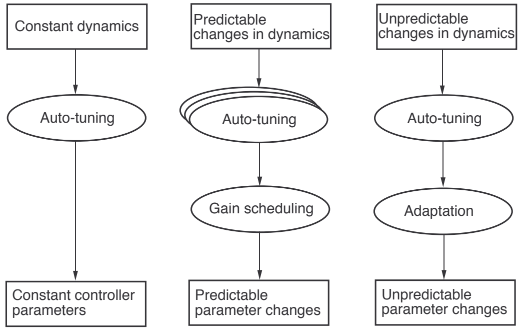
Predictive Control
Lecture 3

- **Autotuning of PID controllers**
- **Gain Scheduling**

Material: Lecture slides, Lab 1

Slides based on Johansson 2007, Åström 2010 and Bernhardsson 2012

When to Use Different Techniques?



Predictions about PID Control

- 1982: The ASEA Novtune Team 1982. (Novatune is a useful general digital control law with adaptation)
  PID Control will soon be obsolete
- 1989: Conference on Model Predictive Control.
  Using a PI controller is like driving a car only looking at the rear view mirror: It will soon be replaced by Model Predictive Control.
- 2002: Desbobough and Miller (Honeywell)
  Based on a survey of over 11000 controllers in the refining, chemicals and pulp and paper industries, 98% of regulatory controllers utilise PID feedback

Views from the Field

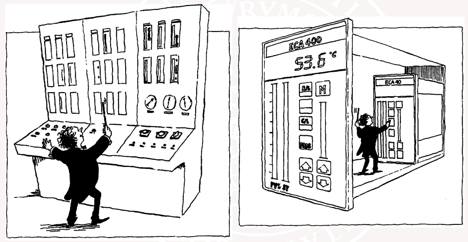
Canadian mill audit. Average paper mill has 2000 loops, 97% use PI the remaining 3% are PID, adaptive etc. (B. Bialkowski CCA'93).

- Default settings
- Poor control performance due to bad tuning
- Poor control performance due to valves, actuators or positioner problems

"Process Performance is not as good as you think." (D. Ender, Control Engineering 1993).

- More than 30% of installed controllers operate in manual
- More than 30% of the loops increase short term variability
- About 25% of the loops use default settings
- About 30% of the loops have equipment problems

Automatic Tuning



Automatic Tuning

Tune controller automatically on demand

Many approaches

- Empirical - Mimic a good process engineer
- Model based

Experiments

- Open or closed loop
- Step responses
- Relay feedback

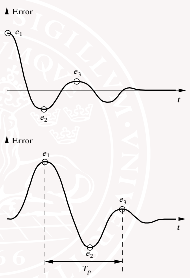
Methods

- Pattern recognition
- Rules crisp of fuzzy
- System identification
- Control design

Available in virtually all process control systems

The Foxboro EXACT

- Mimic an experienced instrument engineer
- Pattern recognition
- Rule based
- Key idea
- Start with reasonable parameters and improve them
- Requires pretuning



Johnson Control PRAC

- PRAC is an automatic tuner for a PI controller based on pattern recognition
- Similar to Foxboro EXACT
- Yokogawa had a similar system
- Both Foxboro and Yokogawa are also developing model based systems
- Based on empirical rules
- Prior information
  - K and T_i
  - Sampling period T
- Good operational experiences
- Weakness

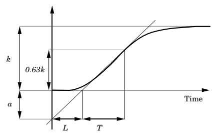
Auto-tuning Techniques

- The Ziegler-Nichols method
- Transient response methods
- Frequency response methods

Transient Response Methods

Step response methods—The three parameter model

$$G(s) = \frac{k}{1+sT}e^{-sL}$$



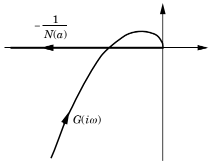
Controller	aK_c	T_i/L	T_d/L	T_p/L
P	1			4
PI	0.9	3		5.7
PID	1.2	2	0.5	3.4

The Ziegler-Nichols method

Ziegler-Nichols Frequency Response Method

Idea: Run a proportional controller, increase gain until the system starts to oscillate. Observe "ultimate gain K_u, and "ultimate period T_u.

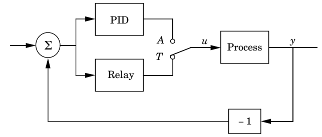
Controller parameters

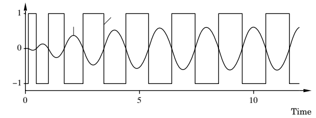


Controller	K_c/K_u	T_i/T_u	T_d/T_u	T_p/T_u
P	0.5			1
PI	0.4	0.8		1.4
PID	0.6	0.5	0.12	0.85

Interpretation: Find features of frequency response

Relay Tuning—Experimental set-up



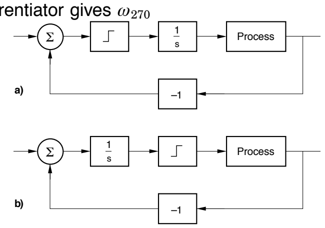


- Closed loop experiment
- Stable limit cycle for large class of processes
- Much control energy close to ω_{180}

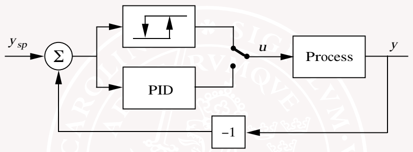
Adding Dynamics in the Feedback Loop

More information obtained by introducing dynamics in the feedback loop

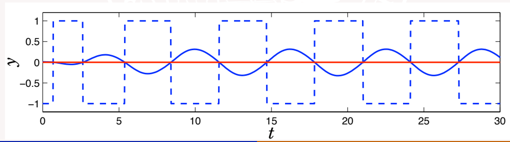
- An integrator gives ω_{90}
- A differentiator gives ω_{270}



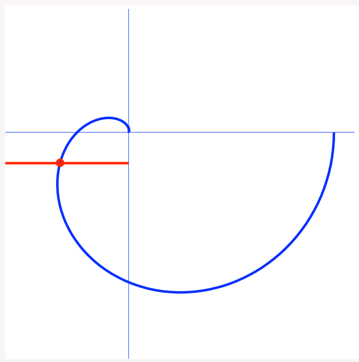
Relay Auto-tuning



What happens when relay feedback is applied to a system with dynamics? Think about a thermostat?



Describing Function Analysis



Practical Details

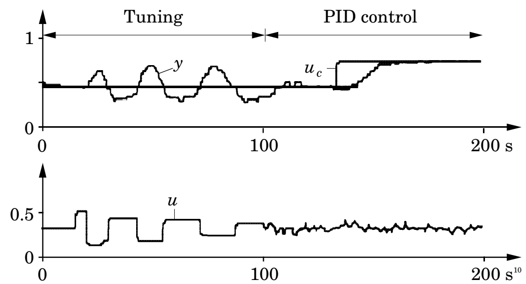
Basic controller

- Bring process to equilibrium
- Measure noise level
- Compute hysteresis width
- Initiate relay
- Monitor each half period
- Change relay amplitude automatically
- Check for steady state
- Compute controller parameters

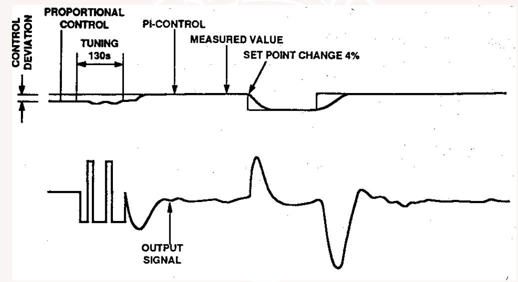
Automatic Tuning of the Double Tank

Consider the double tank used in our laboratory experiments.

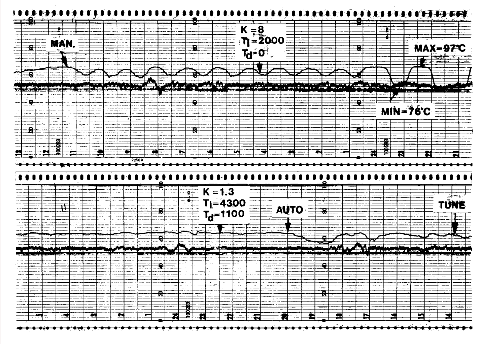
Results obtained with one of our earliest auto-tuners.



Automatic Tuning of a Level Controller



Temperature Control of Distillation Column



Commercial Auto-Tuners

- Easy to use
  - One-button tuning
- Robust
- Many versions
  - Stand alone
  - DCS systems
  - Estimation methods
  - Control design
- Large numbers
- Excellent industrial experience

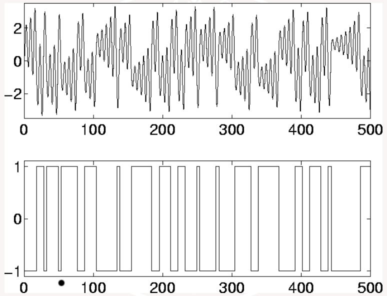
Industrial Single Loop Controller - ECA 400

- PID structure
- Auto-tuning
- Gain scheduling with automatic generation of tables
- Adaptation of feedback gains
- Adaptation of feedforward gain

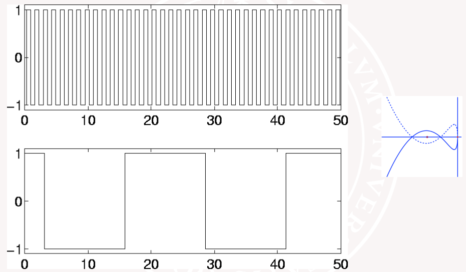
Properties of Relay Auto-tuning

- Safe for stable systems
- Close to industrial practice
  - Compare manual Ziegler-Nichols tuning
  - Easy to explain
- Little prior information. Relay amplitude
- One-button tuning
- Automatic generation of test signal
  - Automatically injects much energy at ω_{180} without for knowing ω_{180} apriori
- Good for pre-tuning
- Good industrial experience for more than 25 years. Many patents are running out.

Asymmetrical Oscillations $G(s) = \dfrac{1}{s^2 - 0.1s + 1}$



Many Limit Cycles $\dfrac{(s+1)^2}{(s+0.1)^3(s+7)^2}$

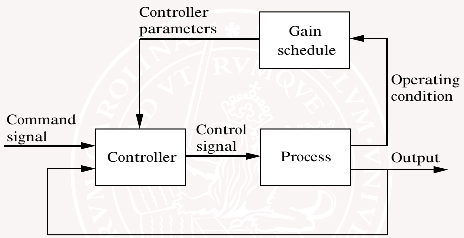


Gain Scheduling

1. What is it?
2. How to find schedules?
3. Applications
4. Conclusions

Discrete-time control → Discrete-event control

Gain Scheduling



Example of scheduling variables

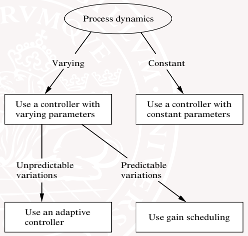
- Production rate
- Machine speed
- Mach number and dynamic pressure

Gain Scheduling

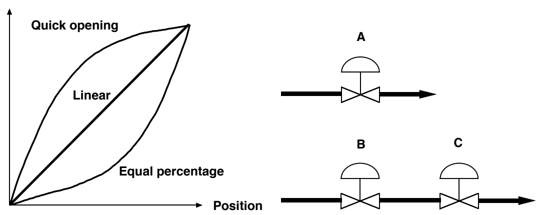
- Many uses
  - Linearization of actuators
  - Surge tank control
  - Control over wide operating regions
- Important issues
  - Choice of scheduling variables
  - Granularity of scheduling table
  - Interpolation schemes
  - Bump-less parameter changes
  - Man machine interfaces
- Importance of auto-tuning

Use of Different Techniques

- Categories
  - Automatic Tuning
  - Gain Scheduling
  - Adaptive feedback
  - Adaptive feedfoward
- Products
  - Tuning tools
  - PID controllers
  - Tool boxes
  - Special purpose systems built into instruments

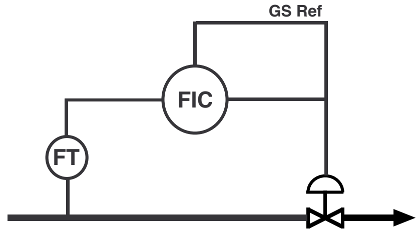


Valve Characteristics



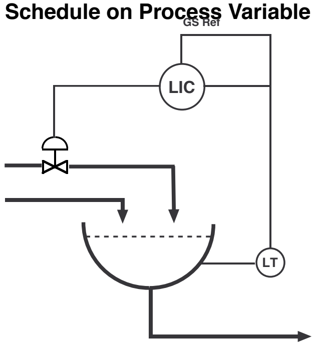
The valve characteristics depend on the installation

Schedule on Controller Output



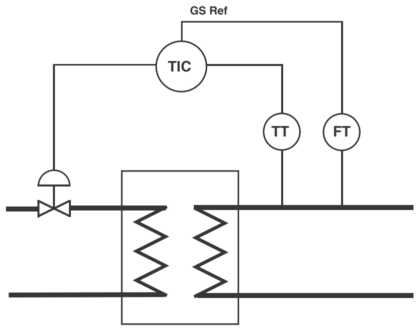
Discuss when this is appropriate

Schedule on Process Variable



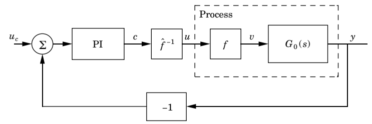
...when appropriate?

Schedule on External Variable

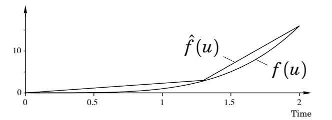


Nonlinear Valve

A typical process control loop



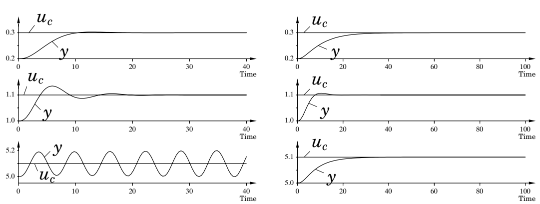
Valve characteristics—Crude approximation!



Results—Without/With Gain Scheduling

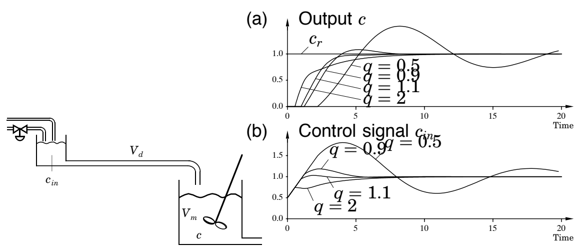
Without gain scheduling

With gain scheduling



Concentration Control

System performance with changing flow?



Variable Sampling Rate—Scheduled sampling

Process model

$$G(s) = \frac{1}{1+sT} e^{-s\tau} \text{ where } T = \frac{V_m}{q}, \qquad \tau = \frac{V_d}{q}$$

Sample the system with period

$$h = \frac{V_d}{nq}$$

The sampled model becomes

$$c(kh+h) = a\,c(kh) + (1-a)u(kh-nh)$$

where

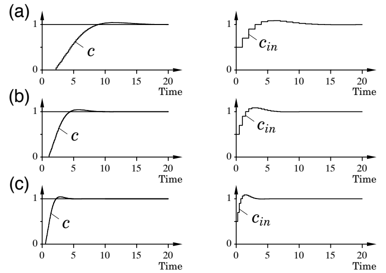
$$a = e^{-qh/V_m} = e^{-V_d/(nV_m)}$$

Notice that the sampled equation does not depend on q!!!

Results

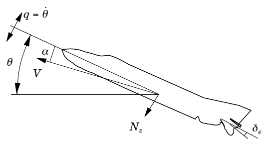
Discrete-event control with flow-dep. sampling $h = 1/(2q)$.

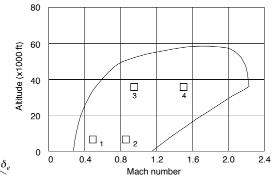
The flows are: (a) $q = 0.5$; (b) $q = 1$; (c) $q = 2$



Flight Control

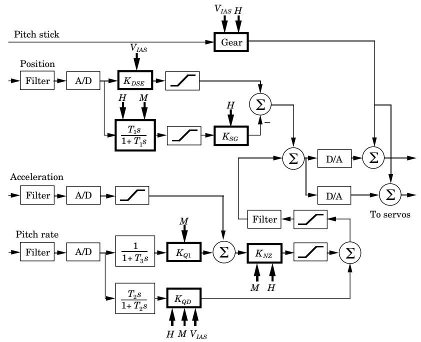
Pitch dynamics



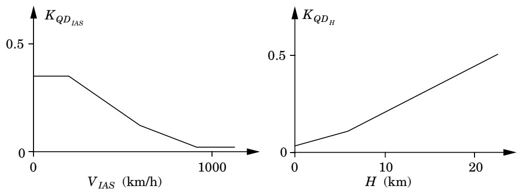


Operating conditions

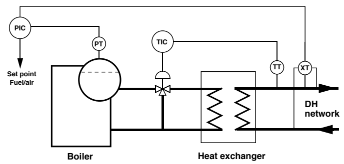
The Pitch Control Channel



Schedule of K_Q with Respect to Indicated Airspeed (IAS) and Height (H)



Schedule



Valve Position	K_c	T_i	T_d
0.00-0.15	1.7	95	23
0.15-0.22	2.0	89	22
0.22-0.35	2.9	82	21
0.35-1.00	4.4	68	17

Bumpless transfer param. change

Two possible implementations of the I-part in a PID controller:

ALT1: $I(k+1) = I(k) + (r(k)-y(k))/T_i$

$U(k) = P(k) + I(k) + D(k)$

ALT2: $I(k+1) = I(k) + r(k)-y(k)$

$U(k) = P(k) + I(k)/ T_i + D(k)$

ALT1 is best since ALT2 will give a bump in the control signal when T_i is changed !

Bumpless transfer manual-Auto

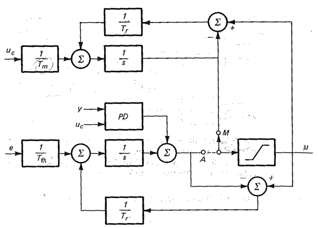
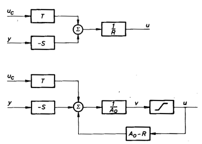


Figure 8.10 PID-regulator with bumpless switching between manual and automatic control.

Bumpless transfer $Ru=-Sy+Tu_c$



$$\begin{cases} A_o v = Tu_c - Sy + (A_o - R)u \\ u = \text{sat } v \end{cases}$$

A_0 chosen as a stable polynomial determining tracking rate

Can be used to "warm-start" controllers and make bumpless transfer between gain-scheduled controllers

Conclusions

- Gain Scheduling very useful technique
  - Linearization of nonlinear actuators
  - Surge tank control
  - Control over wide operating ranges
- Requires good models
- Easy to use when combined with auto-tuning
- Good operational experience
- Issues to be considered
  - Choice of scheduling variables
  - Granularity of scheduling tables
  - Interpolation
  - Bumpless parameter changes
  - Operator interfaces