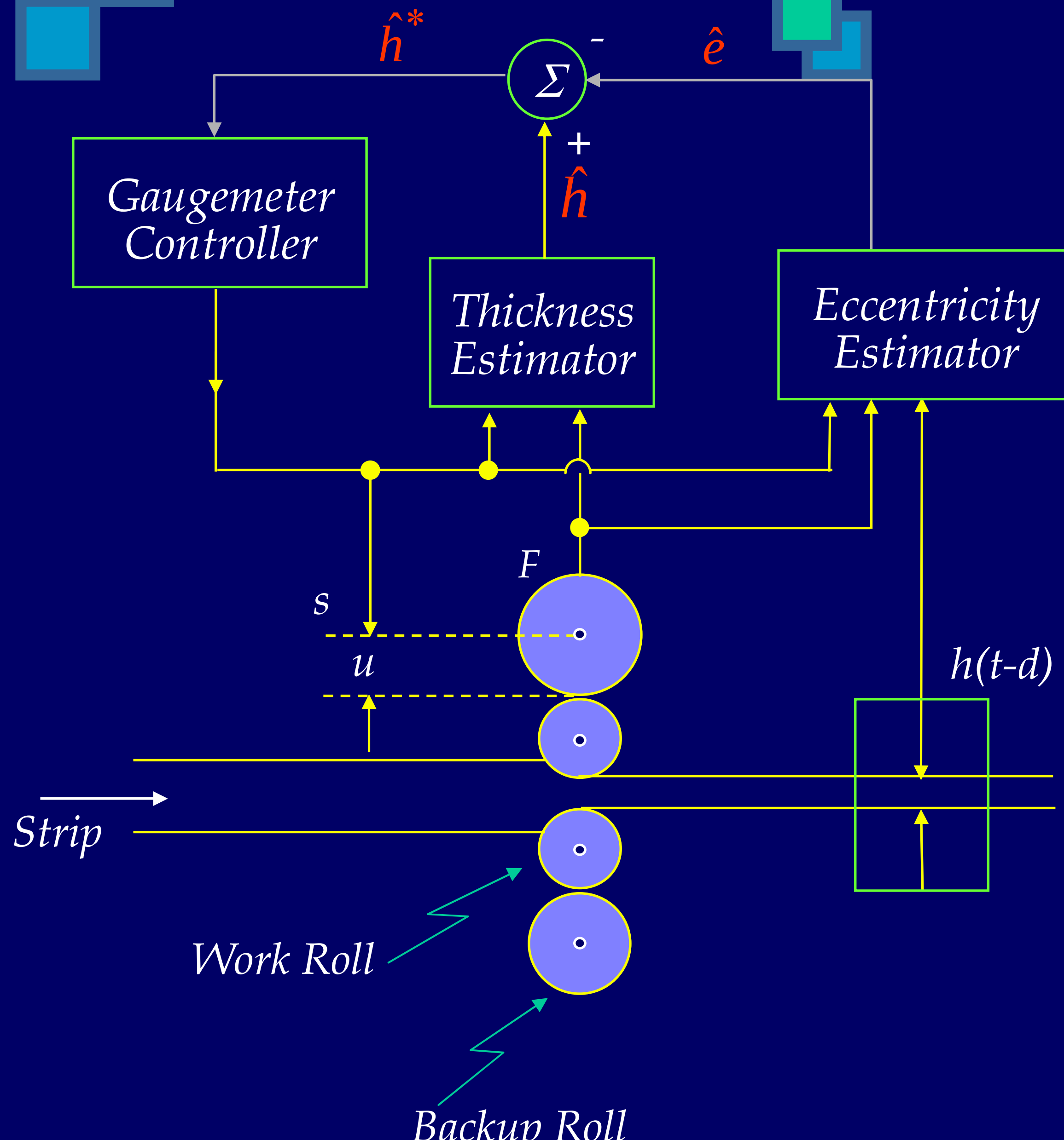
$$S = 0 \Rightarrow T = 1 \qquad (^1/_3 \Rightarrow 1)$$

- Solution ?

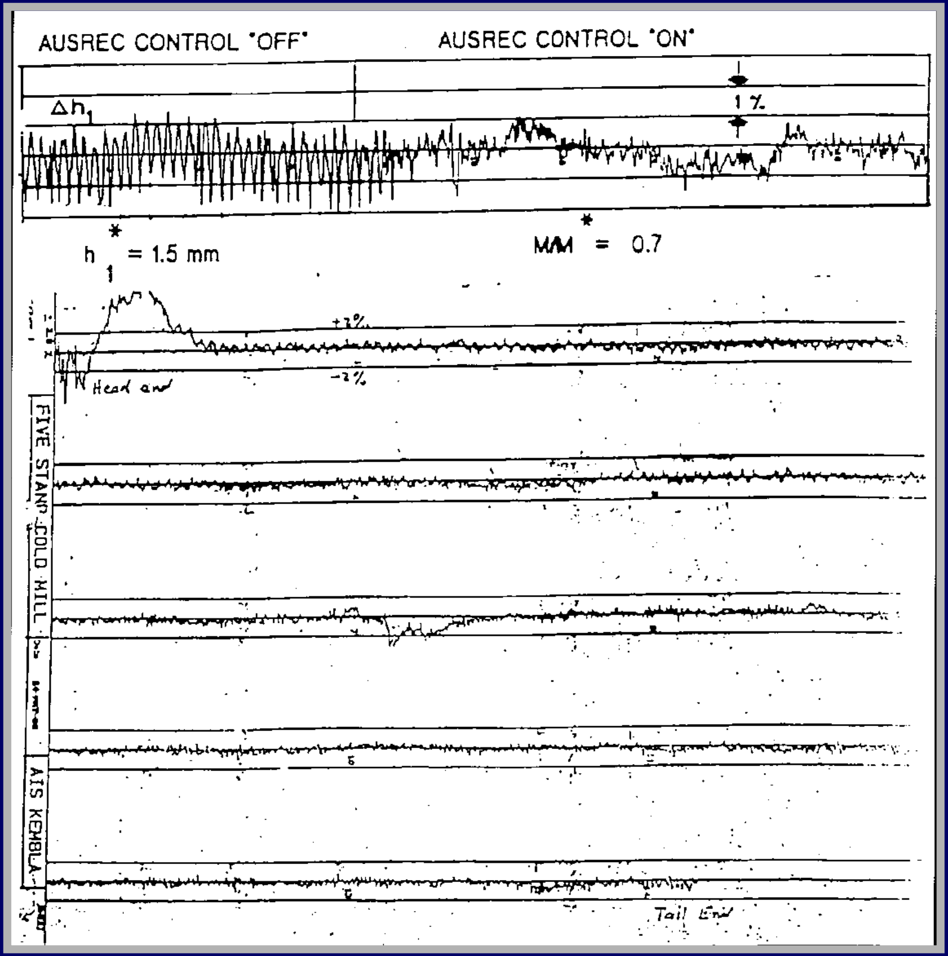
Model as Multiple Sinewaves in Noise

$$y(t) = \sum_{i=1}^{N} A_i Sin(\omega_i t + \phi_i)$$

Apply Kalman Filter to estimate sinusoidal components



$\hat{h}^*$
Σ
-
+
$\hat{e}$
$\hat{h}$
Gaugemeter Controller
Thickness Estimator
Eccentricity Estimator
F
s
u
h(t-d)
Strip
Work Roll
Backup Roll

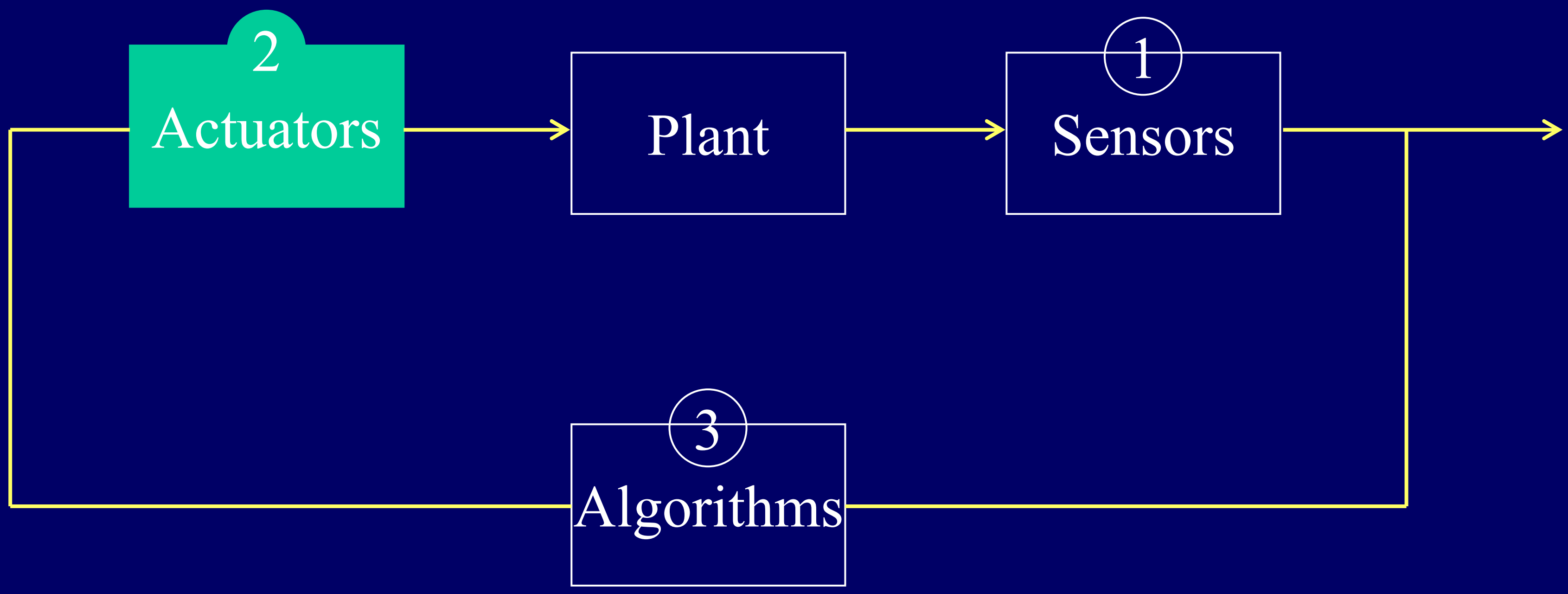


Practical results from a tandem cold mill BHP steel International tinplate mill

Observations from this example:

- Choice of sensor(s) can have a profound effect on achievable performance.
- This is an *architecture* issue that cannot be solved by fancy *optimization* alone!
- Other sensors also possible: mass flow....leads to a nonlinear adaptive controller

Design Issues in Control



Actuators

Actuators are the muscle of control.

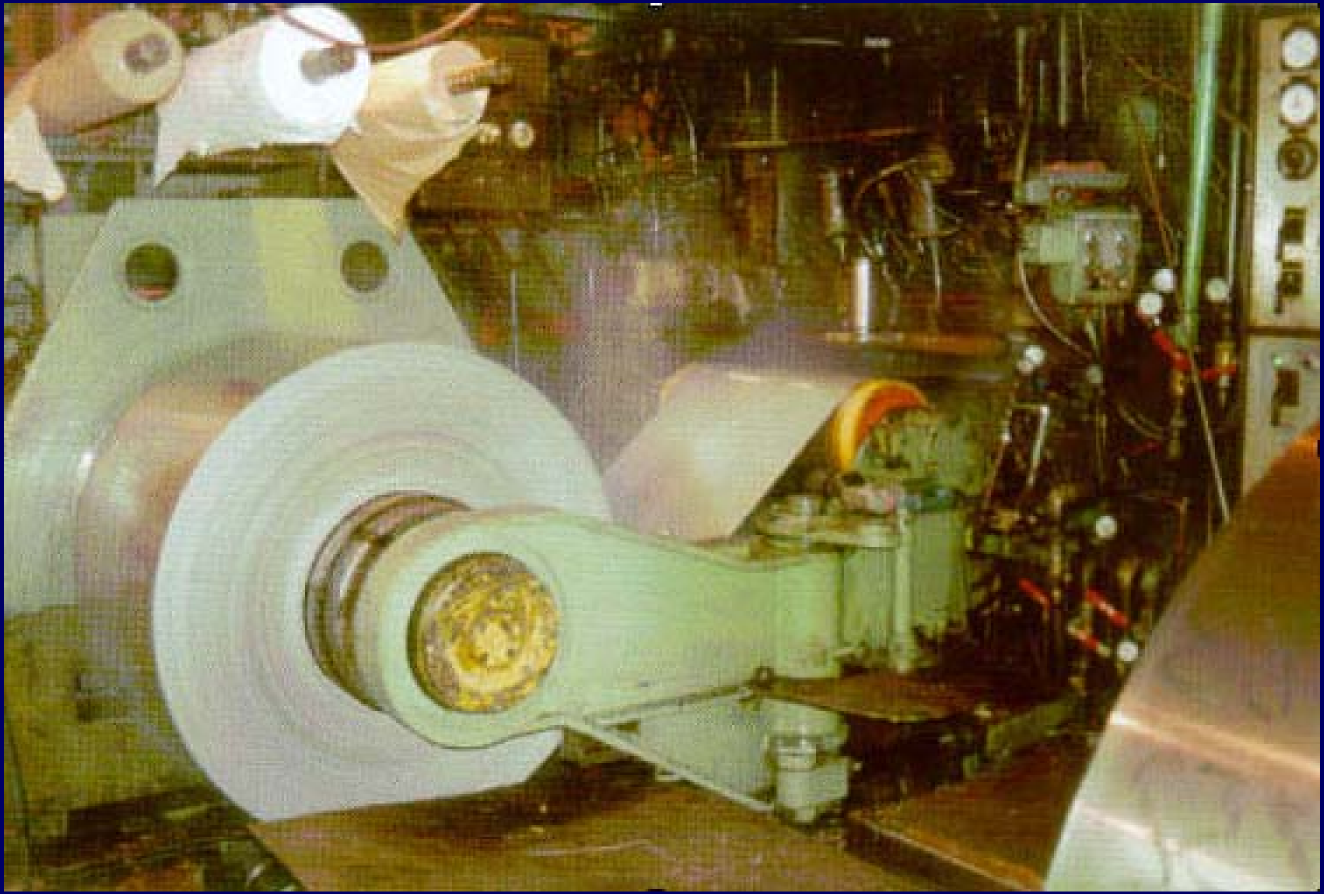
Poor muscles $\longrightarrow$ Poor control

2. Actuators

- (Example 2) One Actuator or two?
- (Example 3) Actuator Limitations

Example 2:

Hold-up Effect in Reversing Mills.



The good news

$\Rightarrow$ "Measure" h to 0.1% accuracy

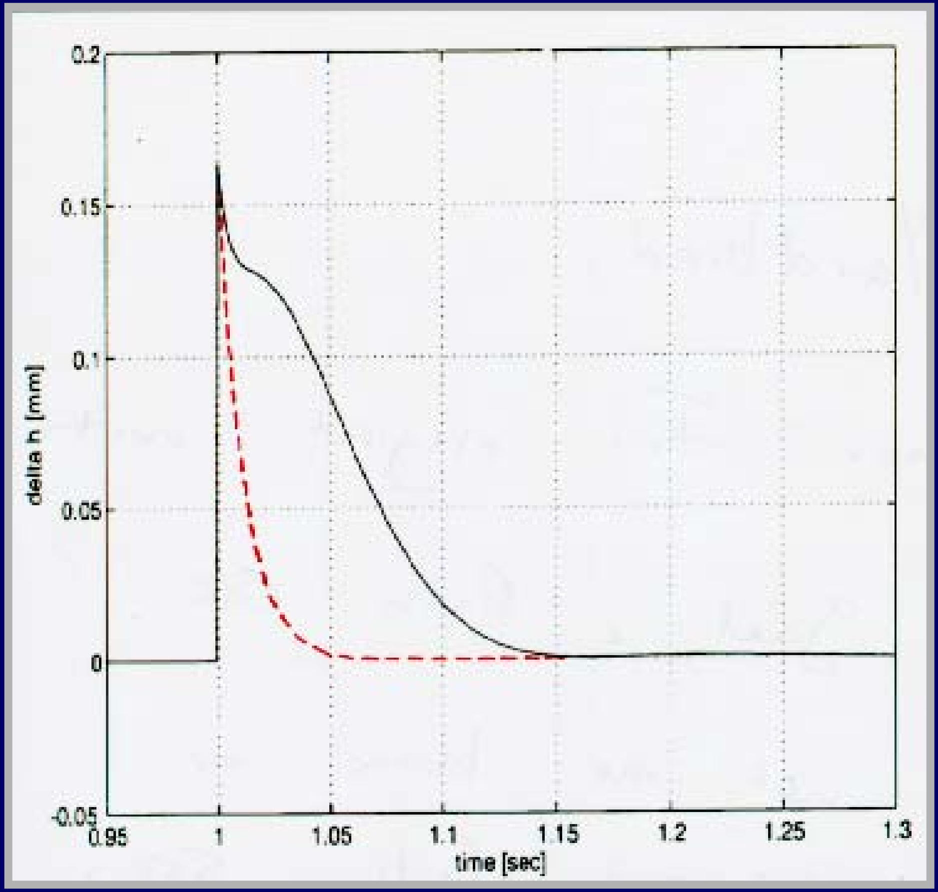
(Sensor ✓)

+

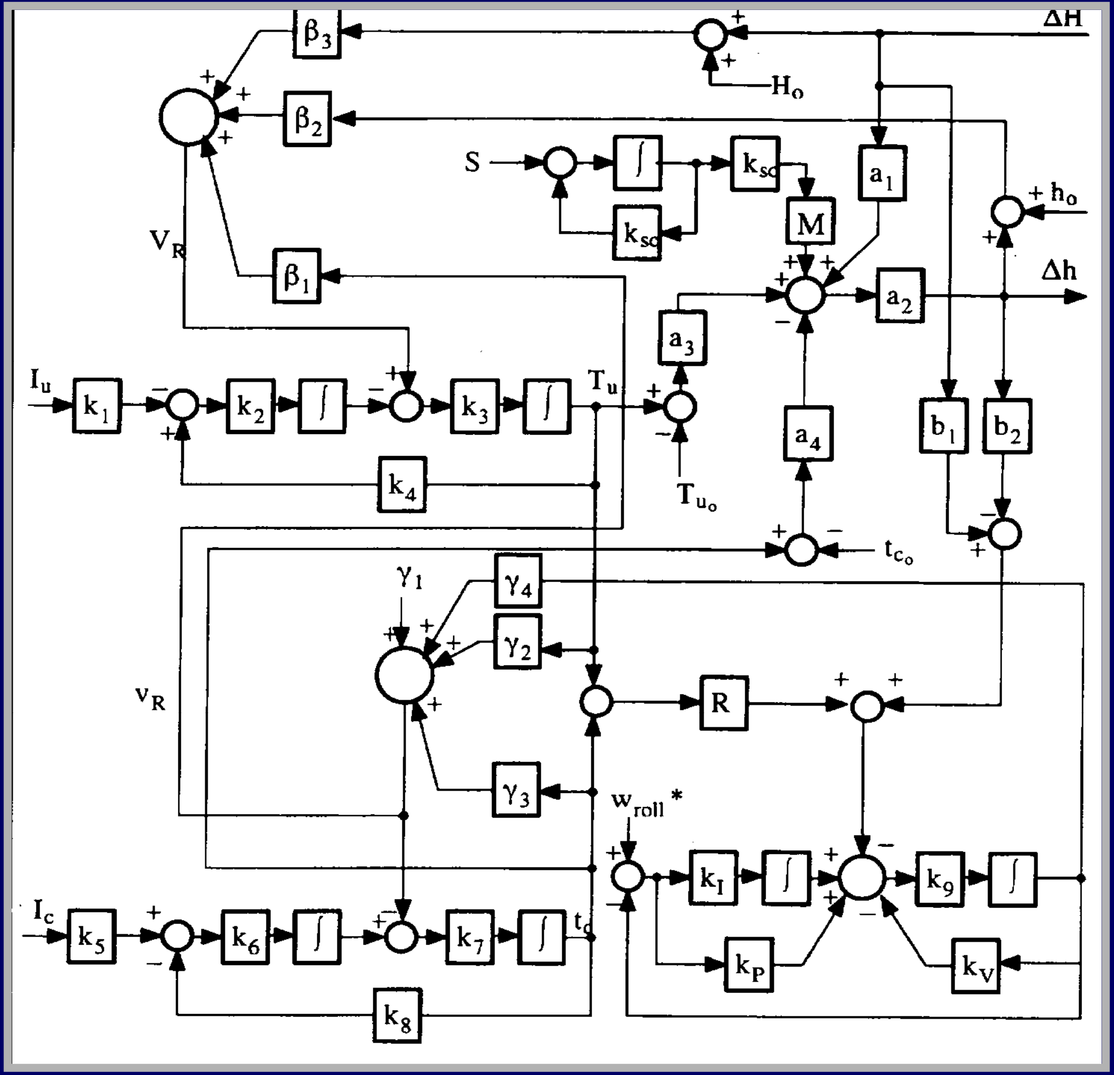
High Speed Hydraulic actuators (7 msec. response times)

(Actuator ✓)

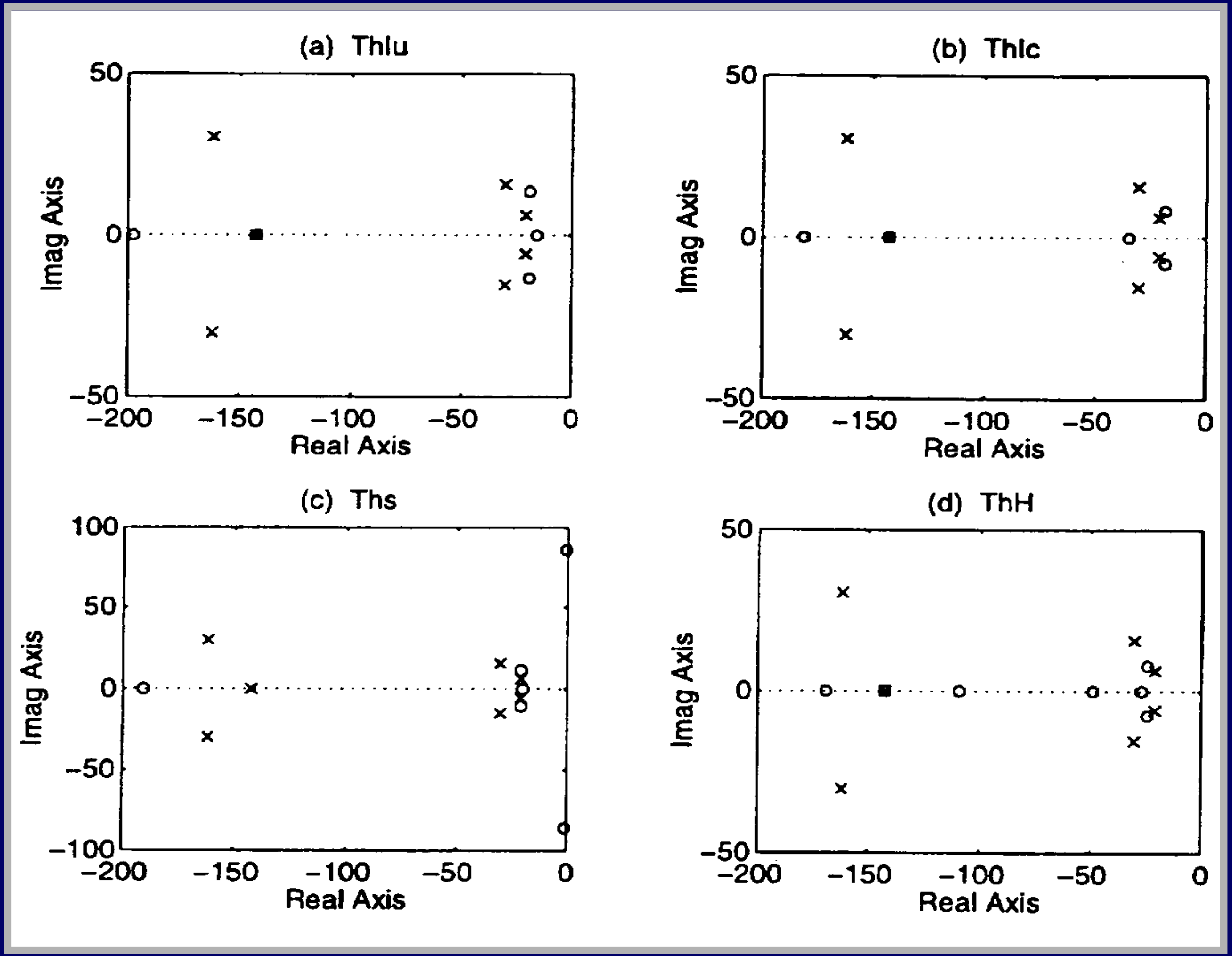
The bad news: *Performance is disappointing*



Attempt to use Screw Alone



Linearized model blockmodel



Poles and zeros configuration of linear model

Fundamental Limitations

Zeros at $\pm j\omega_0$

$$\int e^{-st} e(t) dt = E(s)$$

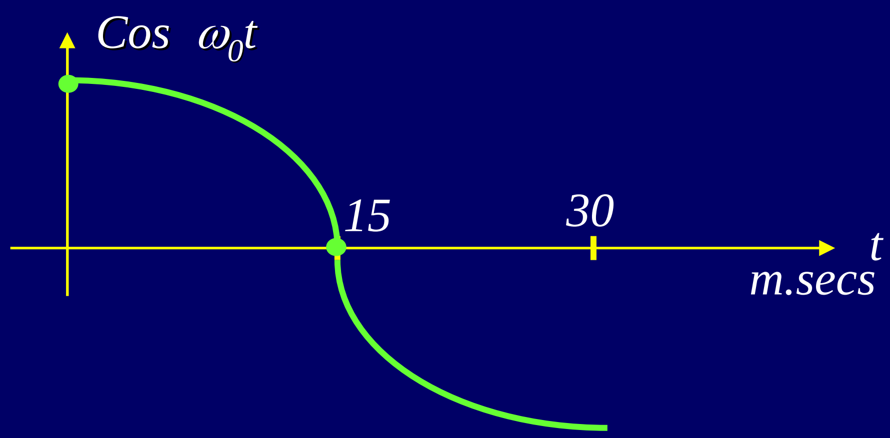
$$= \left[1 - T(s)\right] \frac{1}{s}$$

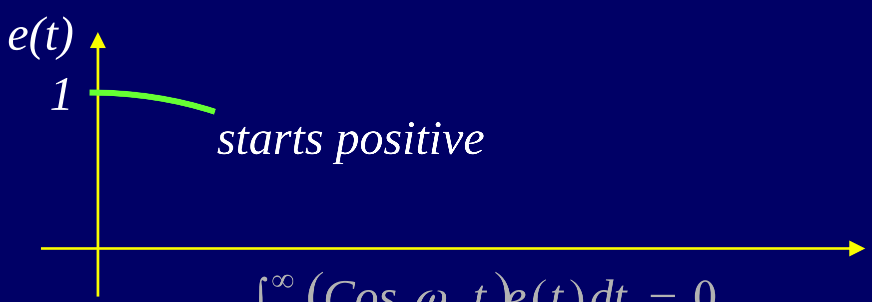
At $s = \pm j\omega_0$

$$\int e^{\mp j\omega_0 t} e(t) dt = \frac{1}{\pm j\omega_0}$$

$$\int [\cos \omega_0 t]\, e(t)\, dt = \frac{1}{\omega_0}$$

In our case $\omega_0 = 90$ rad sec^{-1}





$$\int_0^\infty (\cos \omega_0 t)\, e(t)\, dt = 0$$

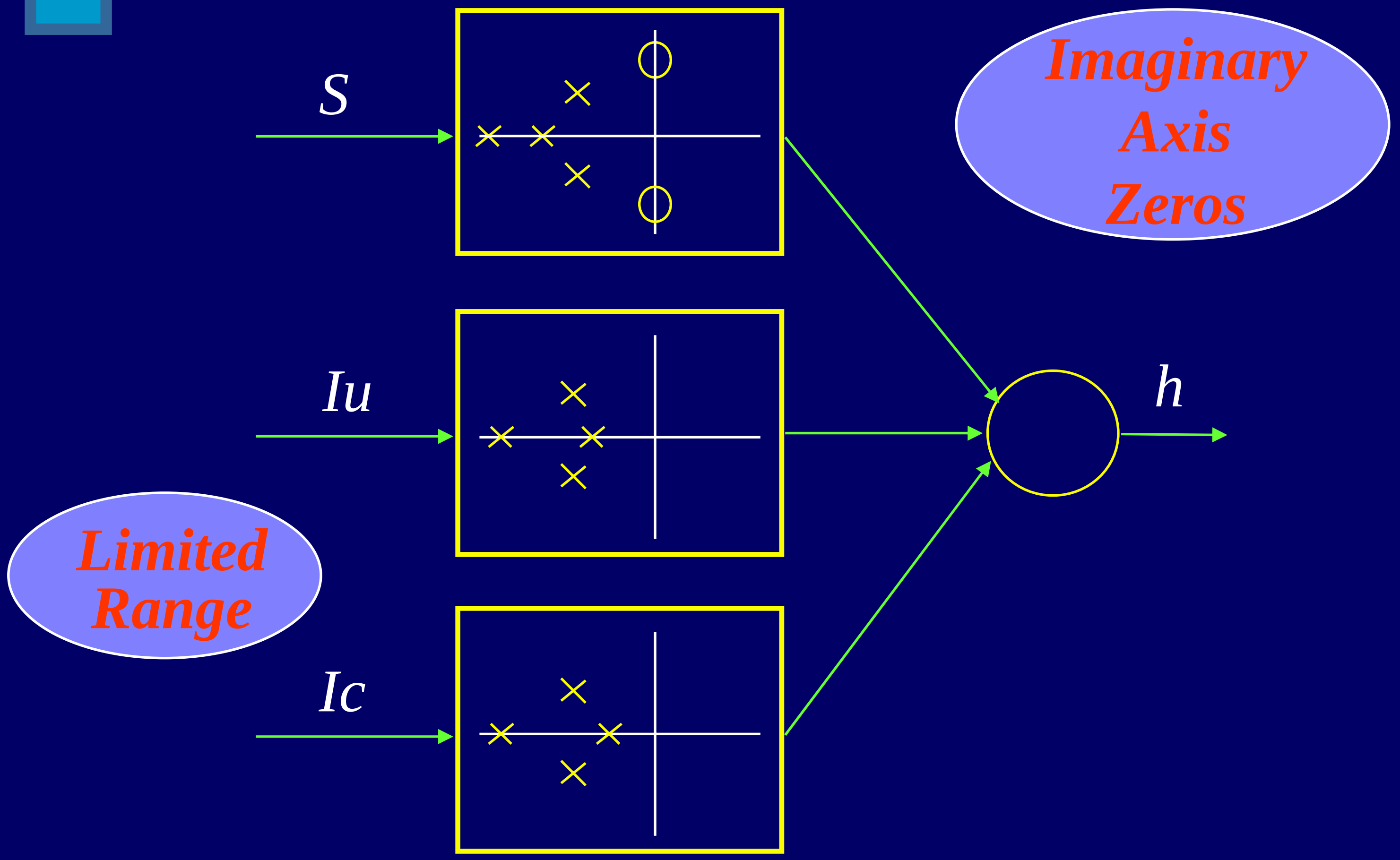
Only 2 Possibilities

- $e(t)$ changes sign quickly with large -ve values

or

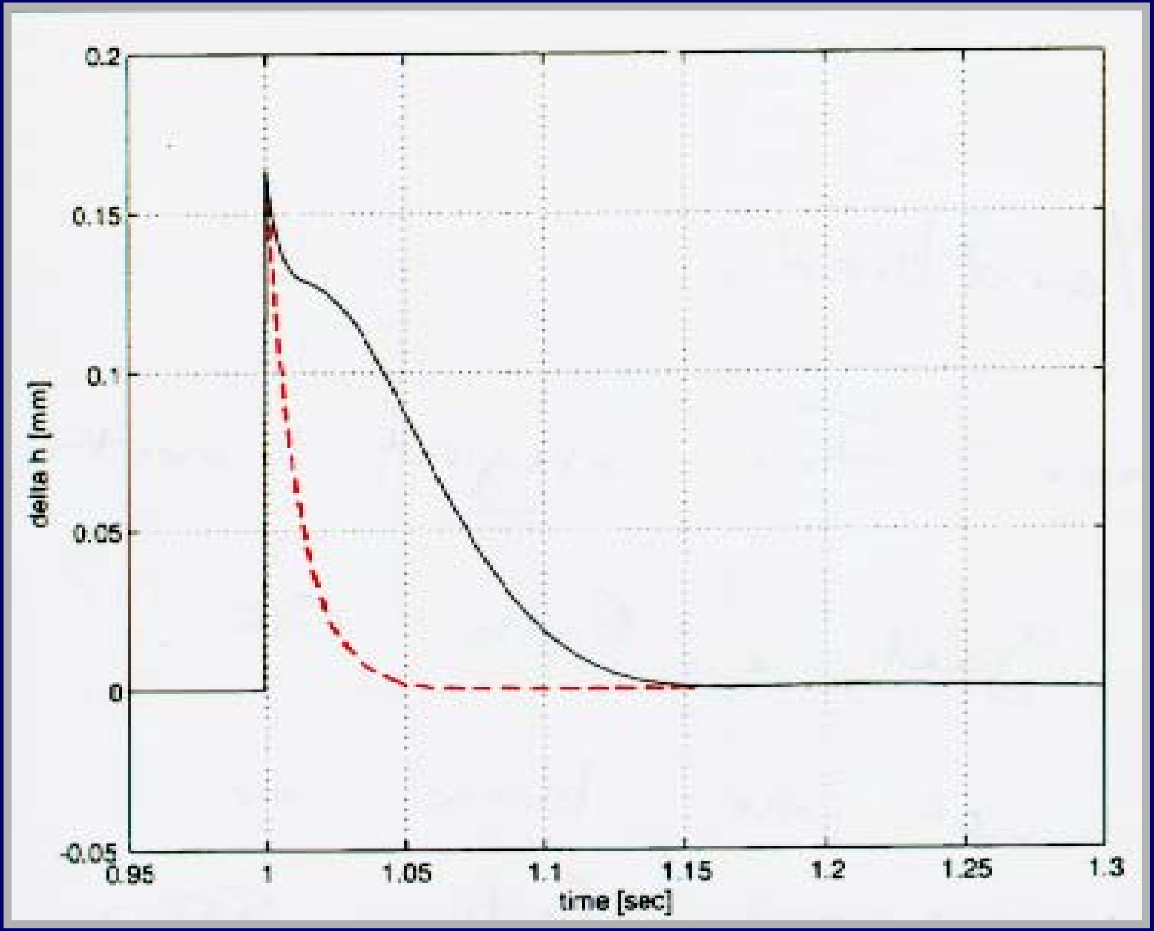
- $e(t)$ remains large in the period 15-30 msec.

- Physical explanation!



Change the Architecture

Result with Coordinated Controller



Observations from this example:

- Choice of actuator(s) can have a profound effect on achievable performance
- Again, this is *architecture* not *optimization* !

2. Actuators

(Example 2) One Actuator or two?

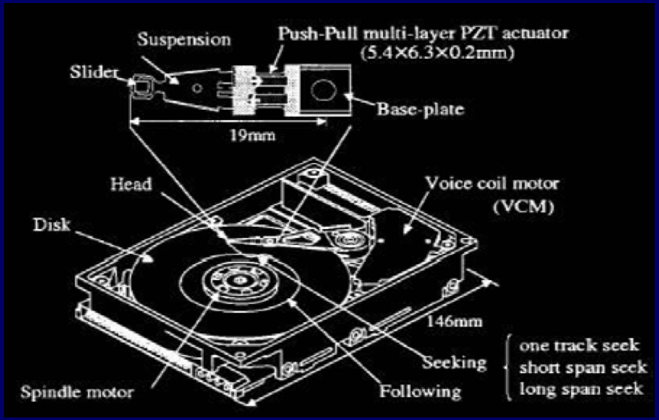
(Example 3) Actuator Limitations

Example 3: *Dual-stage systems*

Consisting of two control actuators:

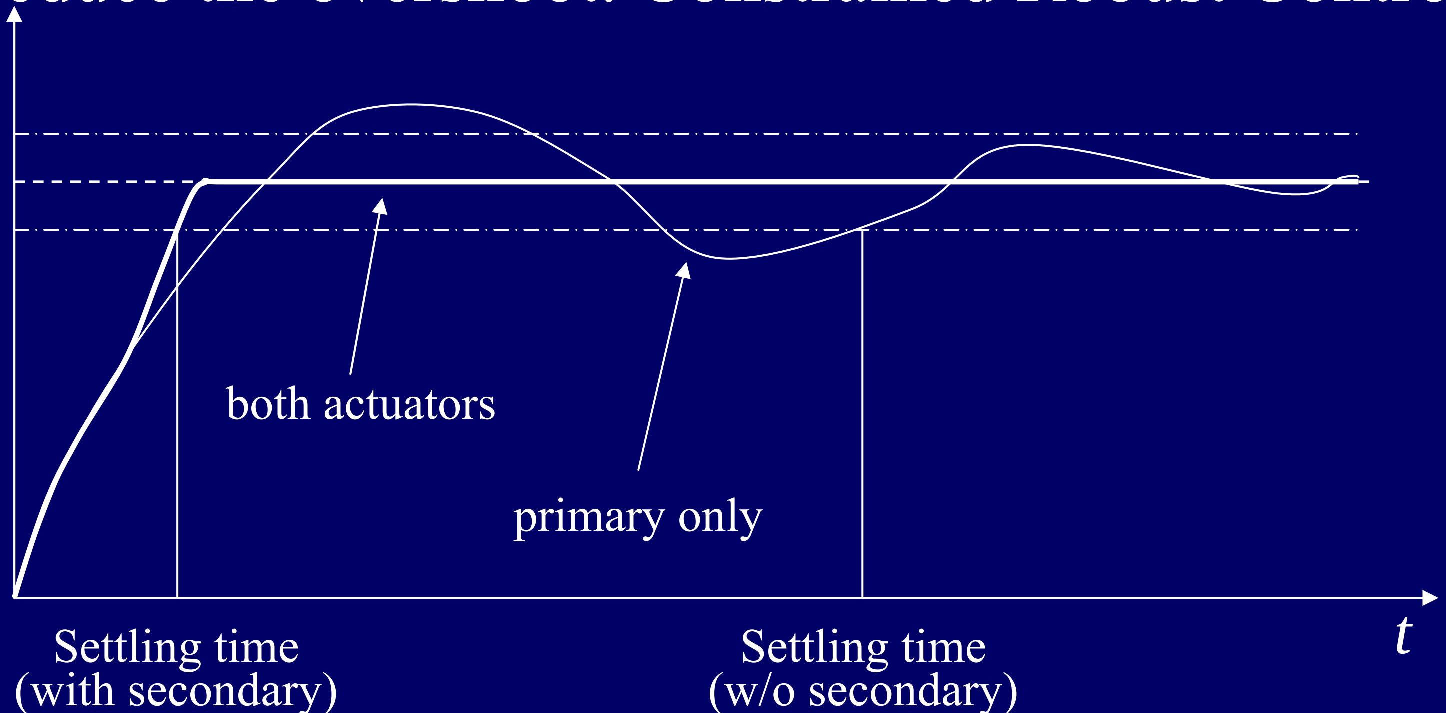
- **Base actuator:** Providing long range, low precision, low bandwidth manoeuvres
- **Micro-actuator:** Providing micro-range, high precision, high bandwidth manipulations

Purpose: Long range, high precision, high bandwidth actuation.

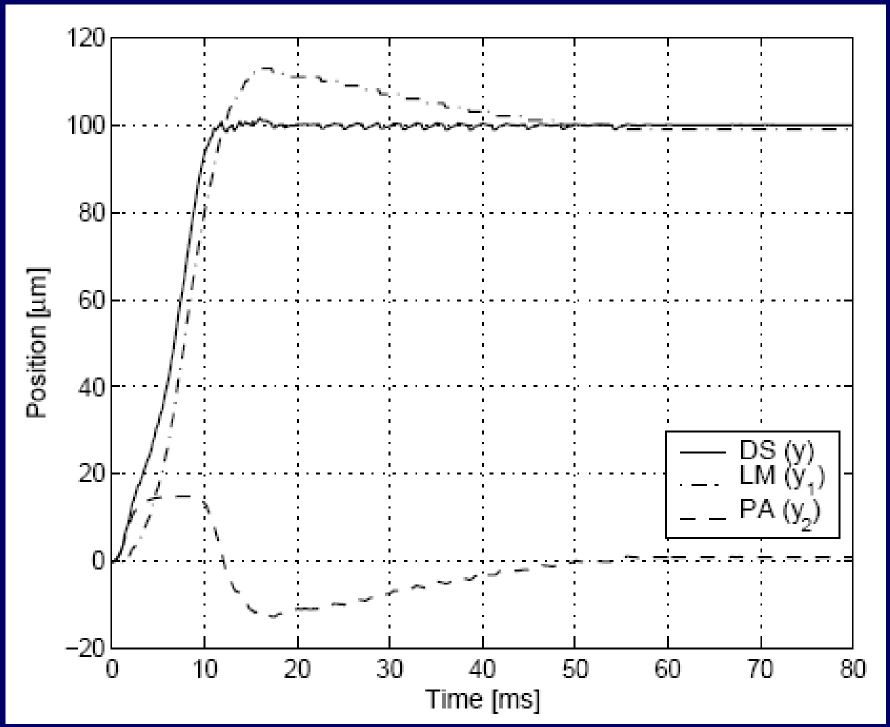


Optimal design (*rough idea*):

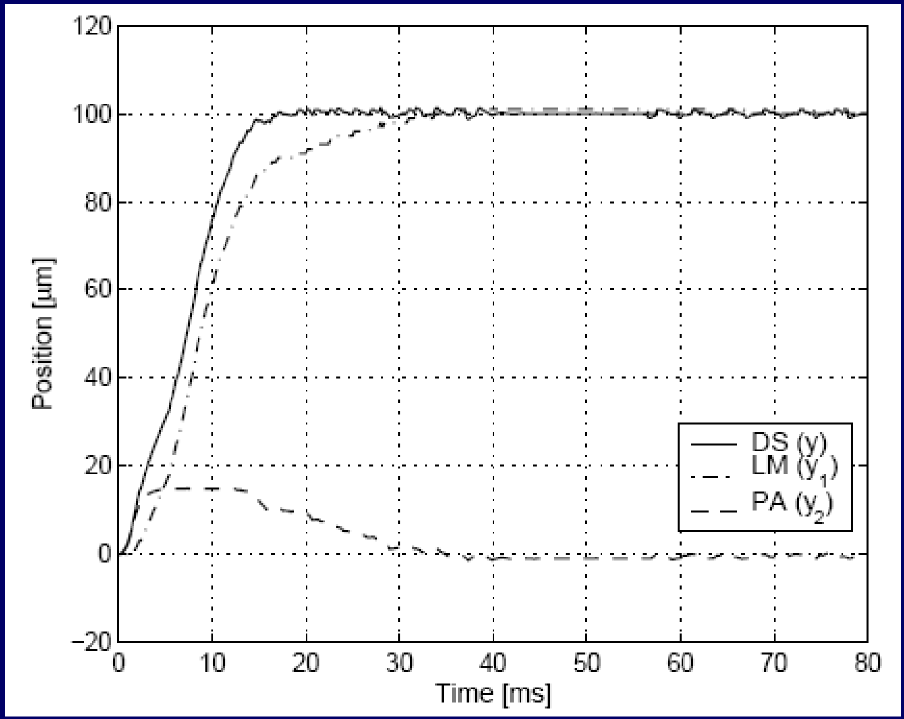
Design the primary actuator controller to yield a closed-loop system for faster rise time by allowing some overshoot, and asking the secondary actuator controller loop to reduce the overshoot. Constrained Robust Control.



Experimental Results: *Travel range = 100 μ*

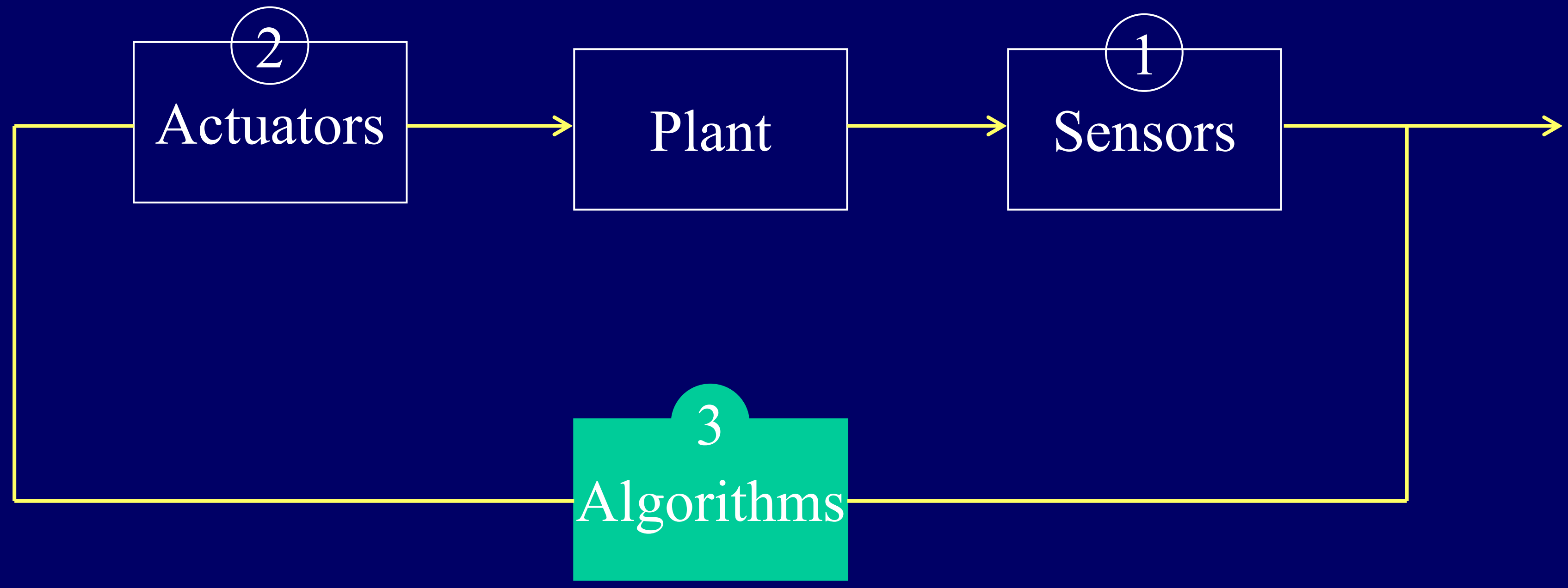


Proposed control
(settling time = 11msec)



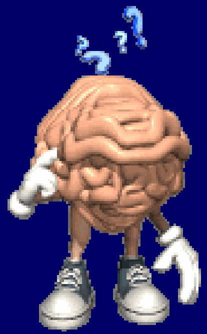
Conventional control
(settling time = 16.5msec)

Design Issues in Control



Algorithms

- Algorithms are the intelligence of control



Poor Intelligence

⟶ Poor Control

3. Algorithms

- (Example 4) Plant Wide Control Control

(Example 5) Accounting for inescapable actuator/sensor limitations

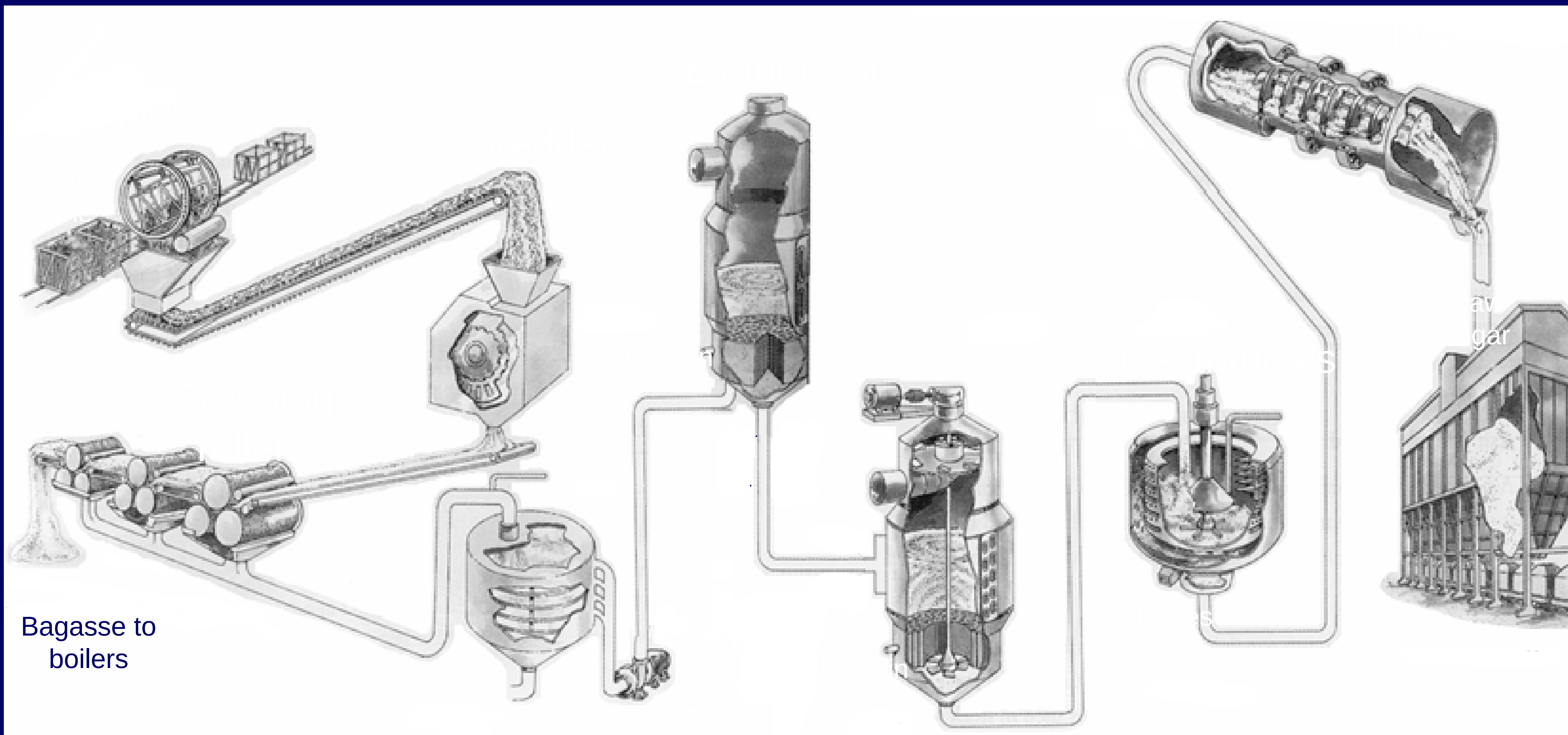
Plant Wide Control:

Simplistic Viewpoint: Centralized control solves all control problems

- Measure everything and use it to calculate what to do.
- In practice one always needs to make decisions about
  - what sensors?
  - what actuators ?
  - how to interconnect ?

Non convex - so Physical insight crucial

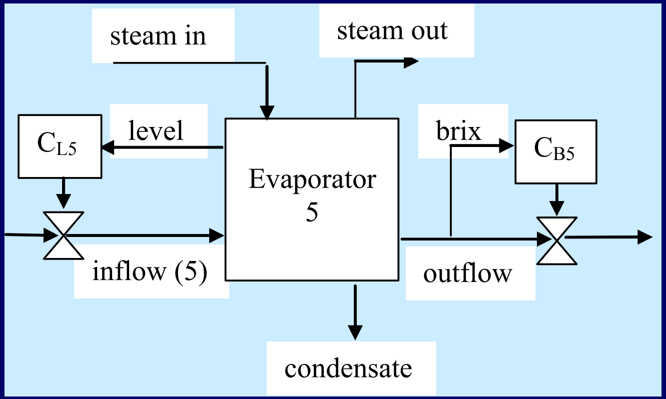
Example 4: Plant Wide Control of *Sugar Mill for co-generation…need greater stability. Brix (Concentration) control in Evaporators*



Clarifiers

Vacuum pans

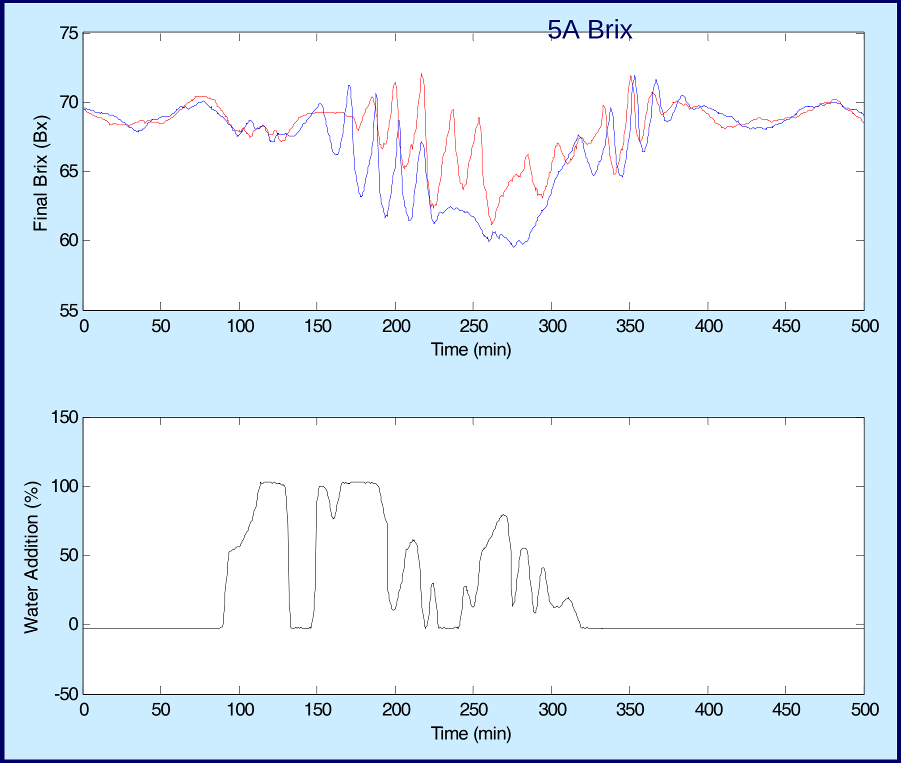
Current Evaporator Control



- Level in each vessel is controlled
  - Optimum level for heat transfer
  - Controlled by a valve effecting *inflow*
- Final brix controlled
  - Maintain a high concentration (Brix)
  - Controlled by a valve effecting *outflow*

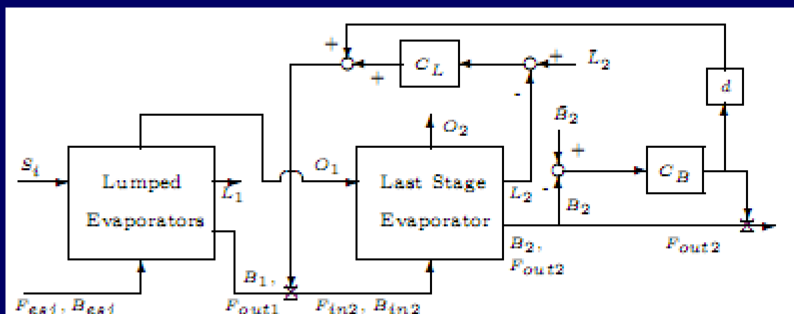
- Only PI and PID controllers are used for controlling the evaporator set
- The existing control was adequate in context of co-generation.

Short Period Oscillations



- Examination of historical data, short period oscillations are preceded by water addition
- Usually occurs during extended periods when the crushing mill is stopped
- Leads to the liquid flowing into the final effect having a much lower concentration than normal

Improved the Control



$$\begin{bmatrix} F_{in}(t) \\ F_{out}(t) \end{bmatrix} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \begin{bmatrix} u_l(t) \\ u_b(t) \end{bmatrix}$$

$u_l(t)$ = Output of level controller

$u_b(t)$ = Output of brix controller

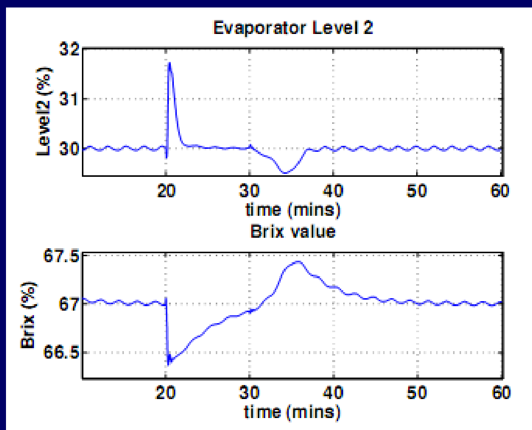
- Interaction between level and brix controllers evident from trends during periods of water addition
- Want to decouple the two controllers
- Can be done in the simulation with

$$d = \frac{\frac{\left(1 - f(L(t))\frac{h_{out}}{h_v}\right)}{E_{vol}}}{\frac{\left(1 - f(L(t))\frac{h_{in}}{h_v}\right)}{E_{vol}}} = \frac{h_v - f\left(L(t)\right)h_{out}}{h_v - f\left(L(t)\right)h_{in}}$$

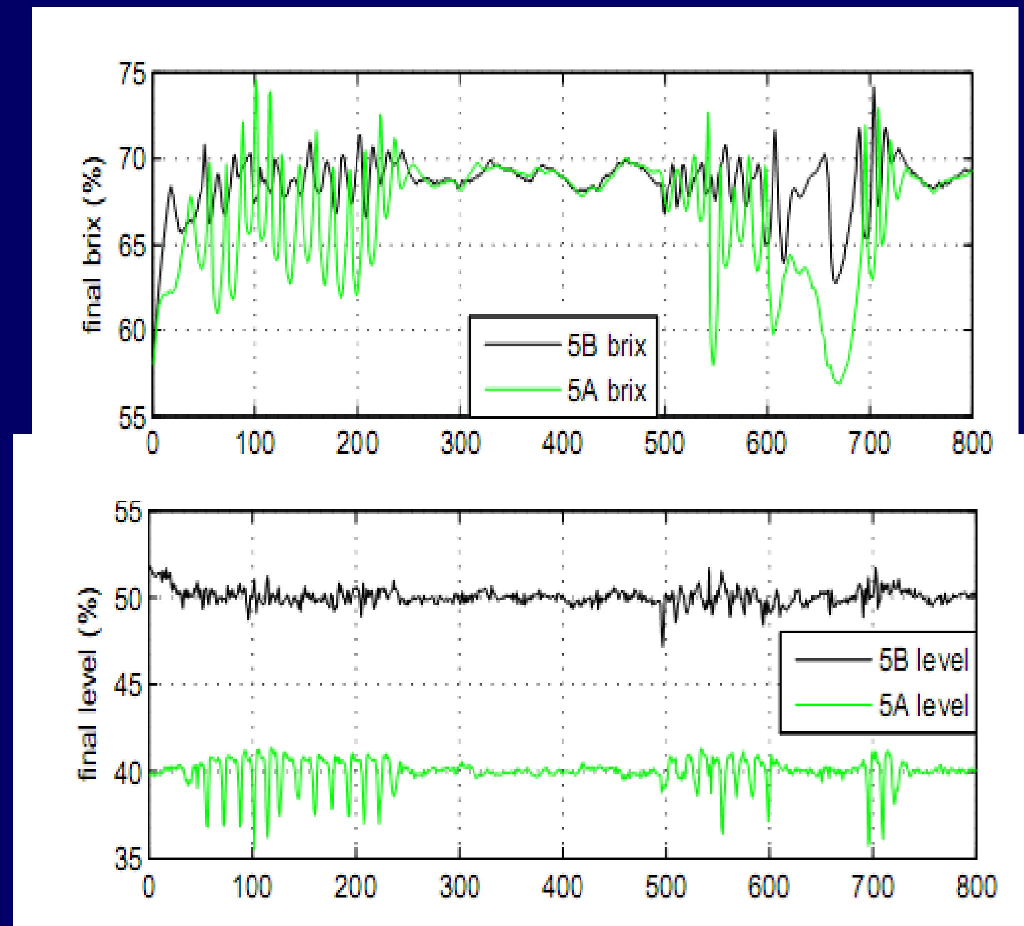
(Assumes flow characteristics for inflow and outflow of evaporator are identical)

Results of New Control: better evaporator control + feedforward

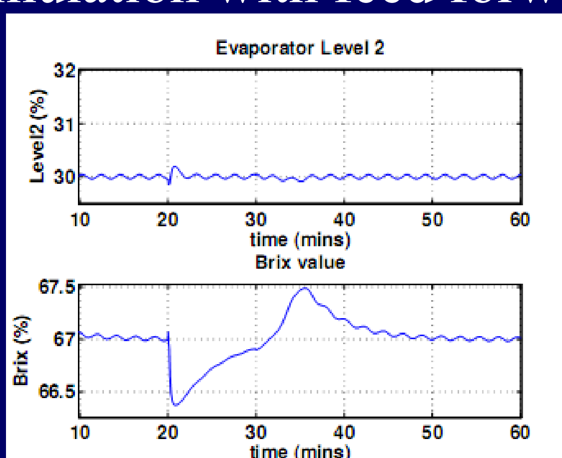
Simulation without feed forward



Logged data from plant



Simulation with feed forward



Observations from this example:

- Choice of connections can be more important than optimizing the parameters within a given architecture.

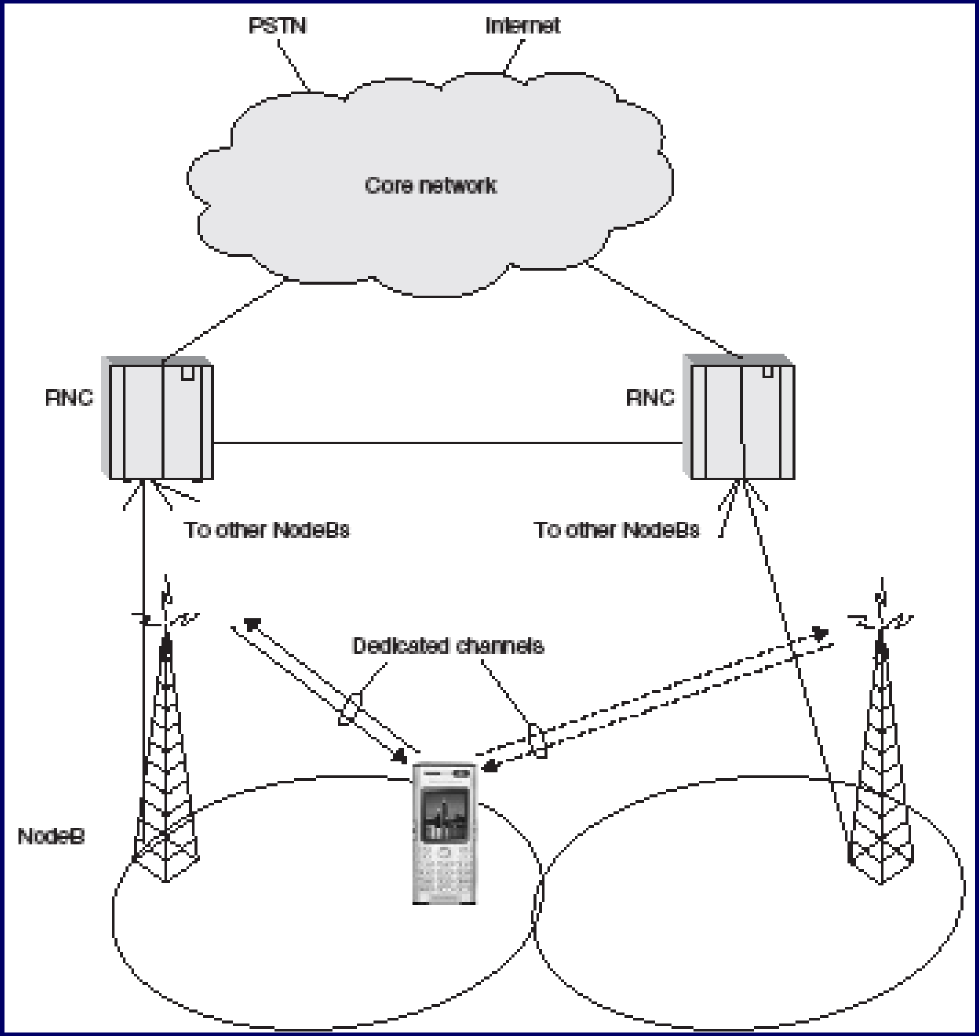
3. Algorithms

(Example 4) Centralized Control

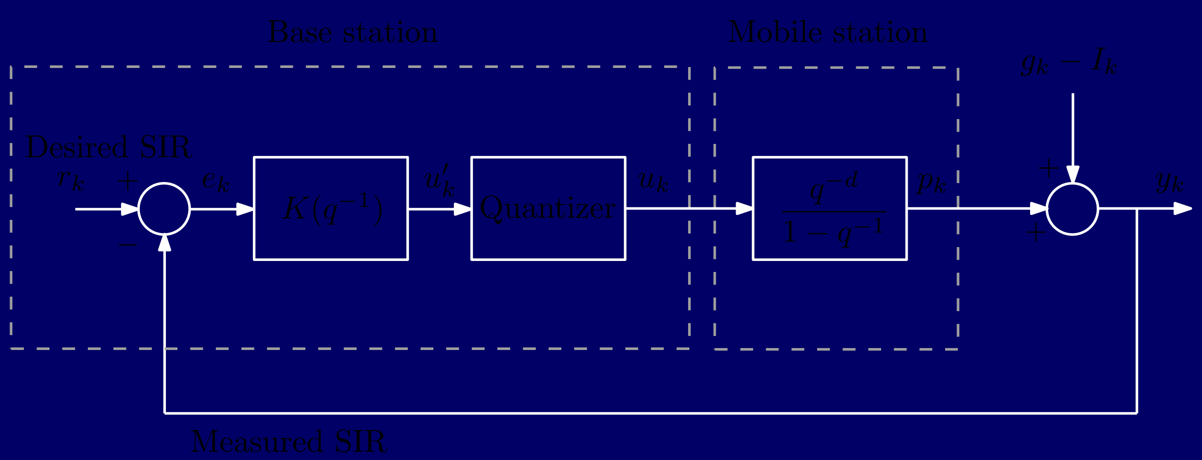
(Example 5) Accounting for inescapable actuator/sensor limitations

Example 5

Three-degree-of-freedom inner-loop power Control in WCDMA



- Typical inner power control loop



q^{-1} = backward shift operator

p_k = transmitted power

g_k = gain

I_k = interference

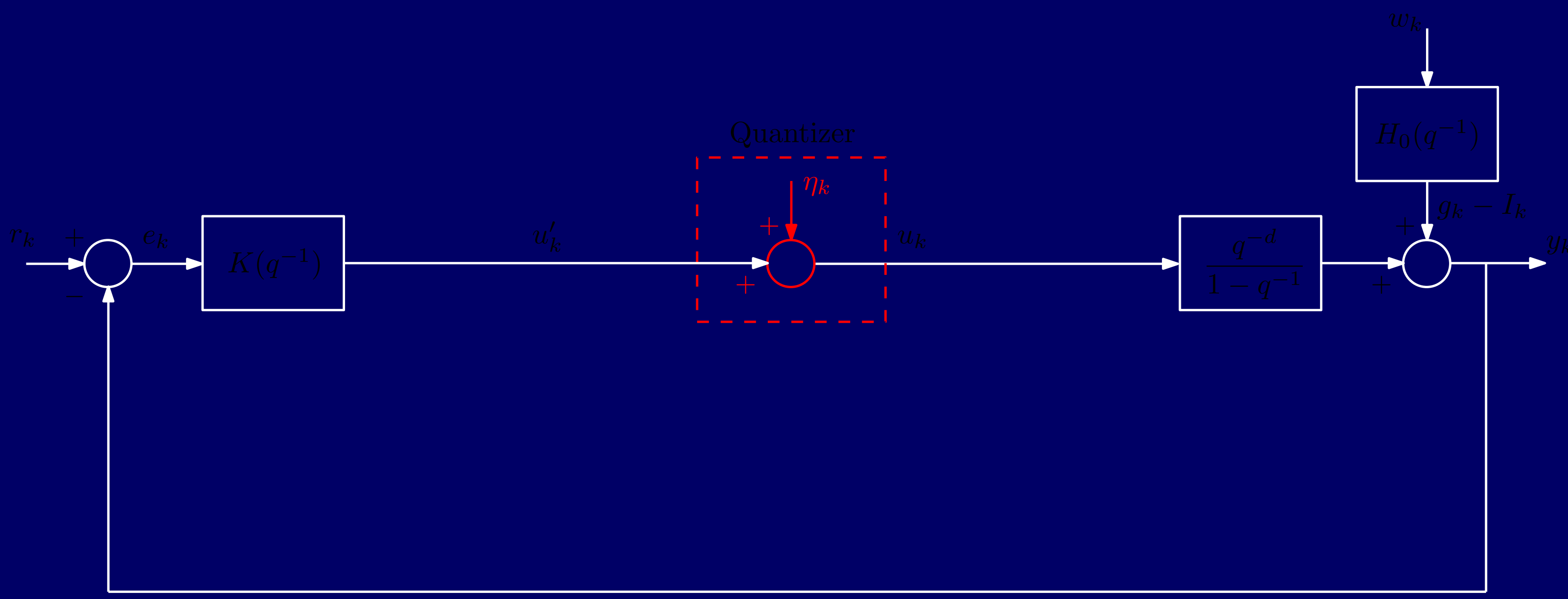
y_k = SIR

r_k = desired SIR

u_k = power increment

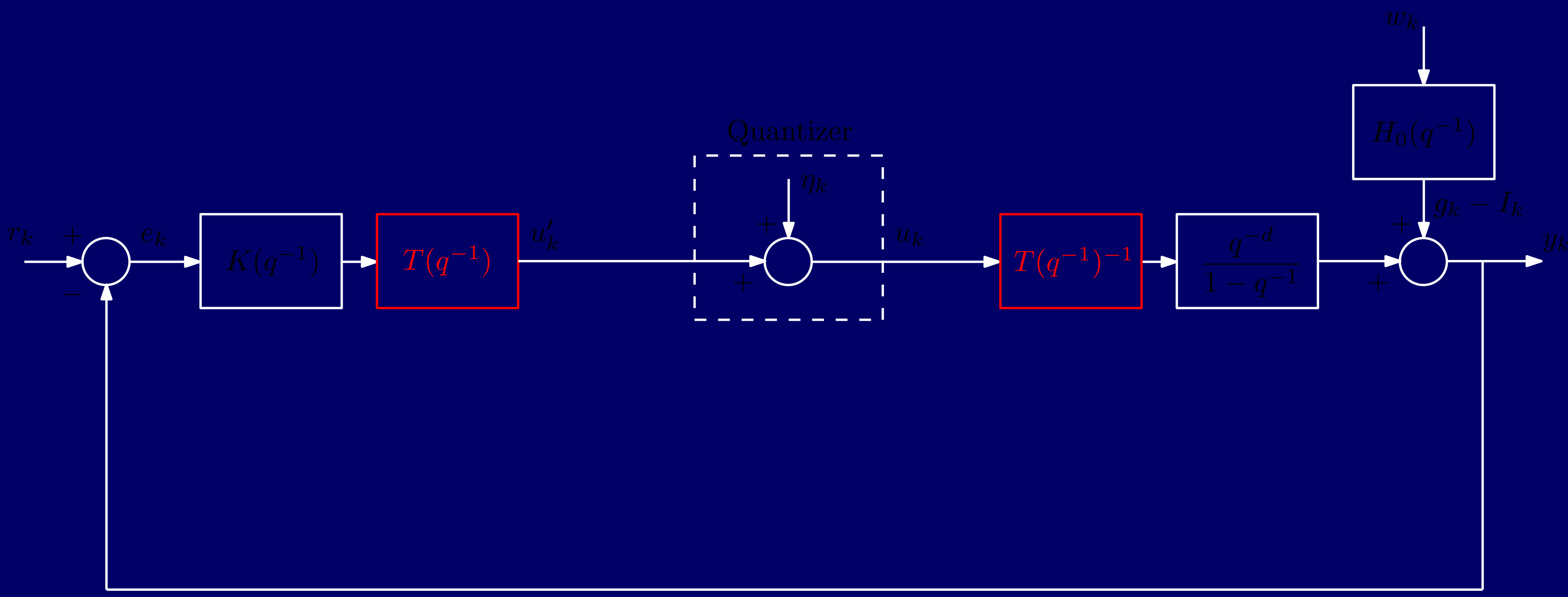
- The inner loop power control signal is transmitted as 1 bit, *i.e.* $\pm$ 1 dB.
- This represents a major and inescapable limitation.

1st DOF



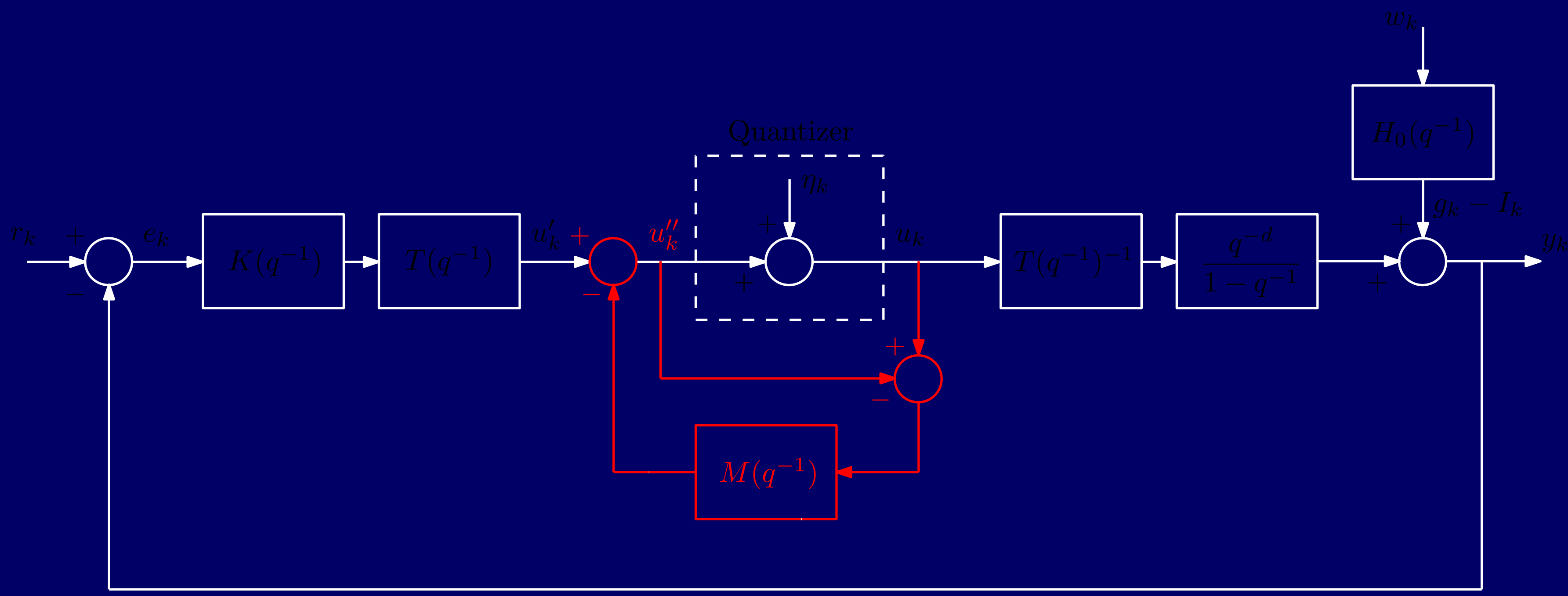
- Treat the quantizer as a noise source
- Model $g_k - I_k$ as $H_0(q^{-1})w_k$
- $K(q^{-1})$ affects $w_k \rightarrow y_k$, $\eta_k \rightarrow y_k$, $w_k \rightarrow u'_k$

2nd DOF



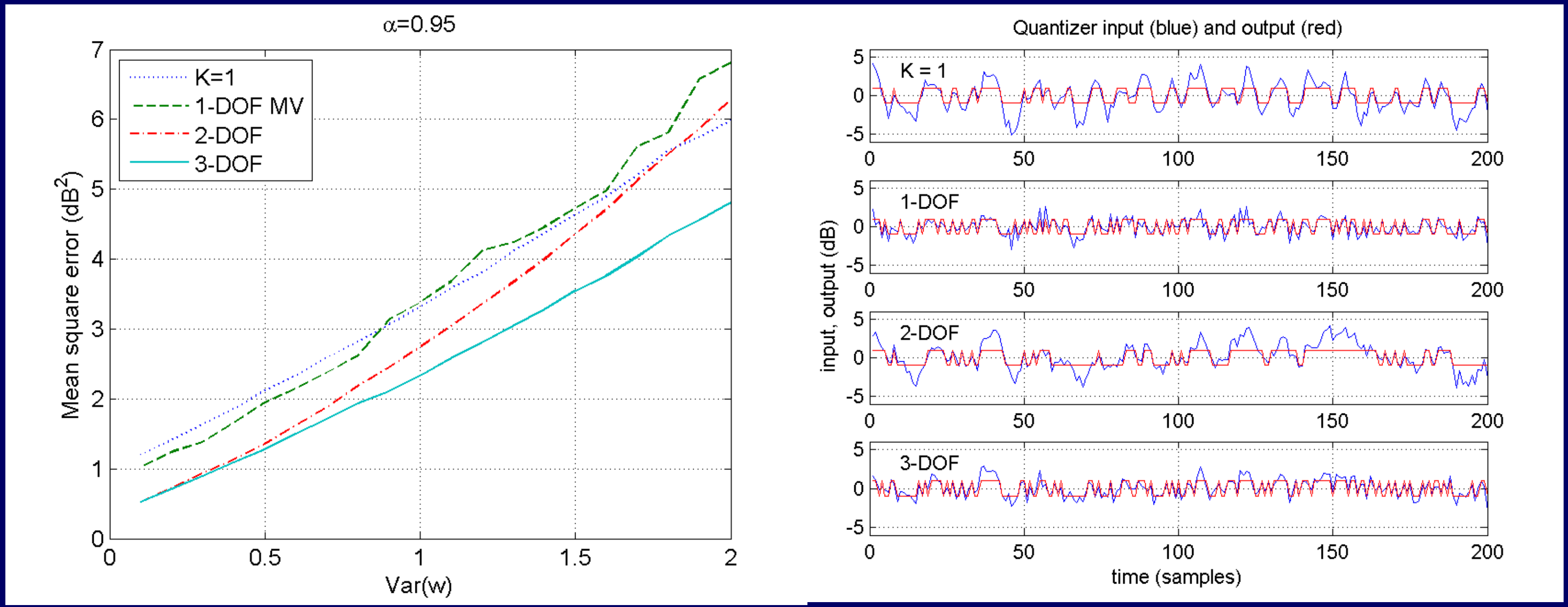
- $T(q^{-1})$ and $T(q^{-1})^{-1}$ do not affect $w_k \rightarrow y_k$
- $T(q^{-1})$ and $T(q^{-1})^{-1}$ do affect $\eta_k \rightarrow y_k$, $w_k \rightarrow u'_k$

3rd DOF



- $M(q^{-1})$ does not affect $w_k \rightarrow y_k$, $w_k \rightarrow u''_k$
- $M(q^{-1})$ does affect $\eta_k \rightarrow y_k$

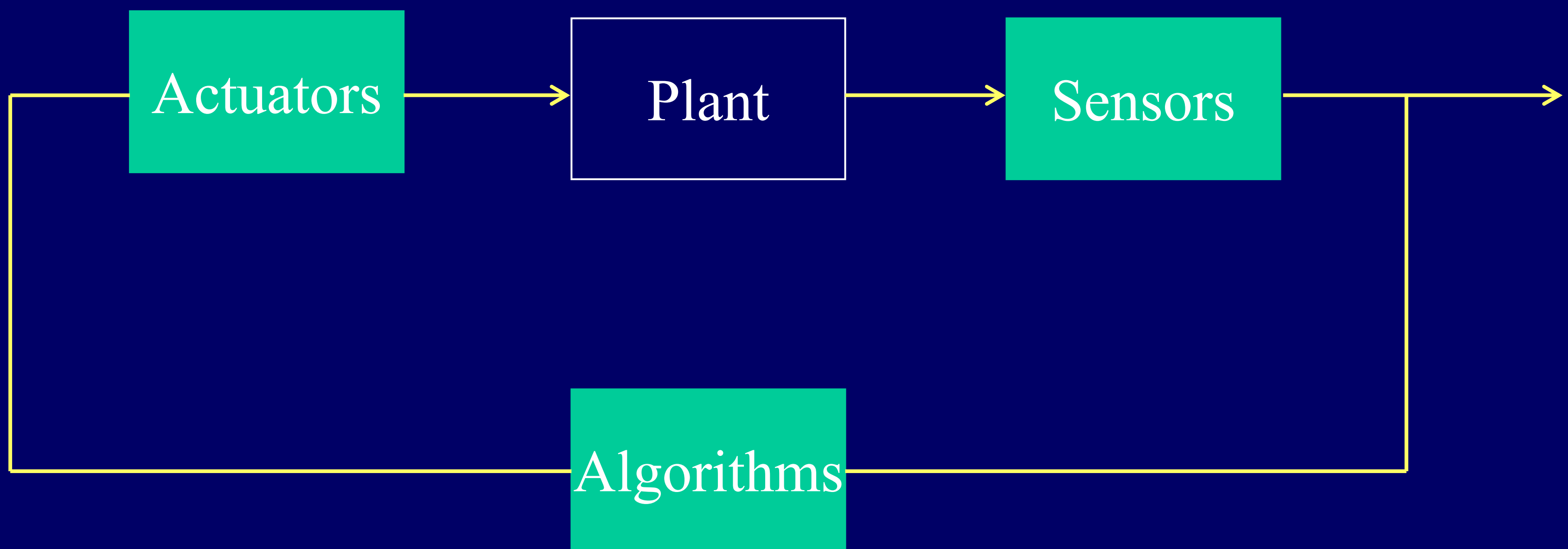
Results



- 1-DOF not much better than: $K(q^{-1}) = 1$.
- 2-DOF better at low noise $(g_k - I_k)$ levels but not at high noise levels.
- 3-DOF best (uniformly).
- Poor performance of 2-DOF due to quantizer overload.

Conclusions

Design Issues in Control



- Control is exciting and important
- Ever expanding opportunities (My Current interests: Telecommunications, Emergency Services, Smart Grid)
- Optimal choice of parameters within a given architecture is important
- However, choosing the architecture is often even more important
- Sensors, Actuators, Algorithms all play a role
- Crucial step is to understand Fundamental Limitations

- Lessons for Industry
  - Most dramatic improvements often come by "looking outside the box" – ie by changing the Architecture
- Lessons for Academics and Students
  - Maybe we need to develop new paradigms for teaching control which place greater emphasis on architecture .
  - Understanding what cannot be done

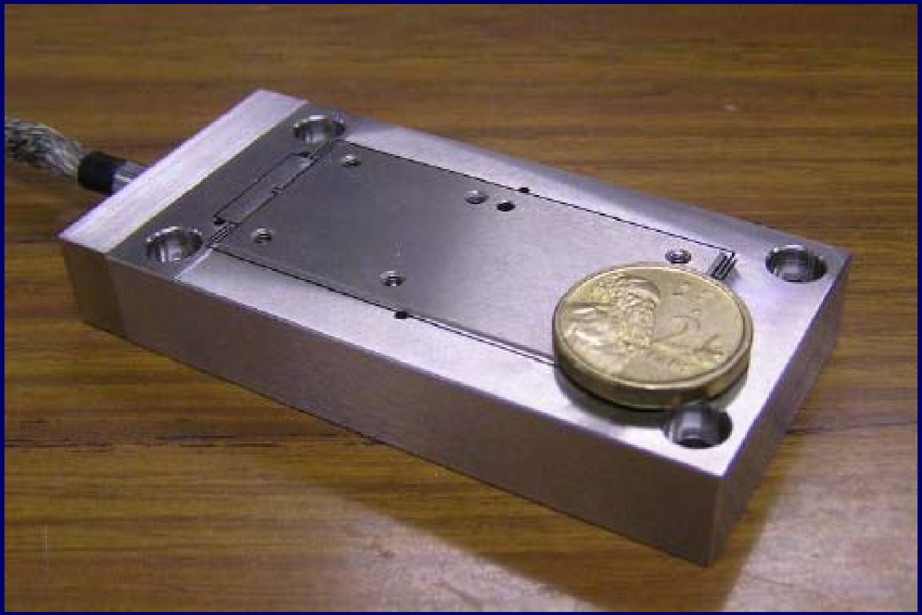
    (and why) is frequently more important than optimizing within a given architecture


Tack Så Mycket

Linear Motor:

- 500 mm travel range
- 1 μm resolution, glass scale encoder,
- power amplifier

Piezoelectric Transducer:



- ±15 μm travel range
- 0.2 nm resolution, capacitive position sensor
- piezoelectric amplifier