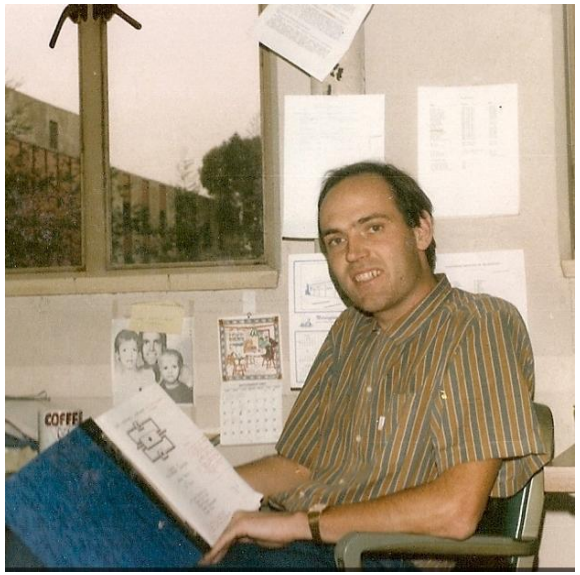
Advanced PID control as agents for the future

Sigurd Skogestad

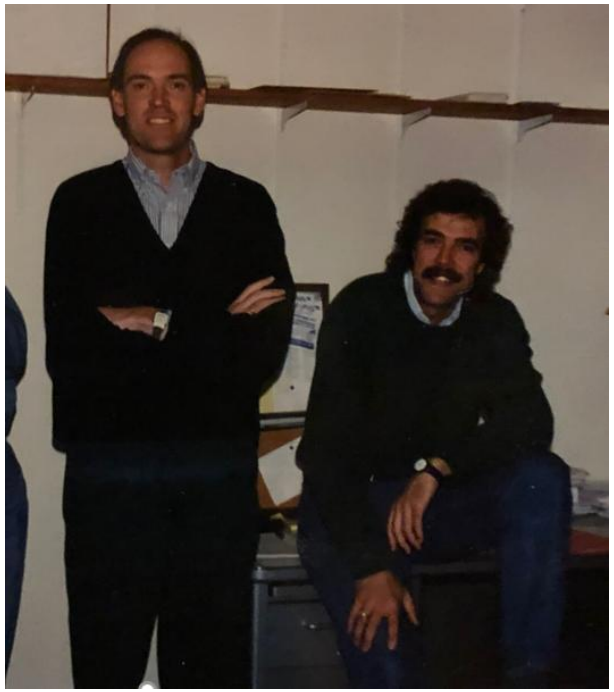
Kyb

17 Nov. 2025

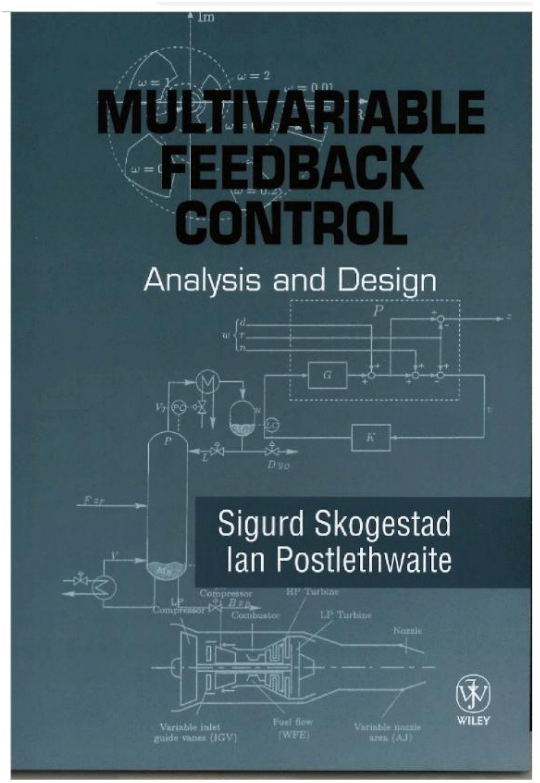
Robust control



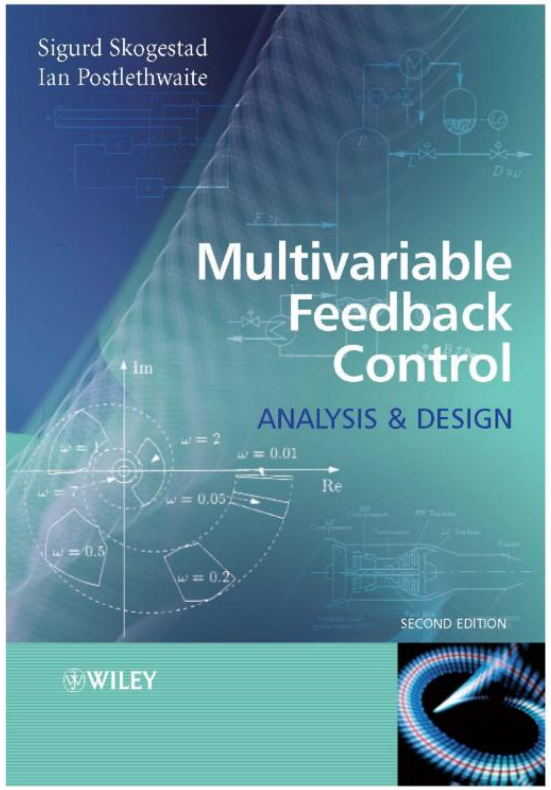
Caltech, 1983-1987



Berkeley, 1994-1995



1996



2005

Abstract

- The first general purpose PID controller (Taylor 100 Fullscope) came on the marked in 1939 so it is approaching 100 years. For some reason, the PID controller was always looked upon by academics as an ad-hoc solution that would soon be replaced by something better and more general. First it was lead-lag compensators, later MPC and now AI. This has also led to little focus on tuning PID controllers, and Ziegler-Nichols' method is still being used by many, in spite of being aggressive and lacking a tuning parameter. This has improved lately, for example with my favorite PID SIMC-rules.
- However, there is still very little academic focus on "advanced PID control" solutions, where the PID controller is combined in a system with other standard control elements. This includes cascade, ratio and split range control, and use of selectors for constraint switching. Especially, the use of max- and min-selectors is still regarded as ad-hoc, but their simplicity and effective will guarantee their use also in the future. To put them into the present AI fold, we may view selectors and other control elements as specialized agents, and a network of these agents make up a complex control system. I will show an example of keeping cows happy.

TAPIR TRYKK

Omarbeidet utgave

REGULERINGSTEKNIKK

Analyse og syntese av lineære reguleringssystemer

BIND 1

1977

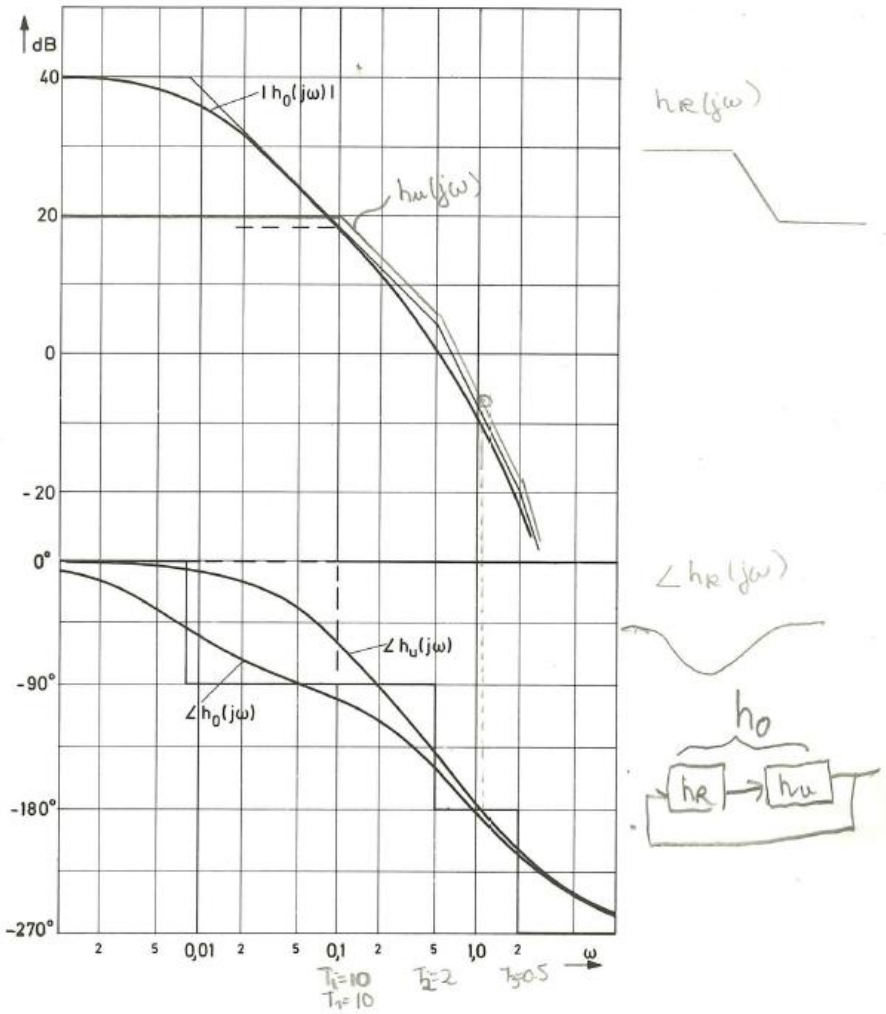
Jens G. Balchen

Professor i teknisk kybernetikk
Norges tekniske høgskole

TAPIR

Main approach to controller design: Lead-lag loop shaping

allerede har $K = 10 = 20$ dB, betyr dette at kompensasjonselementet må en forsterkning mindre enn 1 nemlig $K_2 = 0{,}79$.



Figur 8.15

Vi har sagt at vi vil velge et kompensasjonselement

$$h_R(s) = K_1 \frac{1+T_i s}{1+T_1 s} \qquad (8.35)$$

og vi ser av fig. 8.15 at en forholdsvis rimelig verdi av parameteren T_i vil være $T_i = 10$. Siden sløyfens forsterkning ved lave frekvenser skal være $|h_0(0)| = 100$ finner vi å måtte velge $K_1 = 10$ og $T_1 = 126$. Dette gir

$$h_R(s) = 10 \frac{1+10s}{1+126s} \qquad (8.36)$$

og

$$h_0(s) = \frac{100}{(1+126s)(1+2s)(1+0{,}5s)} \qquad (8.37)$$

Dette systemet har en båndbredde som er omtrent halvparten av den vi tidligere er kommet frem til i (8.20) og som er vist i fig. 8.11. Videre har det nye systemet betydelig mindre evne til å undertrykke dynamiske forstyrrelser. Således vil det nye systemet få $|N(j\omega)| = -20$ dB ved $\omega = 0{,}07$, mens systemet i fig. 8.11 har $|N(j\omega)| = -20$ dB ved $\omega = 0{,}2$. Den vesentligste forskjell på de to systemene er som vi vet at vi i det første har benyttet oss av derivatvirkningen i sløyfen.

Det er åpenbart at vi kunne ha fått resultatet noe bedre med hensyn til respons ved midlere frekvenser ved f.eks. å ha valgt et kompensasjonselement som har følgende sekvens av asymptote vinkelkoeffisienter regnet fra lave frekvenser og oppover: (0, -1, -2, -1, 0). Et slikt element kan oppnås ved å kople i serie (kaskade) to elementer av den type som er vist i andre linje i tab. 8.2. Dette blir ofte gjort for å få et sterkere fall i den resulterende sløyfes asymptotiske amplitudekarakteristikk.

Page 294 (!): PID control

8.3.2 Seriekompensasjon ved hjelp av standard regulatorer

I det foregående har vi til stadighet henvist til visse standardregulatorer som brukes ved prosessregulering. Disse kan betraktes som seriekompensasjonselementer. De er hensiktsmessige ved oppbygging av prosessreguleringssystemer fordi de har parametre som kan innstilles innenfor vide grenser, og en kan som oftest med slike oppnå et relativt tilfredsstillende resultat. Slike standardregulatorer forekommer vanligvis i fire forskjellige former:

a) Proporsjonalregulatorer (P-regulator) som bare er en forsterker med innstillbar forsterkning. På grunn av den fysiske oppbygging av en slik forsterkning (gjerne innbefattet det effektorgan som utgjør pådraget), vil en bare ha konstant forsterkning innenfor et begrenset frekvensbånd, idet uunngåelige poler vil gjøre at forsterkningen synker ved økende frekvens. Dette frekvensbånd vil imidlertid ofte være vesentlig større enn båndbredden av det ferdige reguleringssystem slik at P-regulatoren kan regnes å ha konstant forsterkning til frekvenser høyere enn kryssfrekvenser (ω_c).

b) Proporsjonal + integral-regulator (PI-regulator) som ideelt sett skal ha en karakteristikk som vist i første linje i tab. 8.2. Transferfunksjonen for en ideell PI-regulator skrives vanligvis på formen

$$h_R(s) = K_p\left(1 + \frac{1}{T_i s}\right) = K_p \frac{1+T_i s}{T_i s} \qquad (8.38)$$

der K_p = proporsjonalkonstant og T_i = integraltid.
På grunn av at det kan være vanskelig å realisere en ideell integrasjon, vil vi ofte finne at slike regulatorer får karakteristikker som vist i andre linje i tab. 8.2, nemlig proporsjonal + begrenset integral-regulator.

c) Proporsjonal + derivat-regulator (PD-regulator) som ideelt sett skulle ha en karakteristikk som vist i tredje linje i tab. 8.2, men som i praksis vil få en karakteristikk som vist i fjerde linje i tabellen. Transferfunksjonen for den ideelle PD-regulator har gjerne formen

$$h_R(s) = K_p(1 + T_d s) \qquad (8.39)$$

der T_d = derivattid.

d) Proporsjonal + integral + derivat-regulator (PID-regulator) som ideelt sett skulle ha en karakteristikk som er en kombinasjon av første og tredje linje i tab. 8.2, men som i praksis som oftest vil få den form som er vist i femte linje i tabellen. Transferfunksjonen for en ideell PID-regulator skrives gjerne slik

$$h_R(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \approx K_p \frac{(1+T_i s)(1+T_d s)}{T_i s} \qquad (8.40)$$

Tilnærmelsen i (8.40) er gyldig når $T_d \ll T_i$. Denne regulatortype er meget populær fordi den omfatter alle de funksjoner en vanligvis ønsker, og fordi de tre parametre (K_p, T_i og T_d) i praktisk utførelse kan justeres innenfor vide grenser.

Ved bruk av slike regulatorer i prosessregulering vil problemet være hvordan man skal innjustere de forskjellige parametre for å få tilfredsstilt de spesifikasjoner som er gitt. Avhengig av hvor strenge kravene er, og hvor mye forsinkelse (poler eller transportforsinkelse) det finnes i prosessen vil man i noen tilfeller kunne klare seg med en P-regulator, mens i andre tilfeller vil en av de mer sammensatte regulatorer være nødvendig.

Det er viktig å finne frem til en metode som er enkel å bruke i praksis for innstilling av parametrene i en regulator, selv om en ikke kjenner transferfunksjonen for prosessen i detalj. En

Tune PID: Ziegler-Nichols «closed-loop» method

slik metode er den som ofte refereres til som "Ziegler og Nichols metode" for innstilling av regulatorer. Den er basert på den forutsetning at prosessen er stabil og at prosessens frekvensrespons har amplitude- og fasekarakteristikker som begge er monotont fallende med økende frekvens.

Siden metoden baserer seg på enkle eksperimenter utført på det ferdig monterte system der alle de virkelige komponentene inngår, vil de data man får være ganske realistiske. En metode som baserer seg på individuell bestemmelse av de forskjellige systemkomponenters dynamiske egenskaper vil derimot lett kunne føre til at noe overses eller at gjensidige påvirkninger ikke kommer frem.

Ziegler og Nichols metode kan i korthet beskrives som følger:

For P-regulator:

Regulatorens proposjonalkonstant (K_p) økes gradvis samtidig som små forstyrrelser påtrykkes prosessen inntil man oppnår en stående svingning (eller i det minste en svakt dempet svingning) ved registrering på prosessens utgang. Den verdi av proporsjonalkonstanten man da har, K_{pkrit}, noteres. Likeledes noteres den stående svingnings periode

$$T_k = \frac{1}{f_k} = \frac{2\pi}{\omega_{180}} \qquad (8.41)$$

NB!

En gunstig innstilling av P-regulatoren vil da være

$$K_p = 0{,}5K_{pkrit} = K_{pkrit}(\text{dB}) - 6(\text{dB}) \qquad (8.42)$$

Det som i realiteten gjøres, er at man lar systemet selv generere en svingning og det foretas an frekvensanalyse lukkete sløyfen i nærheten av frekvensen ω_{180}. Den valinnstilling tilsvarer en forsterkningsmargin $\Delta K = 6$ dB. Denne innstilling vil som oftest være akseptabel når sys har relativt sterkt økende negativ fasevinkel, fordi forningsmarginen da vil være utslagsgivende.

For PI-regulator

Regulatorens integraltid settes først størst mulig, dvs. ($T_i = \infty$). (tilsvarer ingen integralvirkning) Proporsjonalkonstanten K_p økes gradvis inntil konstant stående svingning oppnås. Verdiene av K_{pkrit} og T_k noteres. En gunstig parameterkombinasjon vil nå være

$$K_p = 0{,}45K_{pkrit} = K_{pkrit}(\text{dB}) - 7(\text{dB}) \qquad (8.43)$$

$$T_i = 0{,}85T_k \approx 5\frac{1}{\omega_{180}} \quad > \frac{1}{0.2\,\omega_{180}} \qquad (8.44)$$

For PID-regulator

Først settes $T_i \approx \infty$ og $T_d \approx 0$. Proporsjonalkonstanten K_p økes gradvis inntil stående svingning oppnås. Verdiene av K_{pkrit} og T_k noteres. En gunstig kombinasjon av parametre vil nå være

$$K_p = 0{,}6K_{pkrit} = K_{pkrit}(\text{dB}) - 4{,}5(\text{dB}) \qquad (8.45)$$

$$T_i = 0{,}5T_k \approx 3\,\frac{1}{\omega_{180}} \qquad (8.46)$$

$$T_d = 0{,}12T_k \approx 0{,}75\,\frac{1}{\omega_{180}} \qquad (8.47)$$

Vi legger merke til at ved PI-regulator vil integralvirkningen komme inn ved frekvenser lavere enn $0{,}2\omega_{180}$. Ved PID-regulator vil integralvirkningen komme inn ved frekvenser lavere kommer inn ved fre-

llingsteknikken ikke viss korreksjon av i mange praktiske nkelt eksempel.

Disadvantages Ziegler-Nichols:
1. Aggressive settings
2. No tuning parameter
3. Poor for processes with large time delay (θ)

AMERICAN CONTROL CONFERENCE
San Diego, California
June 6-8, 1984

IMPLICATIONS OF INTERNAL MODEL CONTROL FOR PID CONTROLLERS

Manfred Morari
Sigurd Skogestad

California Institute of Technology
Department of Chemical Engineering
Pasadena, California 91125

Daniel F. Rivera

University of Wisconsin
Department of Chemical Engineering
Madison, Wisconsin 53706

Ind. Eng. Chem. Process Des. Dev. **1986**, *25*, 252-265

Internal Model Control. 4. PID Controller Design

Daniel E. Rivera, Manfred Morari,* and Sigurd Skogestad

Chemical Engineering, 206-41, California Institute of Technology, Pasadena, California 91125

For a large number of single input–single output (SISO) models typically used in the process industries, the Internal Model Control (IMC) design procedure is shown to lead to PID controllers, occasionally augmented with a first-order lag. These PID controllers have as their only tuning parameter the closed-loop time constant or, equivalently, the closed-loop bandwidth. On-line adjustments are therefore much simpler than for general PID controllers. As a special case, PI- and PID-tuning rules for systems modeled by a first-order lag with dead time are derived analytically. The superiority of these rules in terms of both closed-loop performance and robustness is demonstrated.

Internal Model Control. 4. PID Controller Design

Daniel E. Rivera, Manfred Morari,* and Sigurd Skogestad

Chemical Engineering, 206-41, California Institute of Technology, Pasadena, California 91125

For a large number of single input–single output (SISO) models typically used in the process industries, the Internal Model Control (IMC) design procedure is shown to lead to PID controllers, occasionally augmented with a first-order lag. These PID controllers have as their only tuning parameter the closed-loop time constant or, equivalently, the al PID controllers. As a dead time are derived ustness is demonstrated.

Table I. IMC-Based PID Controller Parameters[a]

	model	$y/y_s = \tilde{g}_s f$	controller	$k_c k$	τ_I	τ_D	τ_F	comments
A	$\frac{k}{\tau s + 1}$	$\frac{1}{\epsilon s + 1}$	$\frac{1}{k}\frac{\tau s + 1}{\epsilon s}$	$\frac{\tau}{\epsilon}$	τ	–	–	–
B	$\frac{k}{(\tau_1 s + 1)(\tau_2 s + 1)}$	$\frac{1}{\epsilon s + 1}$	$\frac{(\tau_1 s + 1)(\tau_2 s + 1)}{k\epsilon s}$	$\frac{\tau_1 + \tau_2}{\epsilon}$	$\tau_1 + \tau_2$	$\frac{\tau_1\tau_2}{\tau_1 + \tau_2}$	–	–
C	$\frac{k}{\tau^2 s^2 + 2\zeta\tau s + 1}$	$\frac{1}{\epsilon s + 1}$	$\frac{\tau^2 s^2 + 2\zeta\tau s + 1}{k\epsilon s}$	$\frac{2\zeta\tau}{\epsilon}$				
D	$k\frac{-\beta s + 1}{\tau s + 1}$	$\frac{-\beta s + 1}{\epsilon s + 1}$	$\frac{\tau s + 1}{k(\beta + \epsilon)s}$	$\frac{\tau}{\beta + \epsilon}$				
E	$k\frac{-\beta s + 1}{\tau s + 1}$	$\frac{-\beta s + 1}{(\beta s + 1)(\epsilon s + 1)}$	$\frac{\tau s + 1}{ks(\beta\epsilon s + 2\beta + \epsilon)}$	$\frac{\tau}{2\beta + \epsilon}$				
F	$k\frac{-\beta s + 1}{\tau^2 s^2 + 2\zeta\tau + 1}$	$\frac{-\beta s + 1}{\epsilon s + 1}$	$\frac{\tau^2 s^2 + 2\zeta\tau s + 1}{k(\beta + \epsilon)s}$	$\frac{2\zeta\tau}{\beta + \epsilon}$				
G	$k\frac{-\beta s + 1}{\tau^2 s^2 + 2\zeta\tau s + 1}$	$\frac{-\beta s + 1}{(\beta s + 1)(\epsilon s + 1)}$	$\frac{\tau^2 s^2 + 2\zeta\tau s + 1}{k(\beta\epsilon s + 2\beta + \epsilon)s}$	$\frac{2\zeta\tau}{2\beta + \epsilon}$				
H	$\frac{k}{s}$	$\frac{1}{\epsilon s + 1}$	$\frac{1}{k\epsilon}$	$\frac{1}{\epsilon}$				
I	$\frac{k}{s}$	$\frac{2\epsilon + 1}{(\epsilon s + 1)^2}$	$\frac{2\epsilon s + 1}{k\epsilon^2 s}$	$\frac{2}{\epsilon}$				
J	$\frac{k}{s(\tau s + 1)}$	$\frac{1}{\epsilon s + 1}$	$\frac{\tau s + 1}{k\epsilon}$	$\frac{1}{\epsilon}$	–	τ	–	–
K	$\frac{k}{}$	$\frac{2\epsilon s + 1}{}$	$\frac{(\tau s + 1)(2\epsilon s + 1)}{}$	$\frac{2\epsilon + \tau}{}$	$2\epsilon + \tau$	$\frac{2\epsilon\tau}{}$	–	(6)

Table II. IMC-Based PID Parameters for $g(s) = ke^{-\theta s}/(\tau s + 1)$ and Practical Recommendations for ϵ/θ

controller	kk_c	τ_I	τ_D	recommended ϵ/θ ($> 0.1\tau/\theta$ *always*)
PID	$(2\tau + \theta)/(2\epsilon + \theta)$	$\tau + (\theta/2)$	$\tau\theta/(2\tau + \theta)$	>0.8
PI	$\theta/\tau = 0.1$	1.54		>1.7
improved PI	$(2\tau + \theta)/2\epsilon$	$\tau + (\theta/2)$		>1.7

Disadvantage IMC-PID (=Lambda tuning):
1.Many rules
2.Poor disturbance response for «slow» processes (with large τ_1/θ)

Probably the best **simple** PID tuning rules in the world

Sigurd Skogestad*
Department of Chemical Engineering
Norwegian University of Science and Technology
N–7491 Trondheim Norway

Presented at AIChE Annual meeting, Reno, NV, USA, 04-09 Nov. 2001
Paper no. 276h
This version: November 19, 2001†

Abstract

The aim of this paper is to present analytic tuning rules which are as simple as possible and still result in a good closed-loop behavior. The starting point has been the IMC PID tuning rules of Rivera, Morari and Skogestad (1986) which have achieved widespread industrial acceptance. The integral term has been modified to improve disturbance rejection for integrating processes. Furthermore, rather than deriving separate rules for each transfer function model, we start by approximating the process by a first-order plus delay processes (using the "half method"), and then use a single tuning rule. This is much simpler and appears to give controller tunings with comparable performance. All the tunings are derived analytically and are thus very suitable for teaching.

1 Introduction

Hundreds, if not thousands, of papers have been written on tuning of PID controllers, and one must question the need for another one. The first justification is that PID controller is by far the most widely used control algorithm in the process industry, and that improvements in tuning of PID controllers will have a significant practical impact. The second justification is that the simple rules and insights presented in this paper may contribute to a significantly improved understanding into how the controller should be tuned.

ELSEVIER

Journal of Process Control 13 (2003) 291–309

JOURNAL OF PROCESS CONTROL

www.elsevier.com/locate/jprocont

Simple analytic rules for model reduction and PID controller tuning☆

Sigurd Skogestad*

Department of Chemical Engineering, Norwegian University of Science and Technology, N-7491 Trondheim, Norway

Received 18 December 2001; received in revised form 25 June 2002; accepted 11 July 2002

Abstract

The aim of this paper is to present analytic rules for PID controller tuning that are simple and still result in good closed-loop behavior. The starting point has been the IMC-PID tuning rules that have achieved widespread industrial acceptance. The rule for the integral term has been modified to improve disturbance rejection for integrating processes. Furthermore, rather than deriving separate rules for each transfer function model, there is a just a single tuning rule for a first-order or second-order time delay model. Simple analytic rules for model reduction are presented to obtain a model in this form, including the "half rule" for obtaining the effective time delay.

Keywords: Process control; Feedback control; IMC; PI-control; Integrating process; Time delay

1. Introduction

Although the proportional-integral-derivative (PID) controller has only three parameters, it is not easy, without a systematic procedure, to find good values (settings) for them. In fact, a visit to a process plant will usually show that a large number of the PID controllers are poorly tuned. The tuning rules presented in this paper have developed mainly as a result of teaching this material, where there are several objectives:

1. The tuning rules should be well motivated, and preferably model-based and analytically derived.
2. They should be simple and easy to memorize.
3. They should work well on a wide range of processes.

Step 2. Derive model-based controller settings. PI-settings result if we start from a first-order model, whereas PID-settings result from a second-order model.

There has been previous work along these lines, including the classical paper by Ziegler amd Nichols [1], the IMC PID-tuning paper by Rivera et al. [2], and the closely related direct synthesis tuning rules in the book by Smith and Corripio [3]. The Ziegler–Nichols settings result in a very good disturbance response for integrating processes, but are otherwise known to result in rather aggressive settings [4,5], and also give poor performance for processes with a dominant delay. On the other hand, the analytically derived IMC-settings in [2] are known to result in a poor disturbance response for integrating processes (e.g., [6,7]), but are robust and

SIMC-PID Tuning Rules

$$G(s) = k\frac{e^{-\theta s}}{(\tau_1 s + 1)(\tau_2 s + 1)}$$

For cascade form PID controller:

$$K_c = \frac{1}{k}\frac{\tau_1}{\tau_c + \theta} = \frac{1}{k'} \cdot \frac{1}{\tau_c + \theta} \tag{1}$$

$$\tau_I = \min\{\tau_1, \frac{4}{k'\ K_c}\} = \min\{\tau_1, 4(\tau_c + \theta)\} \tag{2}$$

$$\tau_D = \tau_2 \tag{3}$$

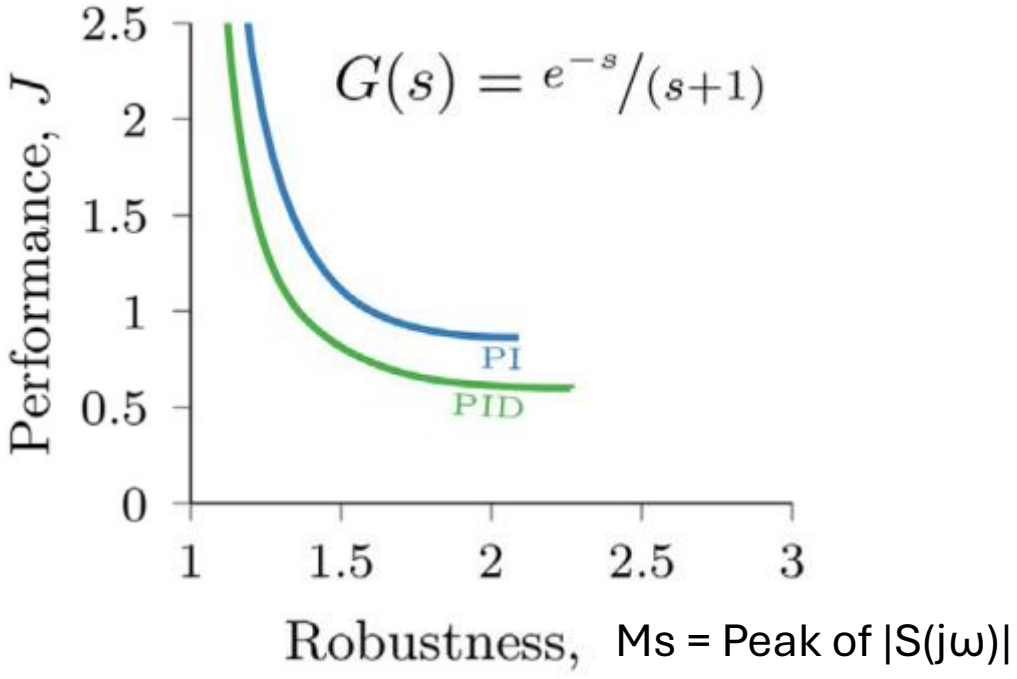
Derivation:

1. First-order setpoint response with response time τ_c (IMC-tuning = "Direct synthesis")
2. Reduce integral time to get better disturbance rejection for slow or integrating process (but avoid slow cycling $\Rightarrow \tau_I \geq \frac{4}{k'\ K_c}$)

One tuning parameter: Desired closed-loop time constant τ_c

Can the SIMC PID-rules be improved?

- No, hardly. They are almost Pareto-optimal (vary τ_c)
- Optimal trade-off between robustness (Ms) and performance (J=IAE for setpoint and disturbance):



Ms = Peak of |S(jω)|

Chriss Grimholt and Sigurd Skogestad, J. Process Control, vol. 70 (2018), 36-46
"Optimal PI and PID control of first-order plus delay processes and evaluation of the original and improved SIMC rules" ,

SIMC-tuning is almost Pareto-optimal!

Trade-off between robustness (Ms) and performance (J=IAE for setpoint and disturbance)

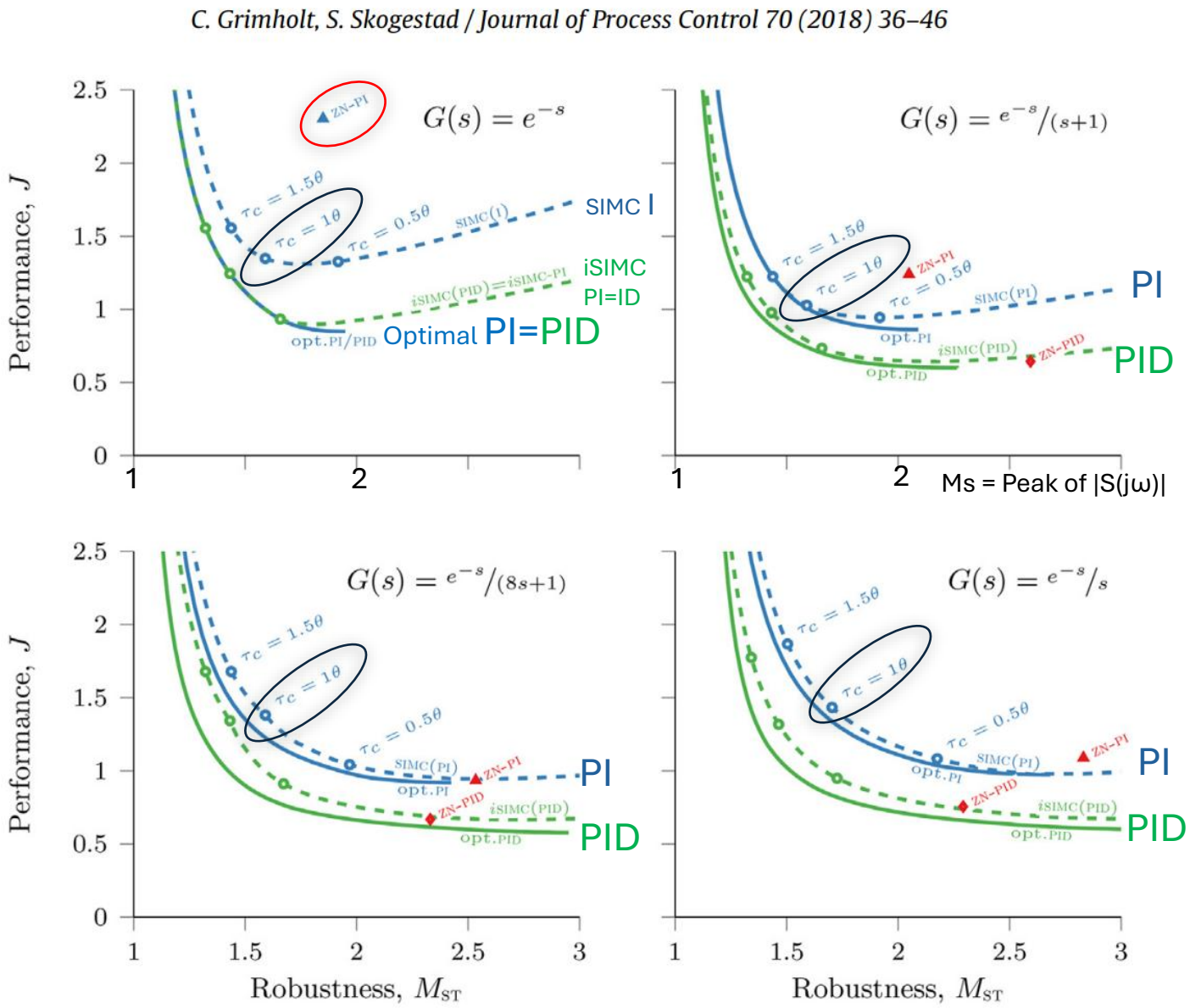
Optimal PI/PID

SIMC PI / iSIMC PID (vary τ_c)

SIMC: Recommend $\tau_C \geq$ Delay θ
for good robustness:

- Ms < 1.6
- GM > 3 (10 dB)

«Improved» iSIMC PID: $\tau_D = \frac{Delay}{3}$ (cascade)



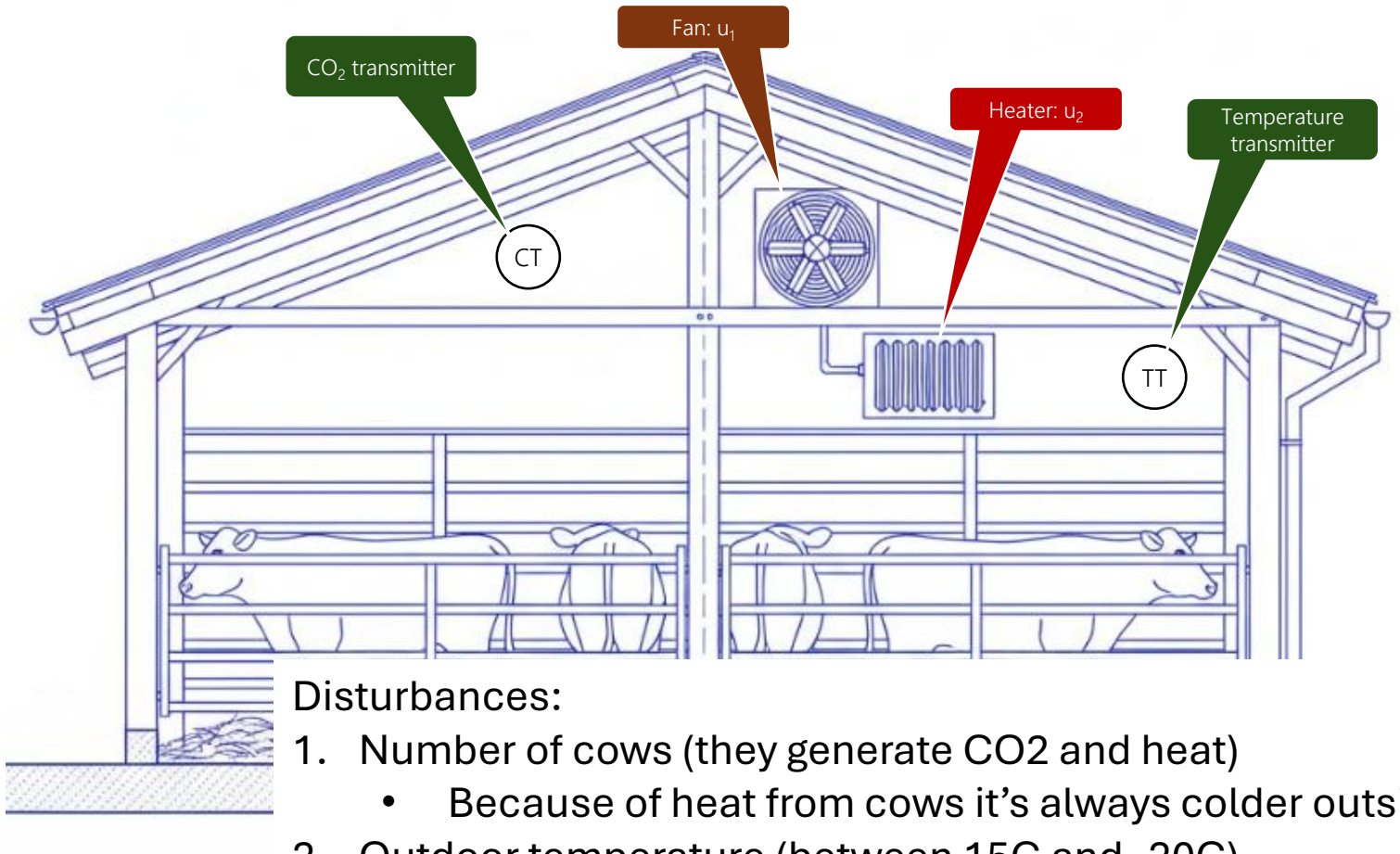
Cow case study (Norway, outdoor 15C to -20C)

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy (cold) cows
- y2=T less than 0C

Even more unhappy (sick) cows
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



Disturbances:
1. Number of cows (they generate CO2 and heat)
   - Because of heat from cows it's always colder outside
2. Outdoor temperature (between 15C and -20C)
   - The cows are outside in the summer

Happy cows

- y1=C (CO_2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows

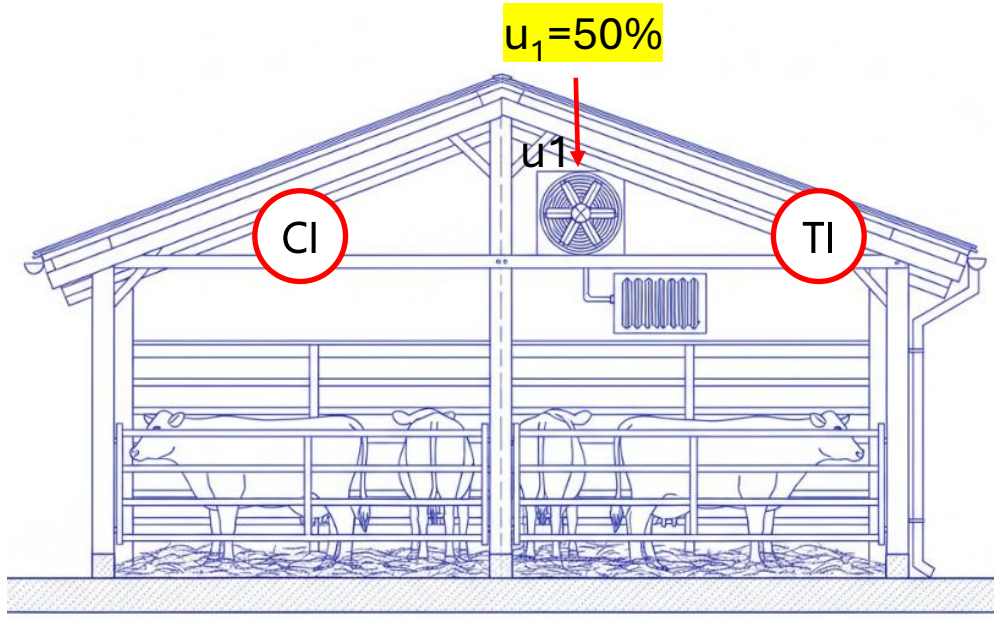
- y2=T less than 0C

Even more unhappy

- y1=C above 3000 ppm (poor air quality)

MVs

- u1=fan (cheap)
- u2=heater (expensive)



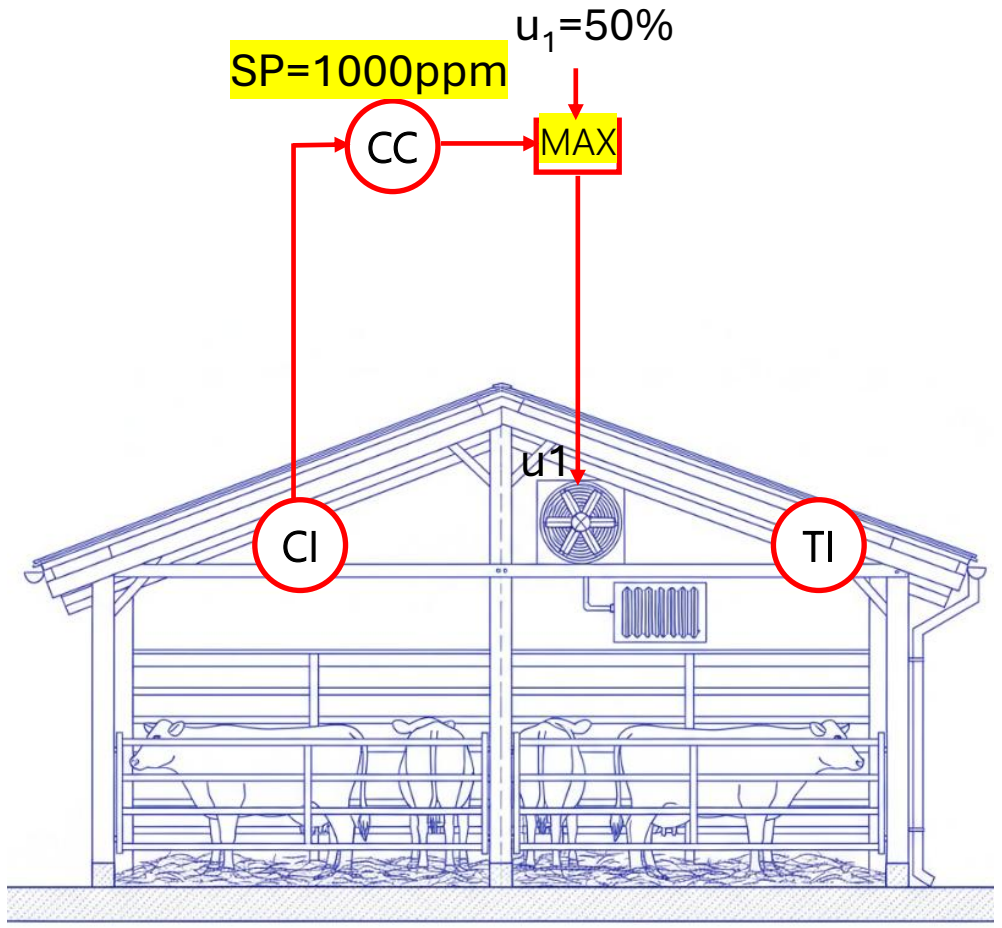
Lower CO2 (less than 1000ppm) is satisfied by large fan speed ⇒ MAX-sel

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



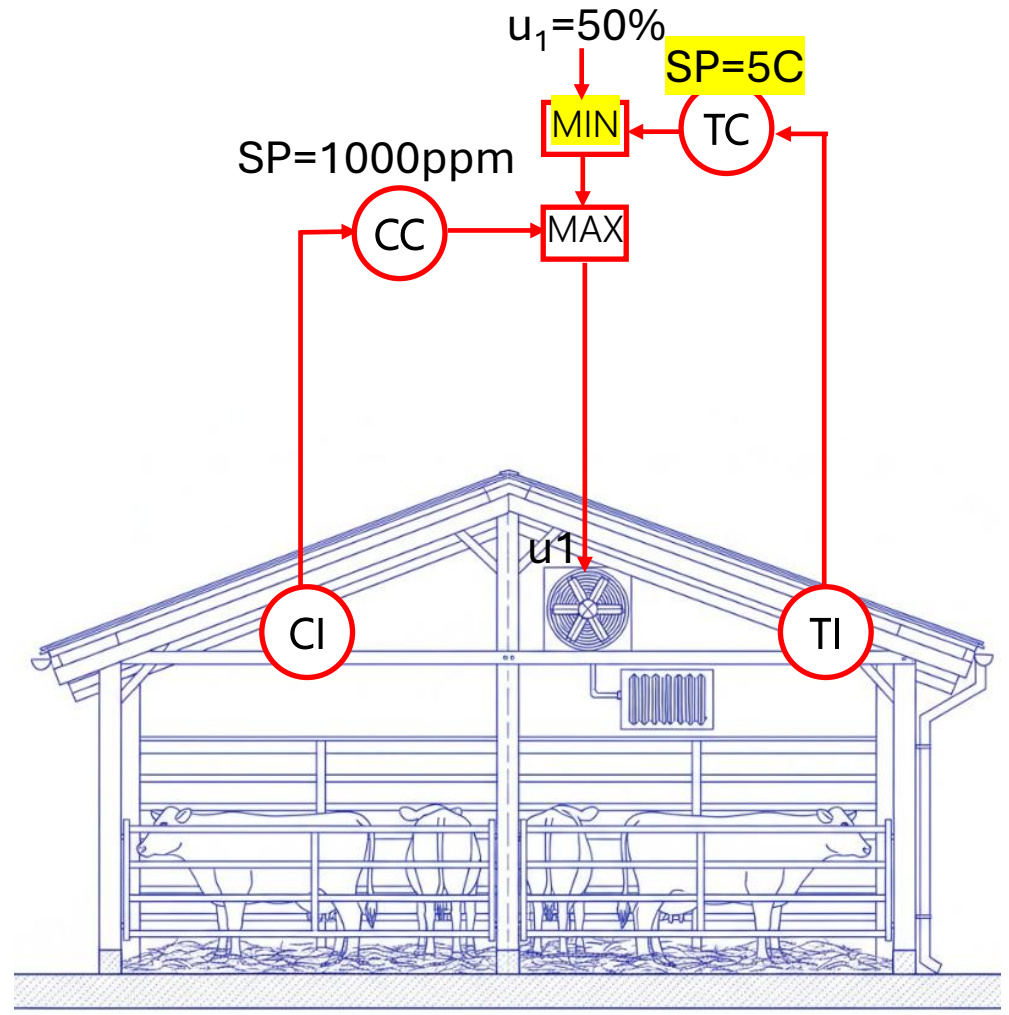
Winter: T (inside) may drop to 5C.
Control: Higher T (above 5C) is satisfied by small fan speed ⇒ MIN-selecto

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



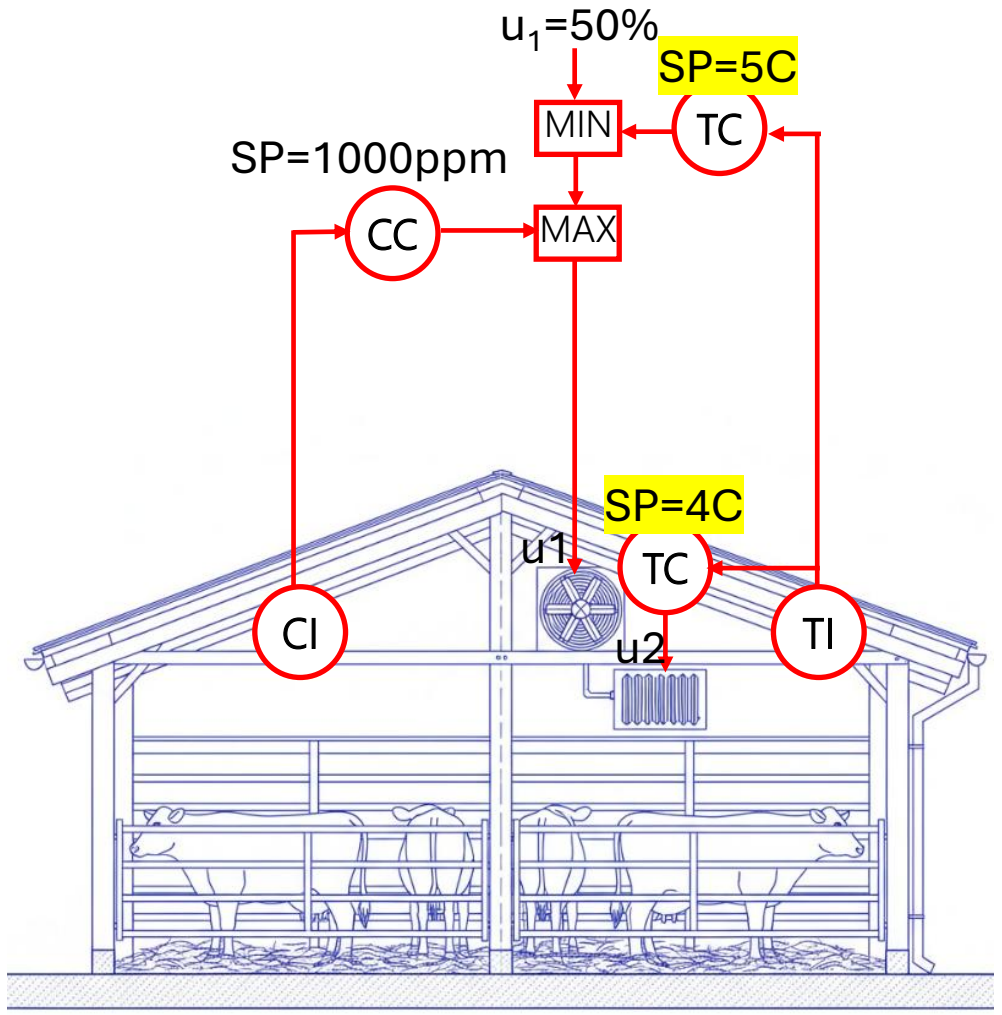
Winter (colder): Cannot reduce fan more because CO2 > 1000 ppm.
Start heater. Use split parallell control (could use split range control instea

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



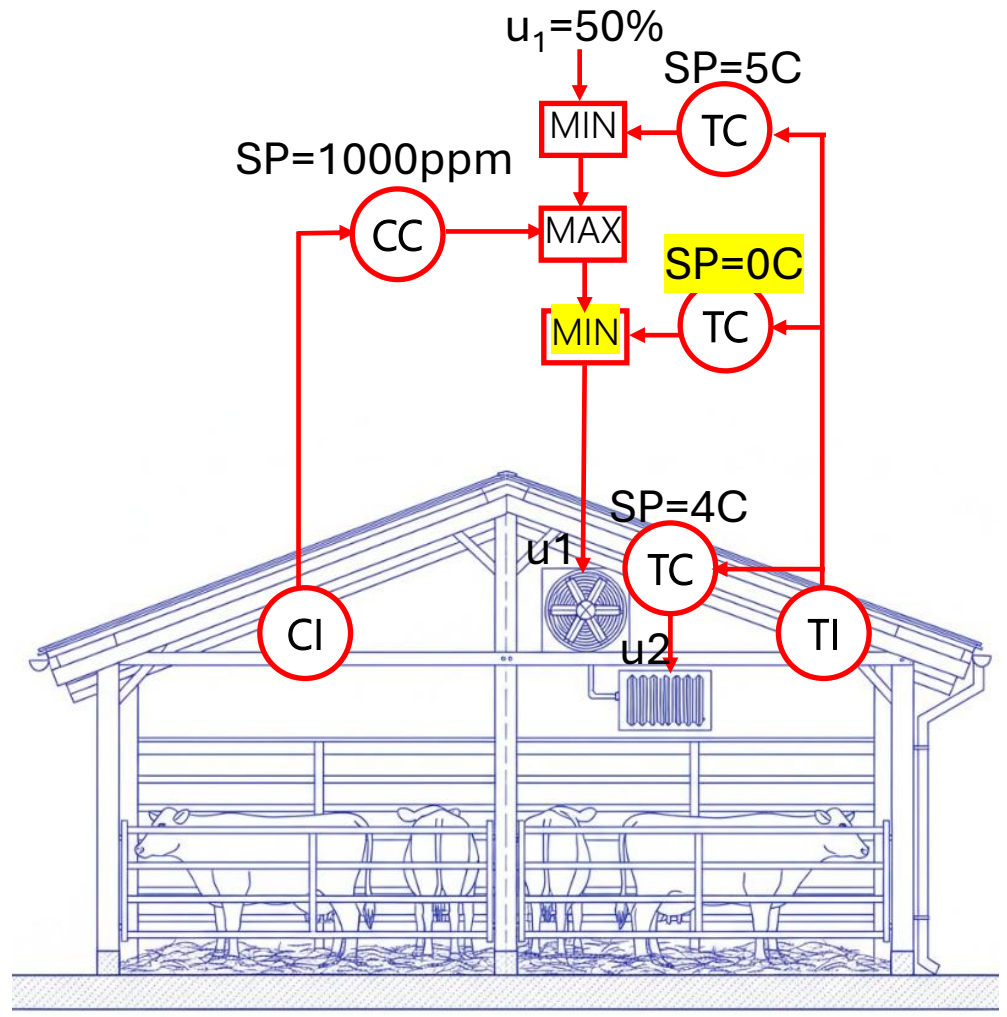
Winter (even colder outide): Heater at max and T drops to 0C.
To avoid freezing unhappy cows: reduce fan speed and accept CO2 > 1000 ppm
Recall: Higher T (above 0C) is satisfied by small fan speed ⇒ MIN-selector

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



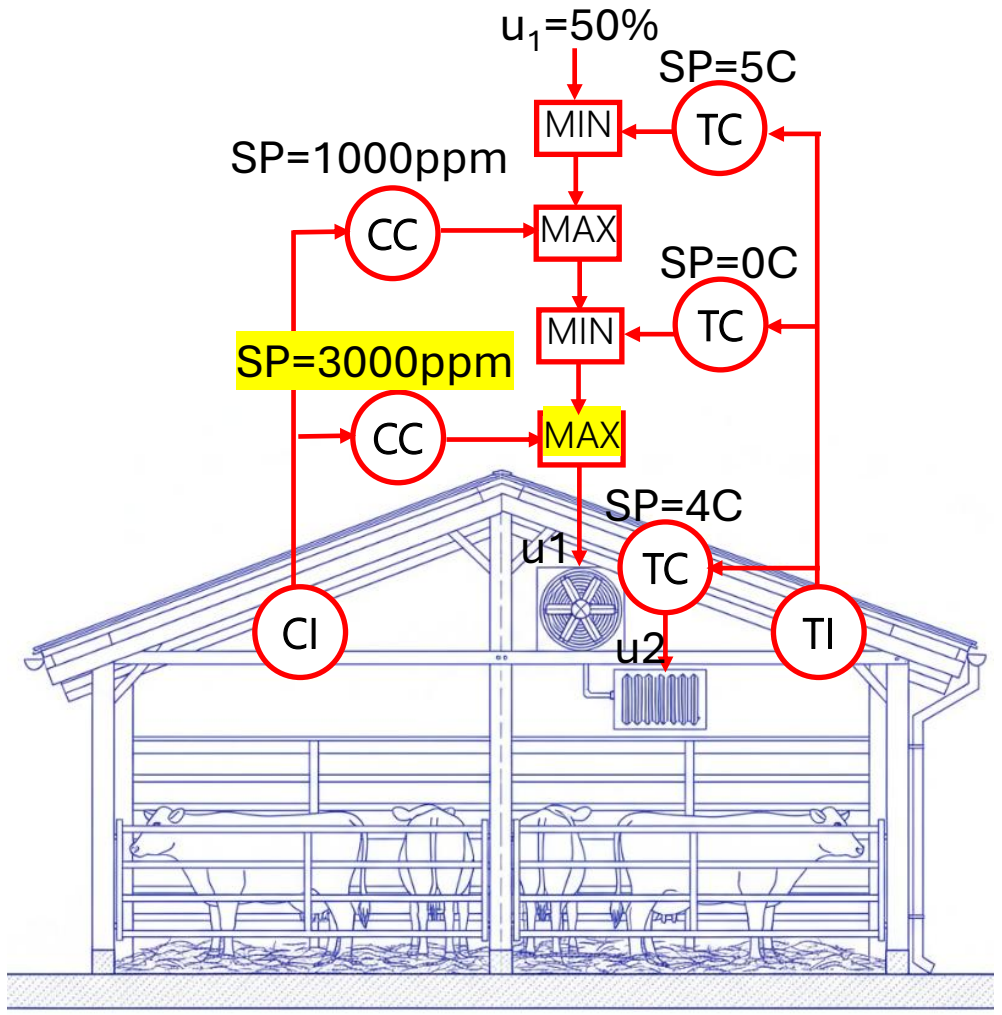
Winter (even colder outside): CO2 reaches unacepptable level (3000ppm)
Recall: Lower CO2 is satisfied by large fan speed ⇒ MAX-selector

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



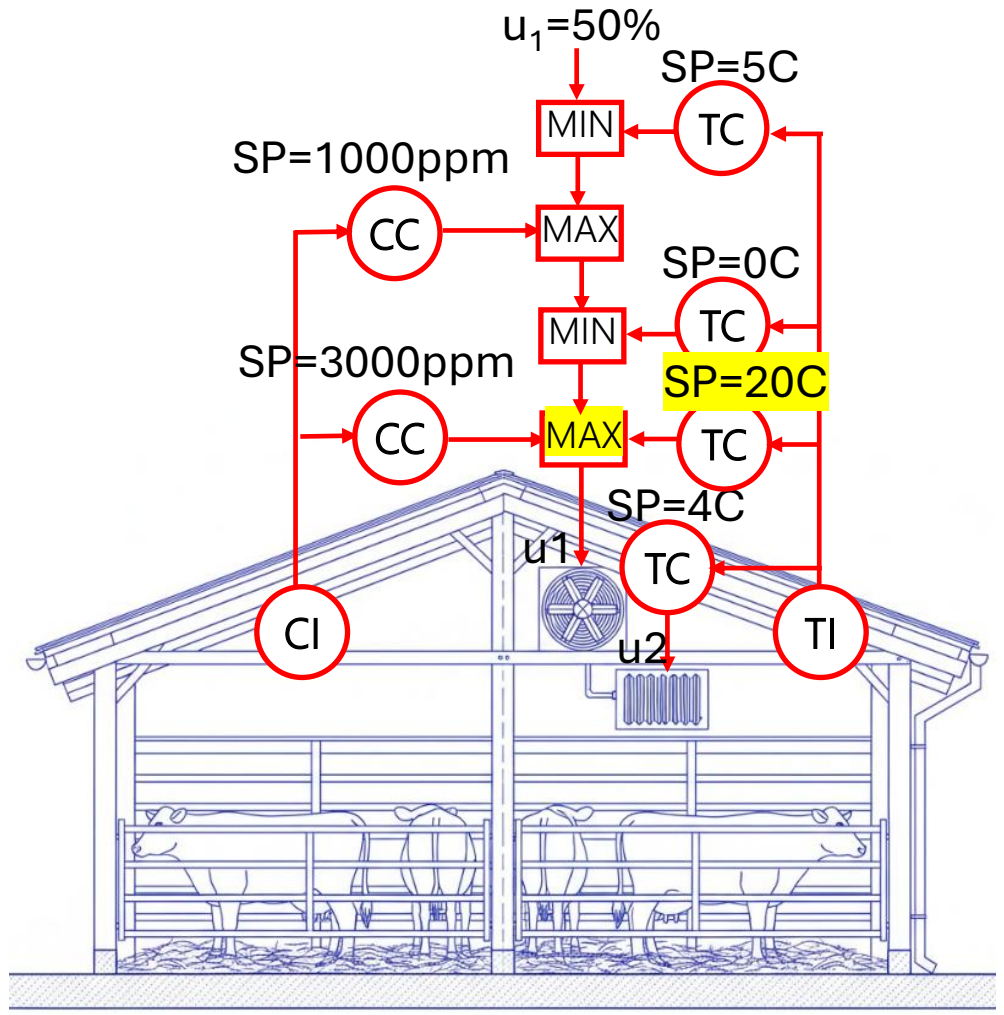
Lower T (below 20C) is satisfied by large fan speed ⇒ MAX-selector
(Consistent with large fan speed (MAX-selector) to keep CO2 < 3000ppm!)

Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

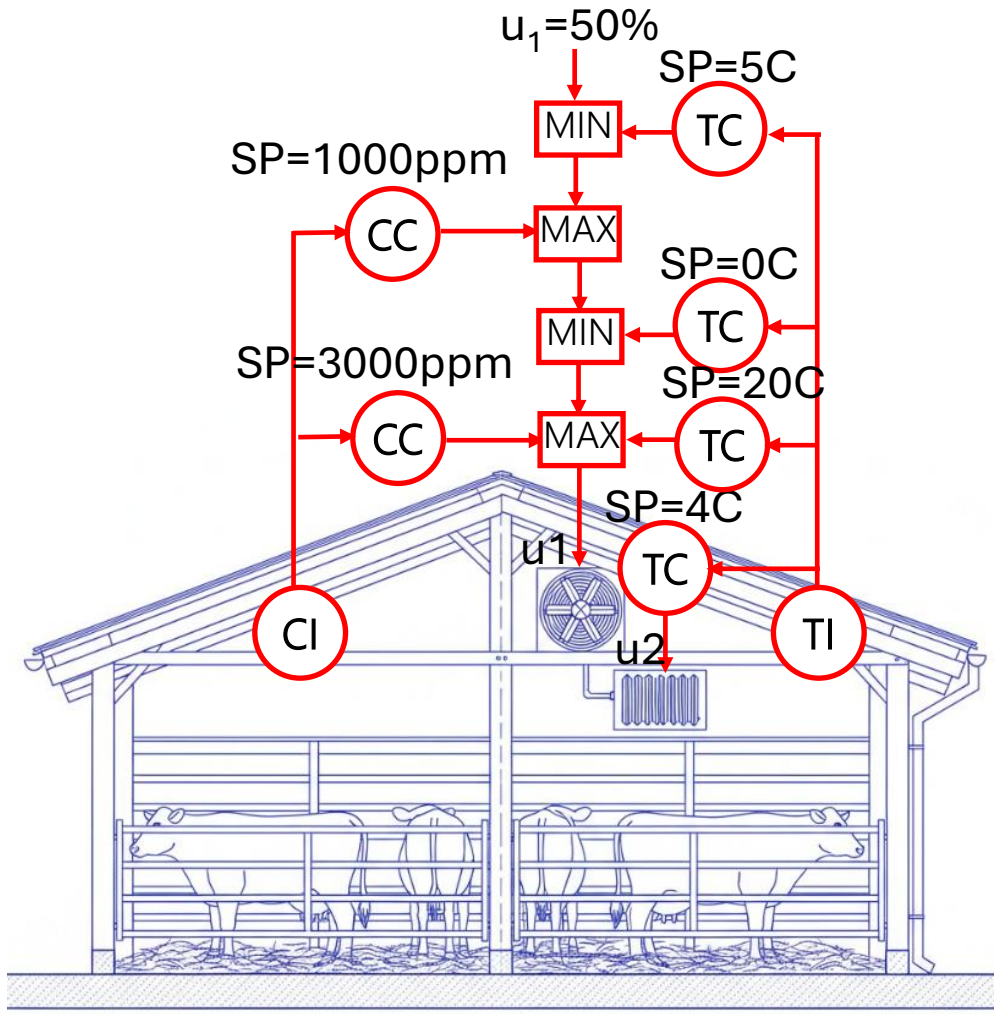
Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)



FINAL OPTIMAL CONTROL STRUCTURE:
4 TCs, 2 CCs, 4 selectors



Happy cows
- y1=C (CO2) less than 1000 ppm
- y2=T between 5C and 20C
- Not too much draft or noise from fan
  - 50% fan speed is good

Unhappy cows
- y2=T less than 0C

Even more unhappy
- y1=C above 3000 ppm (poor air quality)

MVs
- u1=fan (cheap)
- u2=heater (expensive)

If extreme cold: Use blankets for cows
If very hot: Spray water on cows

Annual Reviews in Control 56 (2023) 100903

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Review article

Advanced control using decomposition and simple elements

Sigurd Skogestad

Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ARTICLE INFO

Keywords:
Control structure design
Feedforward control
Cascade control
PID control
Selective control
Override control
Time scale separation
Decentralized control
Distributed control
Horizontal decomposition
Hierarchical decomposition
Layered decomposition
Vertical decomposition
Network architectures

ABSTRACT

The paper explores the standard advanced control elements commonly used in industry for designing advanced control systems. These elements include cascade, ratio, feedforward, decoupling, selectors, split range, and more, collectively referred to as "advanced regulatory control" (ARC). Numerous examples are provided, with a particular focus on process control. The paper emphasizes the shortcomings of model-based optimization methods, such as model predictive control (MPC), and challenges the view that MPC can solve all control problems, while ARC solutions are outdated, ad-hoc and difficult to understand. On the contrary, decomposing the control systems into simple ARC elements is very powerful and allows for designing control systems for complex processes with only limited information. With the knowledge of the control elements presented in the paper, readers should be able to understand most industrial ARC solutions and propose alternatives and improvements. Furthermore, the paper calls for the academic community to enhance the teaching of ARC methods and prioritize research efforts in developing theory and improving design method.

Paper (2023) is open access and is also available on my home page (search for "skogestad")

Implementing optimal operation by switching

- Most people think
  - You need a detailed nonlinear model and an on-line optimizer (RTO) if you want to optimize the process
  - You need a dynamic model and model predictive control (MPC) if you want to handle constraints
  - The alternative is Machine Learning
- No! In many cases you just need to measure the constraints and use PID control
  - «Conventional advanced regulatory control (ARC)»
- How can this be possible?
  - Because optimal operation is usually at constraints
  - Feedback with PID-controllers can be used to identify and control the active constraints
  - For unconstrained degrees of freedom, one often have «self-optimizing» variables

- This fact is not well known, even to control professors
  - Because most industrial ARC-applications seem *ad hoc*
  - Few systematic design methods exists

- Today ARC and MPC are in parallel universes
  - Both are needed in the control engineer's toolbox