Automatic supervision of control loops

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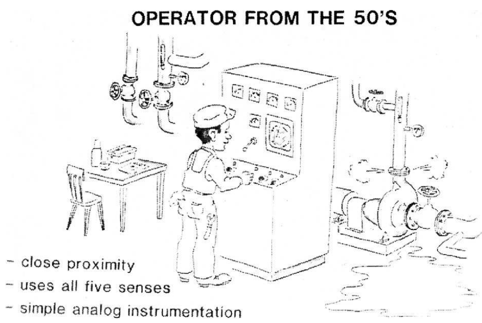
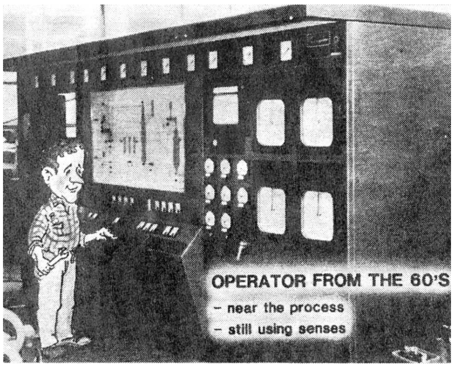
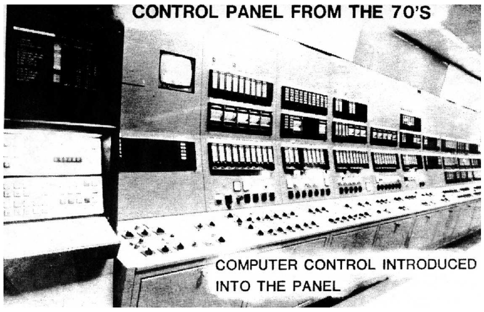
The automation trend



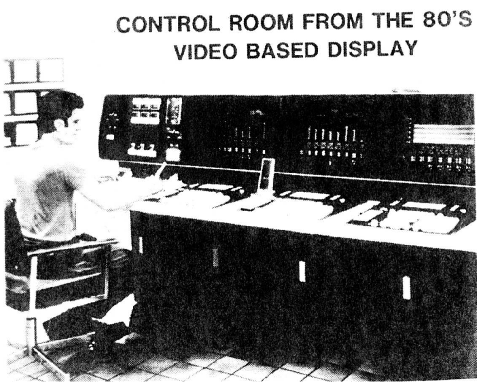
The automation trend



The automation trend



The automation trend



The automation trend

- Fewer operators
- More to supervise
- Control rooms ⇒ sight, hearing, smelling are not used anymore
- More complicated processes
- Higher quality demands

Automatic performance monitoring

- We have improved process control.
- We have lost human performance monitoring.
- We need automatic performance monitoring.

Reasons for poor control loop performance

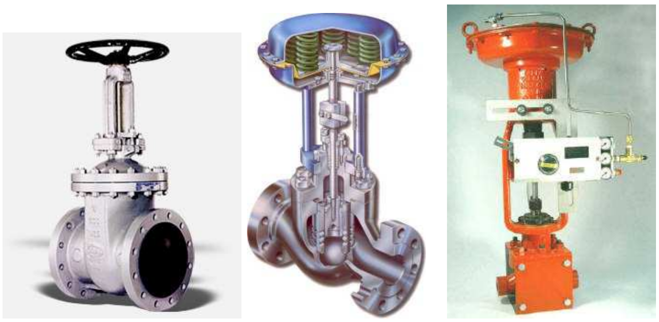
- Equipment problems
  - Stiction in valves
  - Backlash in valves
  - Sensor faults
- Poor controller tuning
  - Never tuned?
  - Nonlinear plant
  - Time-varying plant
- Oscillating load disturbances

Stiction and backlash in control valves

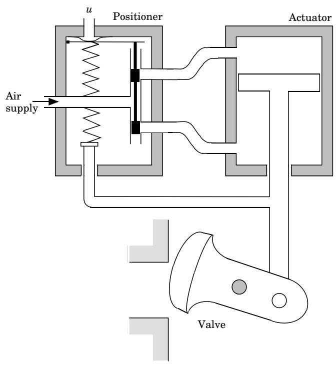
Paper-mill audit: About 30% of all control loops suffer from these problems.

“The single most important cause of process variability in process control.”

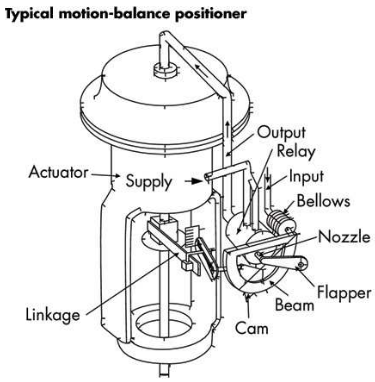
The control valve



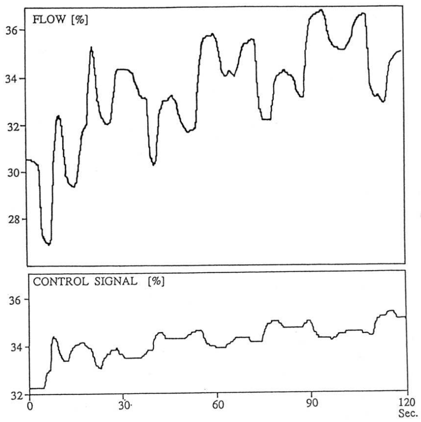
The control valve



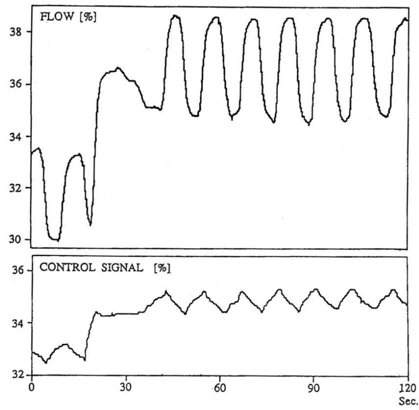
The control valve



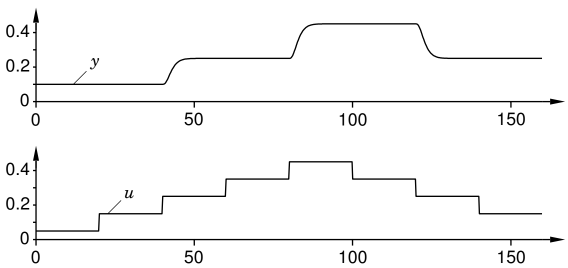
Friction in valves



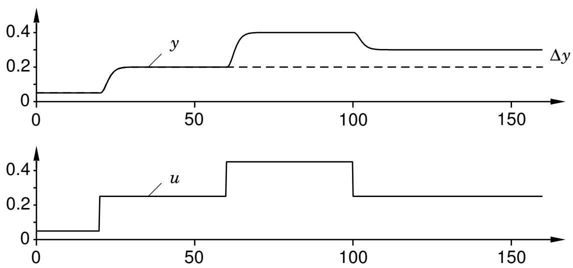
Friction in valves



Diagnosis of friction



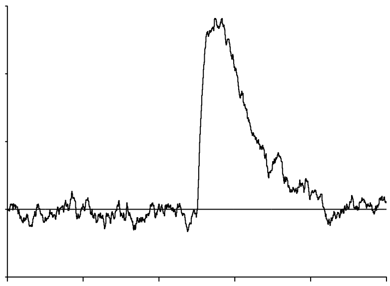
Diagnosis of backlash



Three monitoring tools

- Detection of oscillating control loops
- Detection of sluggish control loops
- Detection of backlash in control loops

Oscillation detection



Oscillation detection

Determine

$$IAE = \int_{t_{i-1}}^{t_i} |e(t)| dt$$

between zero crossings of the control error.

Good control: IAE small

Load disturbances: IAE large

Oscillation detection

The loop is oscillating if the *rate* of load disturbances becomes high.

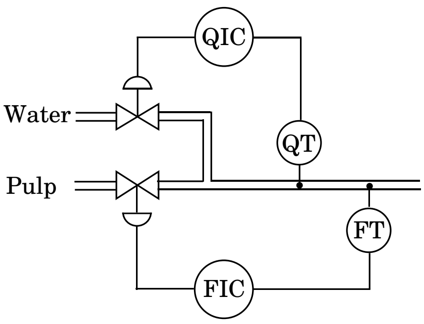
The loop is oscillating if more than n_{lim} load disturbances are detected during a supervision time T_{sup}.

3 parameters: IAE_{lim}, n_{lim}, T_{sup}.

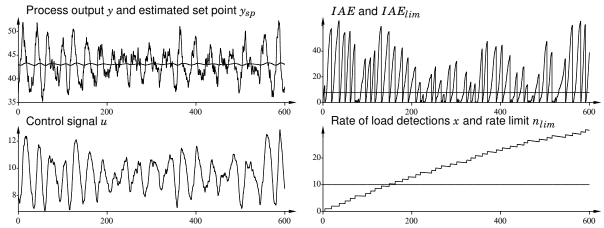
Suggestion:

$$\begin{aligned} IAE_{lim} &= T_i/\pi \\ n_{lim} &= 10 \\ T_{sup} &= 50T_i \end{aligned}$$

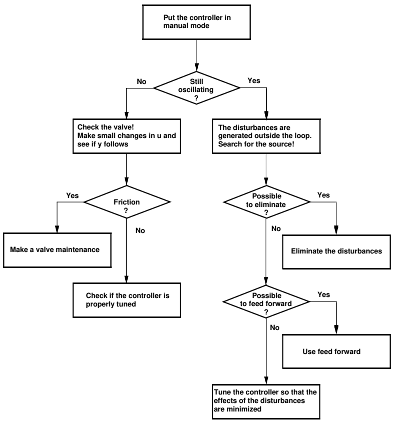
Example – Pulp concentration control



Example



Diagnosis



Frövi Paper Mill

Oscillation detection procedure used in Honeywell TDC3000.

91% of the loops in the carton board mill are supervised.

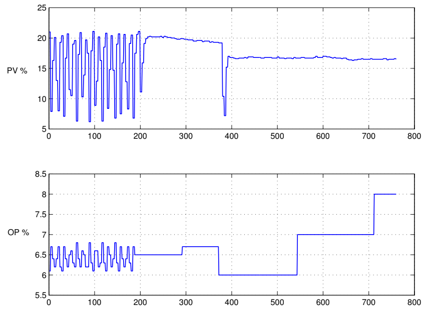
Each loop has an *Oscillation index* that is increased every time a detection is made.

The Oscillation index is reset to zero at maintenance or tuning.

Top-ten list presents the worst loops.

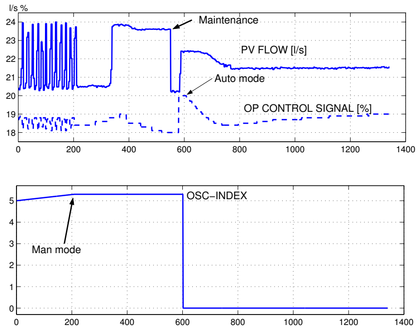
Frövi Paper Mill

Pressure control loop



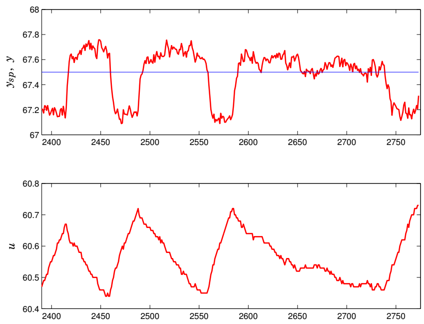
Frövi Paper Mill

Flow control loop



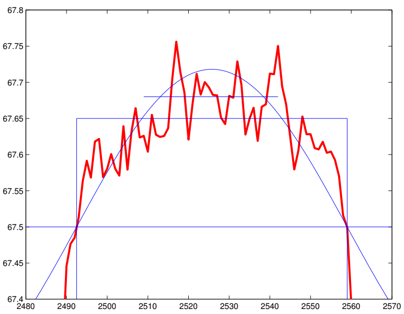
Stiction diagnosis

Recirculation flow loop in distillation column:



Idea: See if it is a square wave!

Stiction diagnosis



Sine wave

$$IAE = \int_{t_{c0}}^{t_{c1}} |e(t)| dt = \int_{0}^{\frac{T_p}{2}} a_{\text{sine}} \sin\left(\frac{2\pi}{T_p} t\right) dt = \frac{a_{\text{sine}} T_p}{\pi}.$$

$$a_{\text{sine}} = \frac{\pi \cdot IAE}{T_p}.$$

Square wave

$$IAE = \int_{t_{c0}}^{t_{c1}} |e(t)| dt = a_{\text{square}} \frac{T_p}{2},$$

$$a_{\text{square}} = \frac{2 \cdot IAE}{T_p}.$$

Sine or square wave?

$$V_{\text{sine}} = \sum_{i=1}^{n} \left(e(t_i) - a_{\text{sine}} \sin\left(\frac{2\pi}{T_p} ih\right)\right)^2$$

$$V_{\text{square}} = \sum_{i=1}^{n} \left(e(t_i) - a_{\text{square}}\right)^2,$$

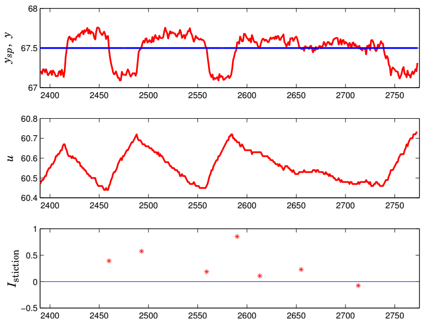
Stiction index

$$I_{\text{stiction}} = \frac{V_{\text{sine}} - V_{\text{square}}}{V_{\text{sine}} + V_{\text{square}}}$$

$I_{\text{stiction}} > 0$	stiction
$I_{\text{stiction}} < 0$	no stiction

Stiction diagnosis – Example 1

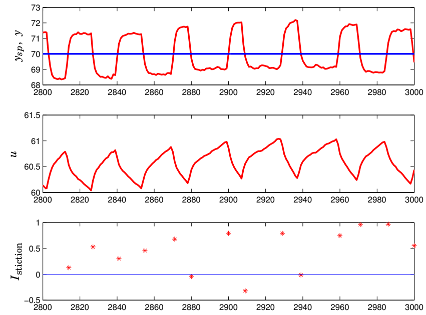
Recirculation flow loop in distillation column: Stiction



$I_{\text{stiction}} = 0.32$

Stiction diagnosis – Example 2

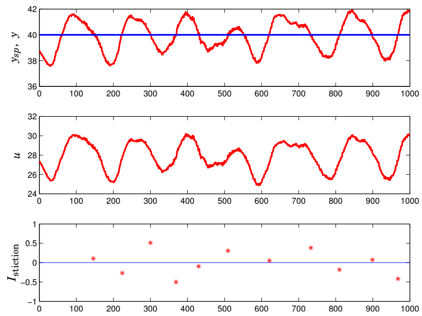
Recirculation flow loop in distillation column: Stiction



$I_{\text{stiction}} = 0.47$

Stiction diagnosis – Example 3

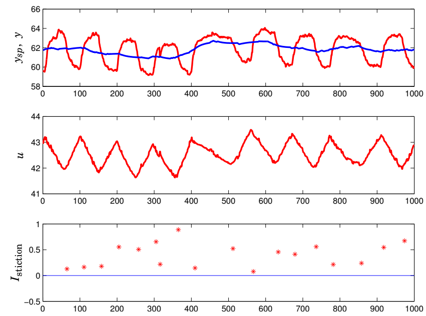
Level control loop in a paper mill: Badly tuned



$I_{\text{stiction}} = -0.0033$

Stiction diagnosis – Example 4

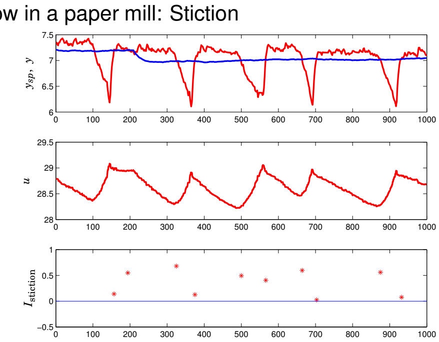
Pulp flow in a paper mill: Stiction



$I_{\text{stiction}} = 0.40$

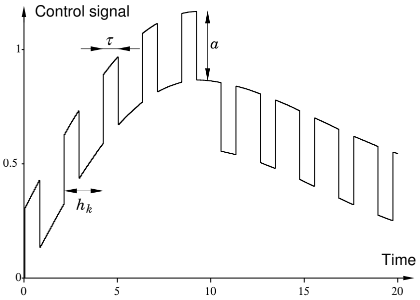
Stiction diagnosis – Example 5

Pulp flow in a paper mill: Stiction



$I_{\text{stiction}} = 0.37$

Friction compensation

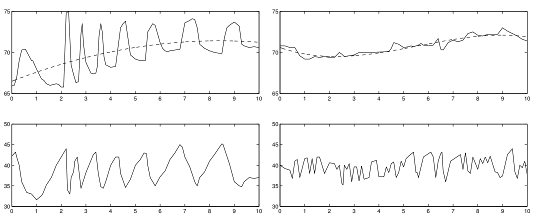


Add short pulses to the control signal in the direction of the rate-of-change.

Control of a centrifuge in a sugar refinery

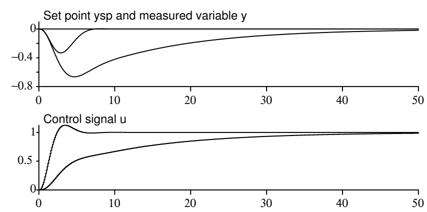
No knocker

Knocker



Detection of sluggish control loops

Good and bad control of load disturbances:



$$t_{\text{pos}} = \begin{cases} t_{\text{pos}} + h & \text{if } \Delta u \Delta y > 0 \\ t_{\text{pos}} & \text{if } \Delta u \Delta y \le 0 \end{cases}$$

$$t_{\text{neg}} = \begin{cases} t_{\text{neg}} + h & \text{if } \Delta u \Delta y < 0 \\ t_{\text{neg}} & \text{if } \Delta u \Delta y \ge 0 \end{cases}$$

Idle Index

$$I_i = \frac{t_{\text{pos}} - t_{\text{neg}}}{t_{\text{pos}} + t_{\text{neg}}} \qquad I_i \in [-1, 1]$$

I_i large ⇒ Sluggish control

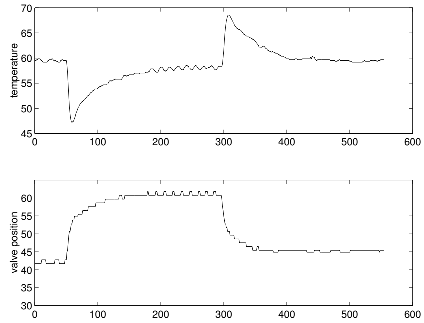
Previous example: $I_i = 0.82$ and $I_i = -0.68$

Recursive version

Filtering important

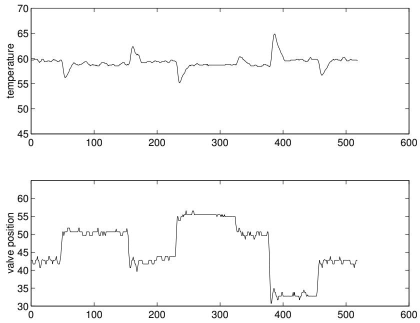
Automatic

Control of a heat exchanger



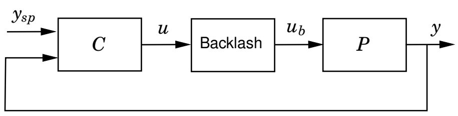
$K = 0.01 \qquad T_i = 30s \qquad I_i = 0.8$

Control of a heat exchanger

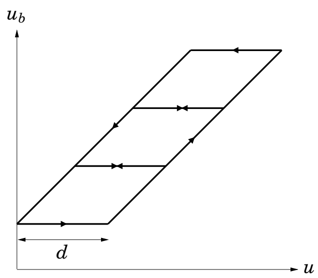


$K = 0.025 \qquad T_i = 8s \qquad I_i = 0.3$

Backlash

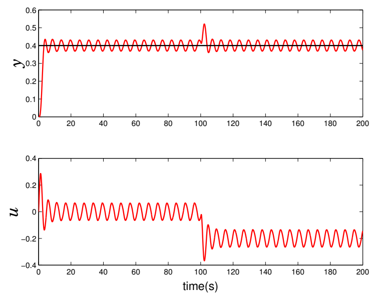


Backlash



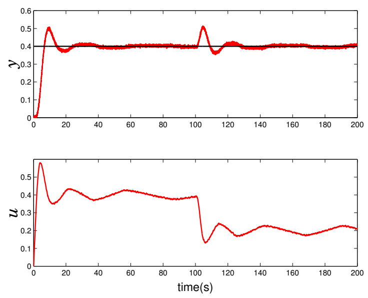
Control with backlash

$$P_1(s) = \frac{1}{s(1 + 0.8s)} e^{-0.2s}$$

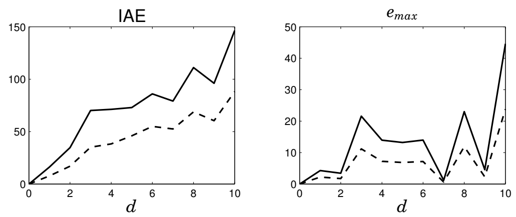


Control with backlash

$$P_2(s) = \frac{1}{(1 + s)^4} \qquad d = 5\%$$



Cost of backlash



Backlash compensation

$$u = u_{FB} + u_{FF},$$

Ideal backlash compensation:

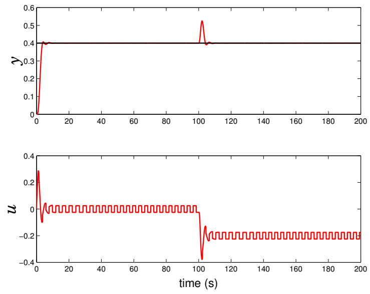
$$u_{FF} = \frac{d}{2}\text{sign}\left(\frac{du}{dt}\right).$$

Realizable compensation:

$$u_{FF} = \frac{\delta}{2}\text{sign}\left(\frac{du_f}{dt}\right) \quad \text{or} \quad u_{FF} = \frac{\delta}{2}\text{sign}\,(e)\,,$$

Backlash compensation

$$P_1(s) = \frac{1}{s(1+0.8s)}e^{-0.2s}$$



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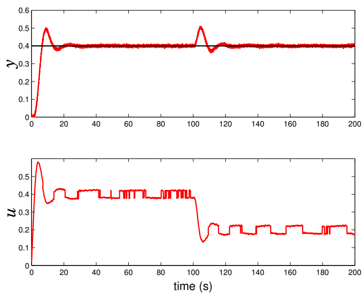

Control with backlash

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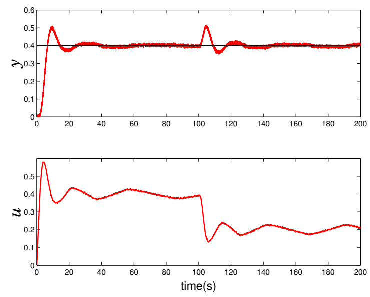
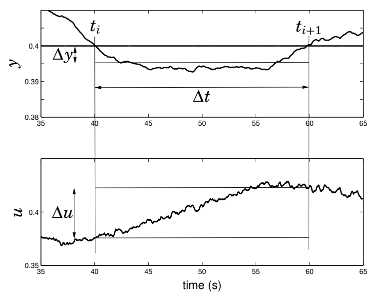


Backlash estimation



$$\Delta u = \Delta u_{\text{true}} + d \approx \frac{K}{T_i}\int_{t_i}^{t_{i+1}} e dt = \frac{K}{T_i}\Delta y \Delta t,$$

$$\Delta y = \int_{t_i}^{t_{i+1}} e dt/\Delta t \approx K_p \Delta u_{\text{true}},$$

Backlash estimation

$$\Delta u = \Delta u_{\text{true}} + d \approx \frac{K}{T_i}\int_{t_i}^{t_{i+1}} e dt = \frac{K}{T_i}\Delta y \Delta t,$$

$$\Delta y = \int_{t_i}^{t_{i+1}} e dt/\Delta t \approx K_p \Delta u_{\text{true}},$$

$$\hat{d} = \Delta u - \Delta u_{\text{true}} = \frac{K}{T_i}\Delta y \Delta t - \frac{\Delta y}{K_p} = \left(\frac{K}{T_i}\Delta t - \frac{1}{K_p}\right)\Delta y.$$

Backlash estimation

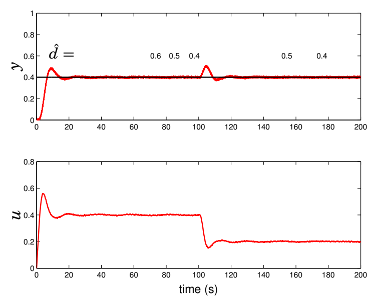
$$\Delta t = t_{i+1} - t_i$$

$$\Delta y = \int_{t_i}^{t_{i+1}} e dt/\Delta t$$

$$\hat{d} = \left(\frac{K}{T_i}\Delta t - \frac{1}{K_p}\right)\Delta y$$

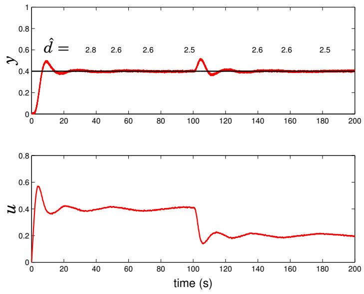
Simulation example

$$d = 1\%$$



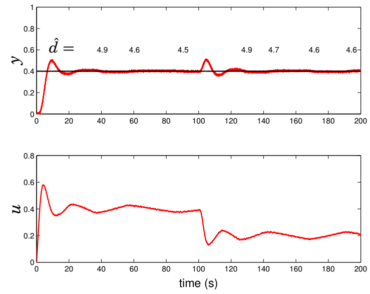
Simulation example

$d = 3\%$



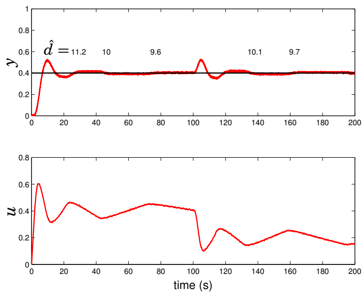
Simulation example

$d = 5\%$

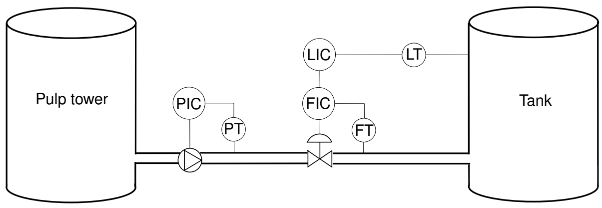


Simulation example

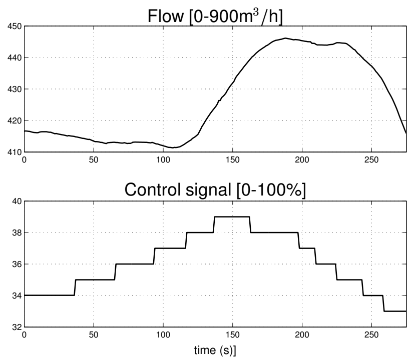
$d = 10\%$



Pulp flow – Hylte

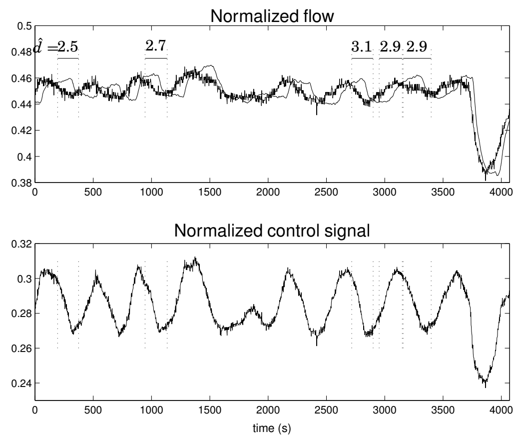


Pulp flow – Hylte

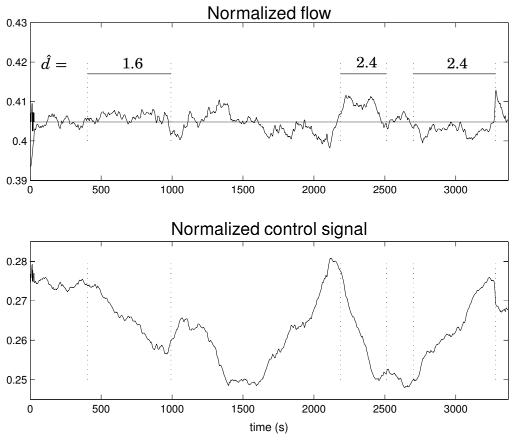


$d \approx 3\%$

Pulp flow – Hylte



Pulp flow – Hylte



Summary

- The automation trend
- We must automize the supervision level
- Stiction and backlash major problems at loop level
- Often not discovered by personnel
- Three functions presented
- Implemented in ABB's 800 system

Future work

- Improve diagnosis of oscillations
- Try to isolate problems in larger process sections