Thermal systems – control problems (part 2)

list of control problems pt. 2

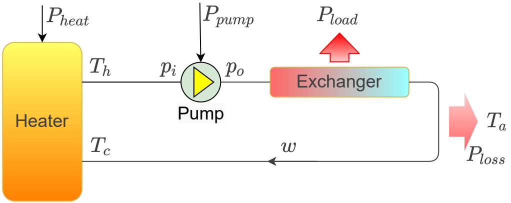
- Thermal control with central/local sources
- Thermal control with actuator equalisation
- Keeping (comfort) variables within limits w/ overrides

↳ practice examples to study this

Foreword

- Suppose you have to provide a certain heat rate to a body or ambient by means of a thermovector fluid (here, liquid).
- This means in general that you need to govern
  - a temperature or a temperature difference across some exchanger,
  - and possibly a fluid flowrate.
- Are the two controls independent?
- Which are the energy-relevant aspects of the problem?
- Let us investigate.

Controlled system



- Assuming no pump heating nor gravity effects (for simplicity and without impairing the following treatise) the heating and pumping powers are respectively

$$\begin{aligned} P_{heat} &= wc(T_h - T_c) \\ P_{pump} &= w\,\frac{p_o - p_i}{\rho} = w\,K_{piping}w^2 = K_{piping}w^3 \end{aligned}$$

• Additional PROBLEM to introduce:

▶ BODY / AMBIENT T control with inner Flow control

{ NOT as the one address → { cascade structure where Flow control is inner loop respect T control }
(while previously we consider the two toghether..) }

For T control:

{ • in an ideal world control signal(s) is/are Power(s) (ideal Thermal power as command var.)
• in REAL life control signal(s) are valve opening(s)

Can we use cascade control with some additional measurements to make Real life more ideal?

(IoT, smart sensors... we are full of measurements → why NOT to use this additional INFO? ☺)

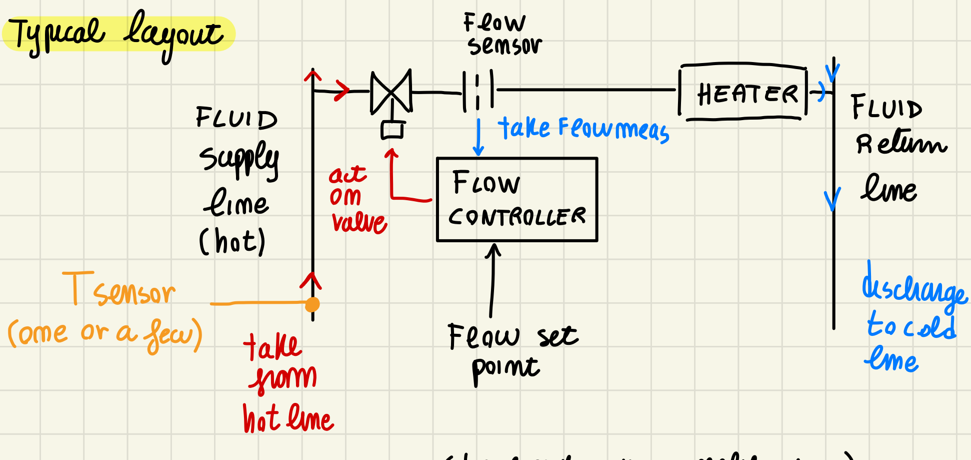
⇓

YES, let us see Why & how

• Reason 1) if one can measure ΔT across a heating (cooling) element, than flow control allows to "almost" control power

⇓

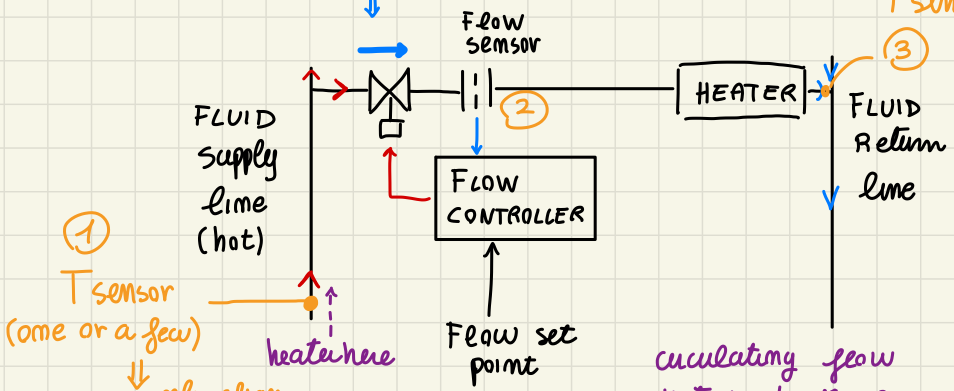
Typical layout



(heat network simplification)

(Layout)

If changing the flow rate taking here, the Temp. doesn't change...



T sensor one per element or group of)

⇓ only changes due to losses! : If well isolated, one measure across line is enough

[T sensor are very common on room Temp control → Typical usage in building → that can be usefull for control purposes

1 & 3 give you ⇒ ΔT across element (heater)

$(W \, c \, \Delta T) =$ POWER hence, if $\Delta T \sim$ constant

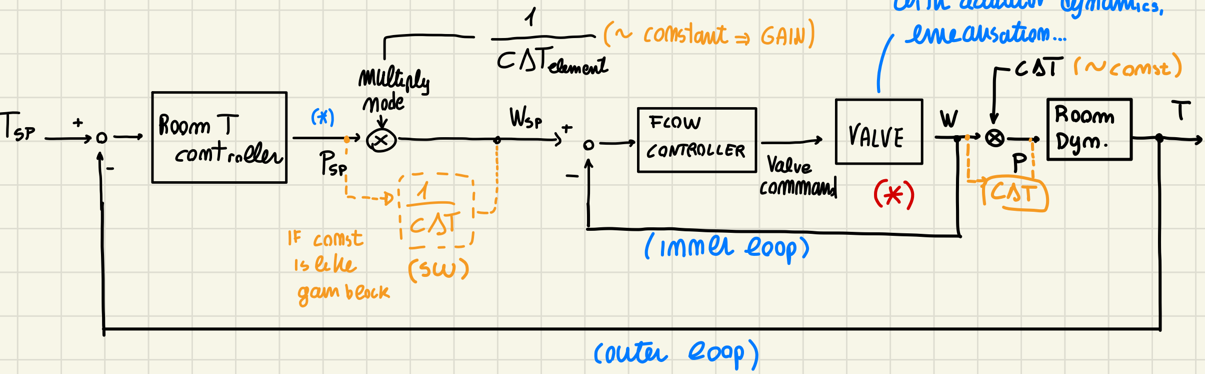
⇒ Power set point becomes ~ Flow set point

(Notice)

↳ the seen scheme are NOT so commonly implemented
(there is an interest on future usage of it!)

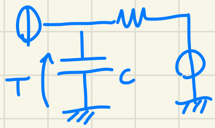
transform it into block diagram! ⇒

let us view the system as BLOCK DIAGRAM (from phisical scheme)



(*) ideally we want power P here so, respect room

↳ BUT NOT power control var → we have a set point request P



electric equivalent

- You have @ end to set a nominal ∆T (if ∆T elem. small change → you properly set up)

IF big ∆T changes → Flow sensors located to get ∆T as nom lin. gain

+ Flow loop!

↳ Flow control valves are lot used today BUT NOT so cheap

($WC\Delta T = P$ ⇝ to get POWER I get W_{sp} by dividing P_{sp} for $C\Delta T$)

$C\Delta T$ ~ multiplicative input OR constant Gain...

set up a flow control and take ∆T measury or assume const to compute s.P

(*) a variation in the supply pressure changes the gain of this block

$\sim\sqrt{\rho\Delta P}$ changing it, different gain! ⇒ Further reason for a Flow loop...

{ usually you don't aspect dominant flow rate, so NO significant Δp
BUT if a supply line you can have Δp! NOT IF good sized net! system.. }

⇒ ... Further reason for a flow loop

↓ motivations:

- IF supply T varies, the power set point to flow s.p ($P_{sp} \rightarrow W_{sp}$) relationship (assuming ΔT measured) compensates
  (measuring ΔT (not const) → can be compensated)
  BUT if supply pressure varies, in the absence of a flow loop only the T loop would notice (far later)
  ↓
  changing supply temperature.. than in a properly design system ΔT emitted can be compensated
  IF ΔP supply vary → you notice effect when ΔT_{ROOM} vary..
  while flow loop intervene immediately

Flow loop: {
- you like to have P as control var, so you use valve opening.. To turn power control into flow instead
- IF supply pressure problems you need flow loop to restore... to have good T control

typical control problem... having inner flow control as internal control syst for temp.

▶ BODY/AMBIENT T control with centralized source (can be storage) plus further local energy inputs

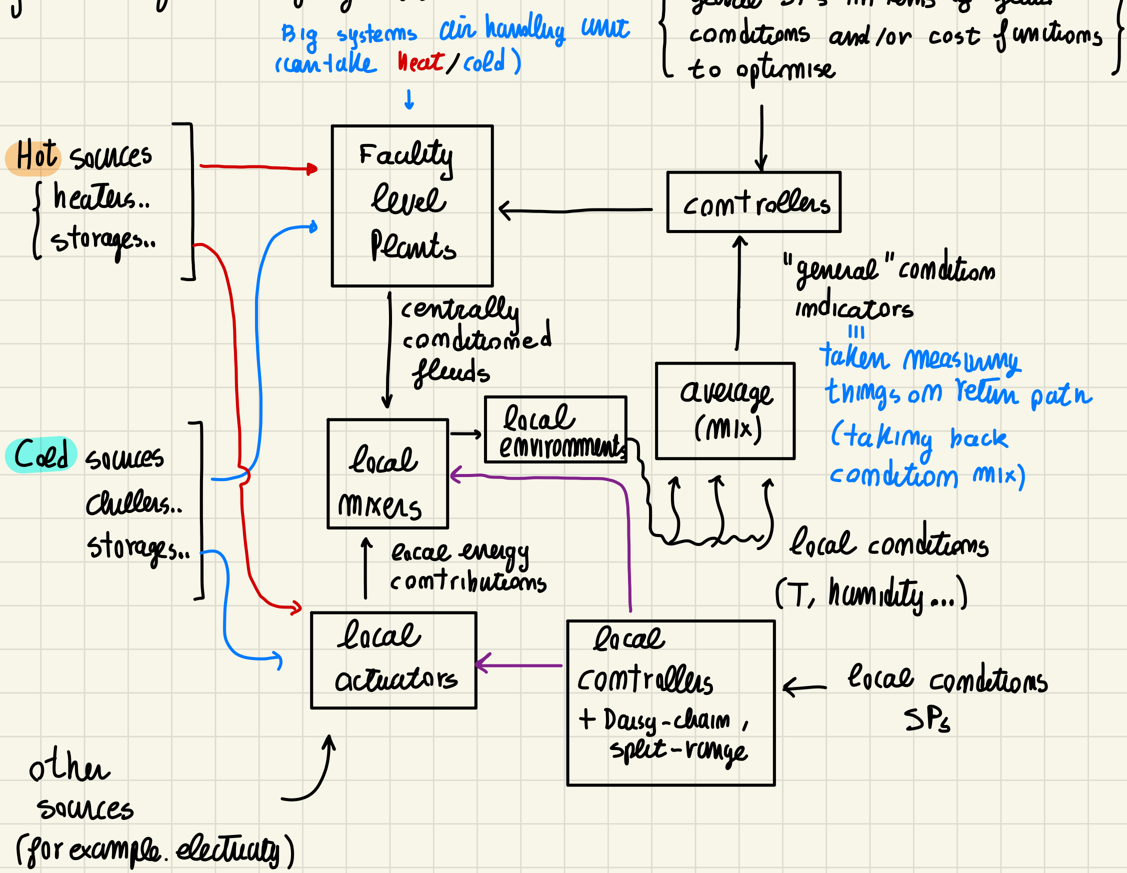
⇒ Daisy-chain & split-range (technique used)

↓

LIBRARY: Coursework.Thermsys_control_problems..._central_local...

in Modelica > coursework > Tcontrol_central_local

• physical layout (highly schematic)



(it is all a crossing of energy flows)

⇓

overall scheme important!

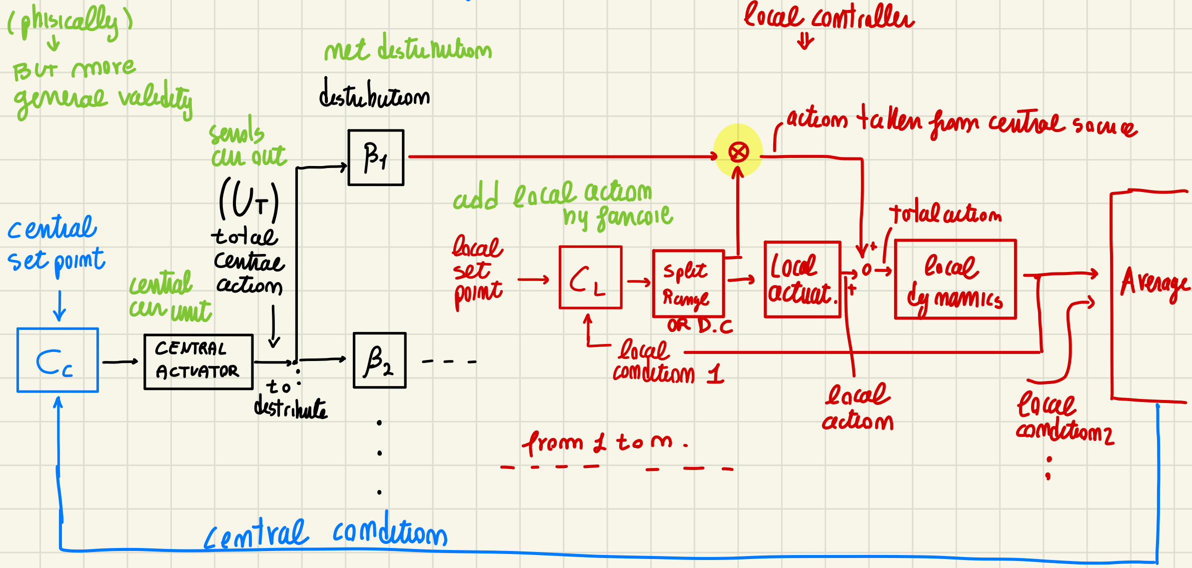
We have global / local automation ⤸

all mix up toghether! the compound of all dictate the energy result of overall

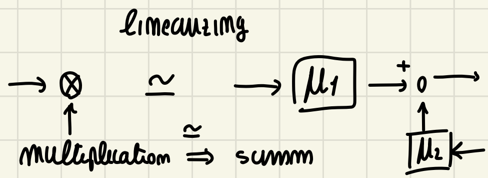
⇓

How to turn it into block diagram ?!

- Let us enucleate a block diagram



⊗ in the small



Split Range.. after C_c decide energy for local entity → where to take that amount of energy?

⇐ central / local source...

central / local storage energy ?
which most effective ?..

• ISSUE 1) you cannot control all local conditions (for example room temp) and their average as well — constrained!

problem, C_C / C_L different controller HOW?! ... unless there is some additional RELEVANT dynamics,

such as a mixing volume large enough

consequence

⇒ the mutual relevance of central & local actions may vary ;
as a meaning case, local controllers may completely take over
(IF enough Reactive... local can cover completely, so central one not work good.. !) → strange behav ⇒ over constrained system
heat up too much!

IDEAS

1) give up external (central) loop, set U_T based for example on climate (spline optimization)

2) compute U_T with a VERY LONG time interval, making the external loop irrelevant at the time scale of the internal ones

• Further reason to not have too much autority for the inner loops: (this structure not only for climatization.. limitations!)

- local controllers view the action of the central one as a load disturbance and IF NOT properly set up, they might try to compensate, thereby working against the overall objective

don't want to acts one against another!

Looking Modelica

Daisy chain output more signals!

central heat capacity :(Faculty level)

Keep T of heat cap.

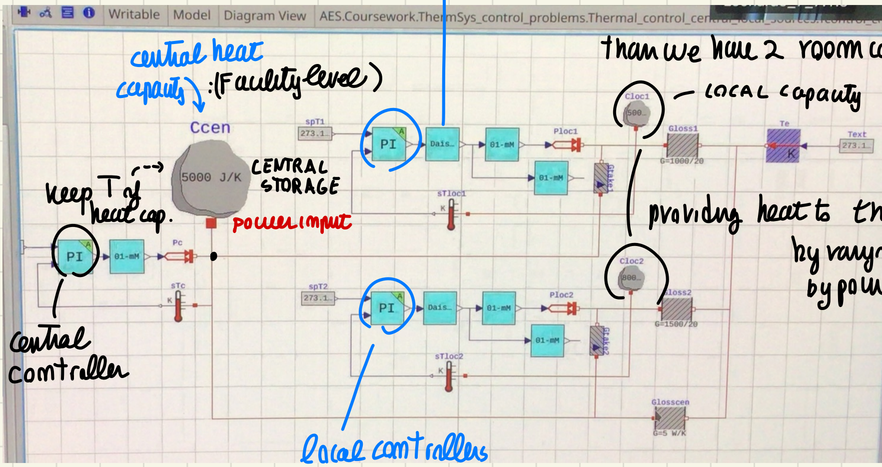
CENTRAL STORAGE

power input

then we have 2 room capacity

— LOCAL capacity

providing heat to the two rooms by varying resistance OR by power input!

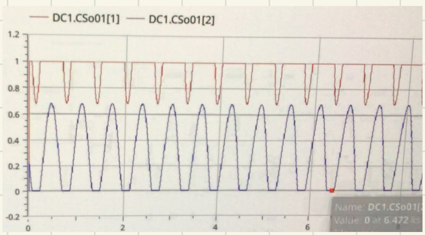


central controller

local controllers acting through dasey-chaim

signals

SIMULATION...



depending if using First local than central or viceversa...

you can work on same condition..

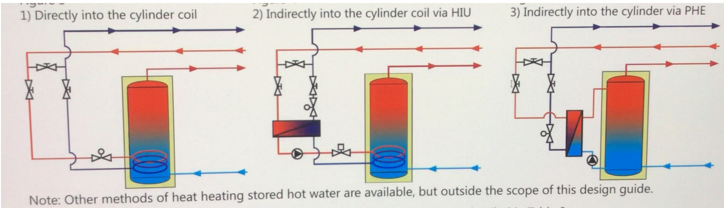
Better solution depends on the cost of change local storage or use central

How we menage central storage?!

[RECAP 10/05]

documents: HWA → Usage of storage devices in heat networks (Hot water Association)

How storage can be used to decouple



introduce storage, (centralized source) at several levels

↳ common usage → gather when available and store the remaining one!

We found a scheme with central energy storage + central controllers and local actuator / energy sources → contribute on local environment

2 level control system

↳ Focus: understand the problems → Ideas! not equations..

⇓ attempt to turn into block diagram with central actuators, and distribute with local energy sources..

↩ and we see an example with central storage + 2 local storage

∀ local part you have split-range to decide the proper control..

Issues.. give you a Reason to add storage!

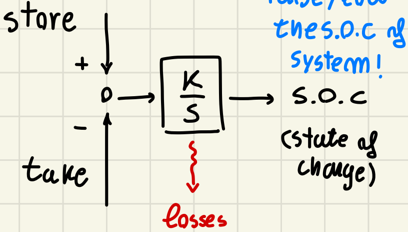
⇓ you can set control on climate or another ideas (2)

How to manage (central) storage

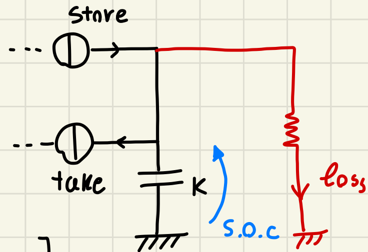
In a nutshell – but for our purposes realistically enough – we can represent the storage element as:

simpler represent as integrator

raise/low the s.o.c of system!



≡ electrically



real capacitor with losses..

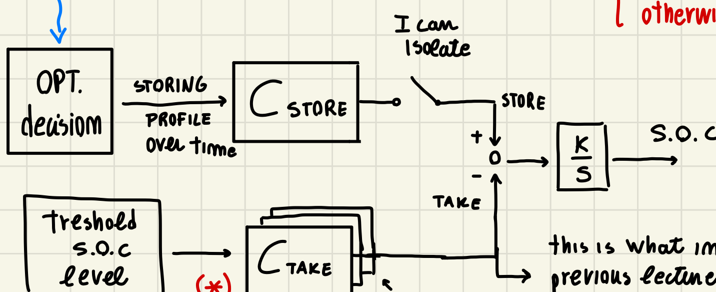
⇓

[how to organize the control of it... considering the two objectives:
- keep s.o.c high enough to fullfill requirements
- manage energy effectively] ?

Typical conceptual structure

(*) this controller can have an override,
- IF s.o.c > threshold : obey to local request
- otherwise : act to keep s.o.c above threshold

info (energy availability, price...)



this is what in the scheme of the previous lecture we interpreted with U_T

local requests (ex: from split range in local controls)

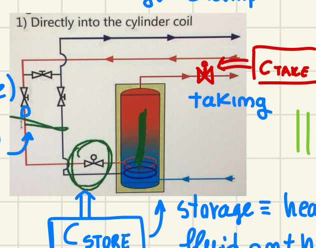
[can be complex. further request to govern actuators..]

s.o.c info (optional)
IF s.o.c < trashold I can act properly!
ask more

I see a demand flow rate

for example..

(store)
taking energy here



|| utilizers

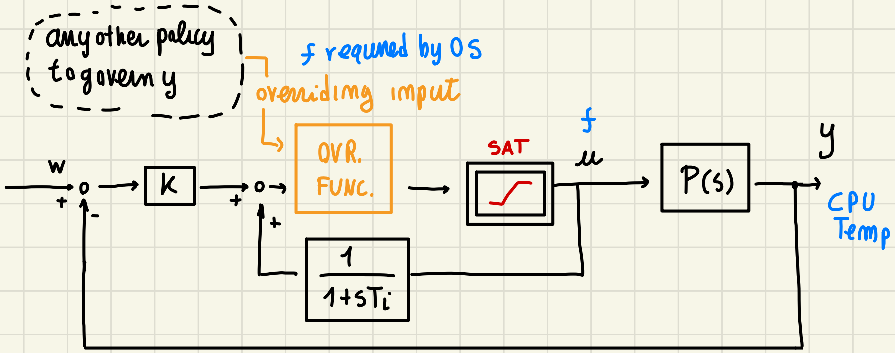
storage ≡ heating up fluid on the tank

So you have 2 controllers... → how they communicate between each other ⟹ for coordination! don't fight one another

What is OVERRIDE CONTROL?

↓

(using a PI as example)



OVR FUNC: (override function) is typically: MAX or MIN

assume for example..

- y = temperature of a CPU
- u = frequency
- w = upper limit temperature
- overriding input = OS governor request (raise freq with load)
- OVR FUNC: min

If f↑ you heat up → consume more!

↳ if below limit T := it try to heat up... OS governor is free (ask f↑)

high load ⇒ raise f → IF so hot that $f_{limit} < f_{gov.}$ ↴ you override the governor

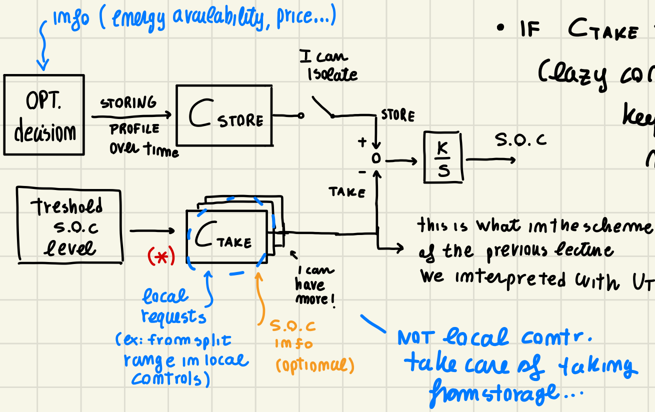
simple PI with override (one line of code) → hierarchy...

(relevant energy problem on computing system)

We can force depending on s.o.c to override the control...

Interaction between controllers → communication through the process

more than one controller connected to the same process, inherently communicate one another!



- IF C_{TAKE} tuned for low bandwidth (lazy controller) ⇒ means that keep local set point, mantain S.O.C by open loop
  ↓
- IF C_{TAKE} reactive.. handly intervention.. request fall on storage

C_{TAKE} "lazy" (ex: and most typically, low bandwidth → slow action)

the action of local "agents" to mantain S.O.C will allow this to flactuate

⇒ most of the burden to keep local set points will fall onto local controllers (If slow storage responce → actuators burden..)

⇒ more use of local energy (NOT from central storage) FOR THE PURPOSE of keeping S.O.C mantained by local charge... we delegate this

C_{TAKE} "reactive"

Handly any local intervention

⇒ any surplus energy request will fall on the storage

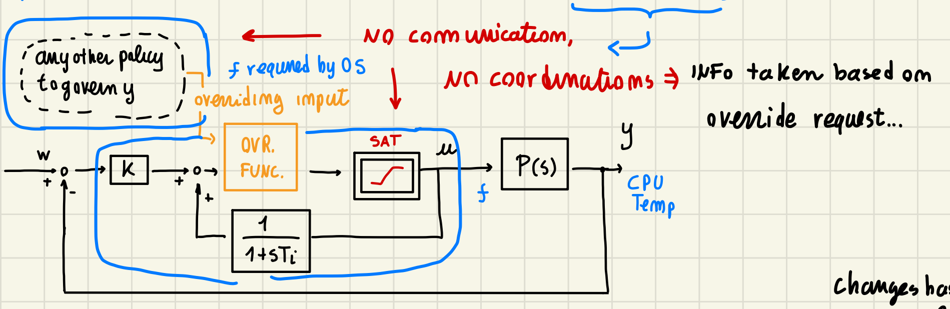
- Decision (have central controller more or less reactive than local ones) depends on convenience

- Local loops NATURALLY CONFORM to this decision. there is NO need for explicit communication as the phisics itself of the process propagates the information

↓

respect CPU example...

There is no communication between the two entities



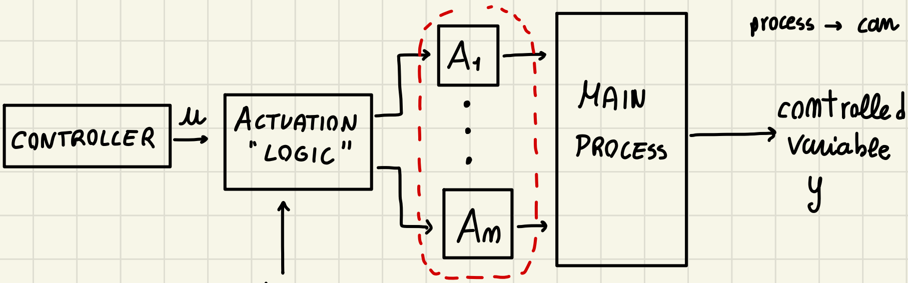
central controllers { fulfill local request, mantain s.o.c → With controller var s.o.c depending on... changes based on local request! If reactive s.o.c rapid change; If lazy s.o.c fluctuate Bad slow

⇓

changing the gains on a controller example... we see more fluctuation!

▶ THERMAL CONTROL WITH EQUALISATION OF ACTUATORS IN A DAISY-CHAIN OR SPLIT-RANGE CONFIGURATION

↳ we deal with a single controller with 2 or more actuators on same process → can make dyn. different to make behav. bad of control
↓
so you try to equalise.. or control in cascade to solve it!



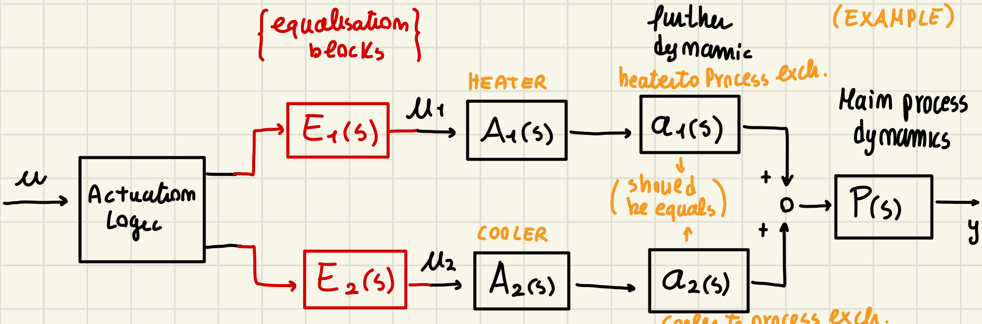
Modulating block

PROBLEM: different dynamics in these blocks

Two main ways to adress the probleem:

1) Simpler one: EQUALISATION (we explain in an LTI setting)

JUST 2 actuators for simplicity (no generality loss)



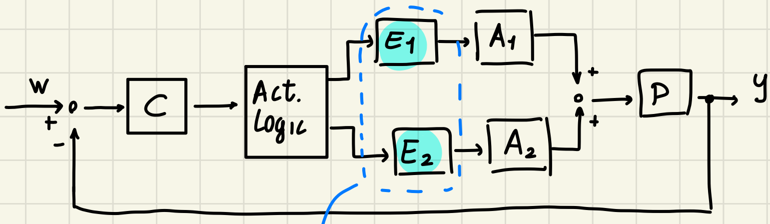
Actuators
↓
for ex: hot/chilled water valve.
(venting unit)

sending fluid to coils where heat exchange happen } ideally equal heat exchange...

Actuator-process interaction (should be uniform in a well designed system)

{For completeness the $a_i(s)$ are hardly ever of significant concern}
↑
it can have different interaction sometimes

Idea: build the control scheme as



choosing E_1, E_2 such that $E_1 \cdot A_1 \simeq E_2 \cdot A_2$ as close as possible!

↓

In practice one can choose a T.F $\alpha(s)$ to describe both equalizer-actuator cascades, tune C for the process αP and than set $E_1 = \alpha / A_1$ $E_2 = \alpha / A_2$ → BUT how to choose α ?

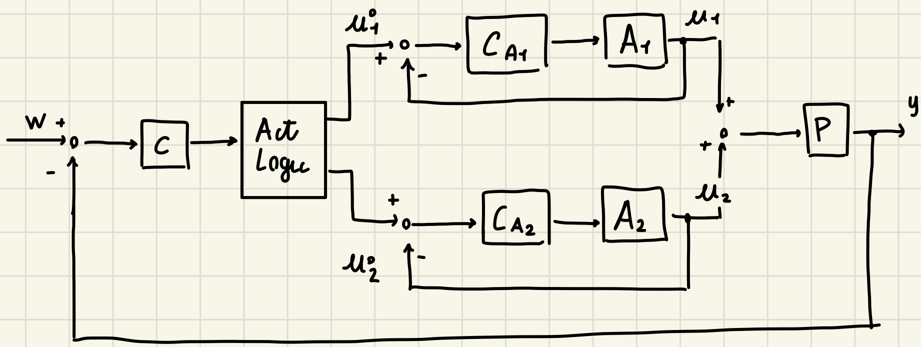
- can slow down the faster of the two actuators
- IF not OK can try to speed up the other, but up to a point owing to saturations (problem 1) phisically possible!
- [In general (we attempt to make 2 T.F equals by dividing, this is for sure not Robust)] not ROBUST: if A_1 and/or A_2 are NOT precise there is NO equalisation (problem 2) simple sol, NOT so Robust

↓

equalisation is NOT obligatory.. I can tune for slowest and have Robust for the other with difference $\mu < 0$, $\mu > 0$ for other τ → tuning for slowest you satisfy the faster! IF too relevant difference you need to equalize

P2: A_i can change dyn → this can cause bad Equalisation

2) complex one: local control loops



Cascade structure: works if the inner loops $C_{A_1} A_1$ and $C_{A_2} A_2$ are faster than the outer one $C \cdot P$ because in that case (ideal) in the control band of the outer loop you have $\frac{u_1}{u_1^\circ} = \frac{u_2}{u_2^\circ} \simeq 1$

ROBUST in the face of modelling errors and/or variations in A_1 and/or A_2 (feedback solve uncertainty)

BUT requires to measure the actuator outputs (often powers ?!)
not a simple task..

↓

You can have decent measurement with small transmittence
(typically used for building if Room/Water T known you can estimate power consumption)
↳ in future also for periphal element
In electric syst → electric consumption computed by efficency hyp.
(you need to measure actuator OUTPUT)

▶ KEEP ONE (OR MORE) VARIABLE(S) WITHIN LIMIT(S) by using one or more actuators

↓

Typical case:

- T control
- Heater & cooler available
- OK having T fluctuate between T_{min} & T_{max}

normally control follow a set point OR reject disturb! → in this case we want a controlled variable inside a range, put the set point to T_{avg} is not necessary! We are spending useless energy → if fluctuate $T \in (T_{min}, T_{max})$ not necessity to cool/heat. While to keep T_{avg} I need to heat, cool all the time!

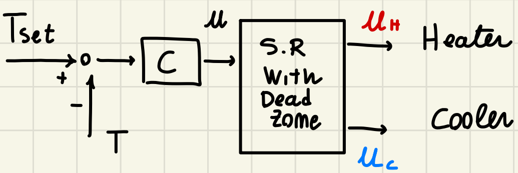
- Set Point at some "intermediate" value is NOT energy-efficient:

  IF: $T_{min} \leq T \leq T_{max}$ I do NOT want to heat NOR to cool!

⇓

Idea 1: dead zone on control

ex: $T_{SET} = \dfrac{T_{max} + T_{min}}{2}$



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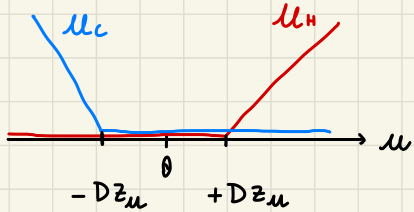
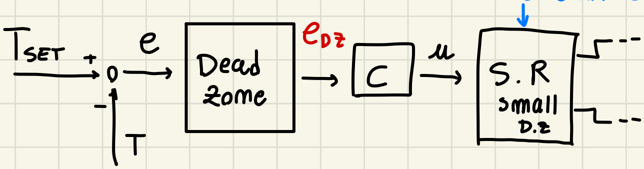


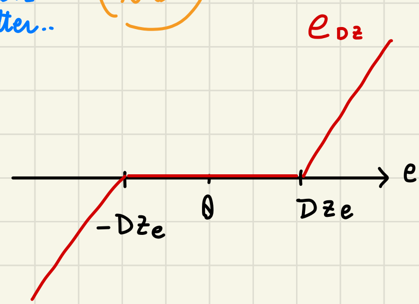
(dead zone amplitude)

Idea 2 dead zone on error

with small D.Z to avoid chatter..

NO





If small error $e \to e_{DZ} \simeq 0$ do nothing!

IF instead $e > DZe$ act...

⇓

since small DZ on S.R → IF control is 0 also S.R get 0 OUTPUT

evidence PRO & CONS of Idea 2:

(- IF small $e \Rightarrow$ you see 0 on C input.. BUT this does NOT means 0 on c output unless integral action!)

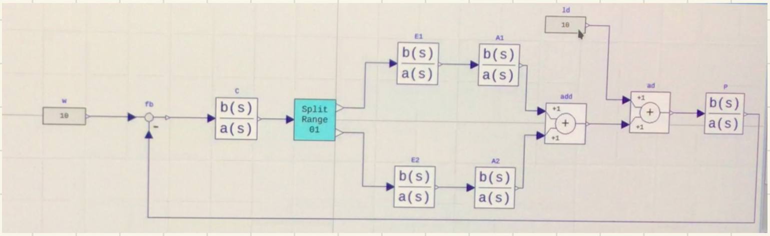
Beware. $e_{D.Z} = 0$ does not imply $u = 0$ unless NO integral action (& transient exhausted)

(prevent small useless moovement of actuator putting D.Z on actuator to stay @ constant e value..) → BUT it does NOT WORK as we want!

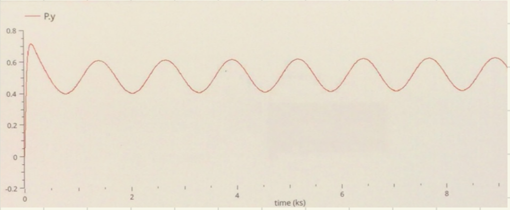
- While Idea 1 could WORK! → let's try it on Modelica example

Introducing a disturbance...

load disturbance ed: 0.4+0.2*sin(time/200)

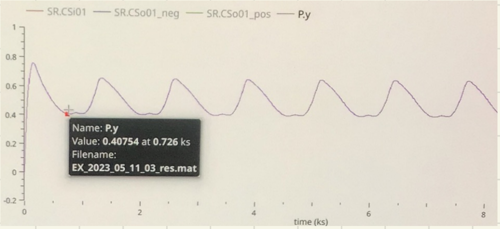


Simulating it...



attenuated disturbance.

IF adding dead zone.. of 10%.



IF 0.01% dead zones increase...

(• • •)

It is NOT easy to relate dead zone amplitude with oscillation amplitude of controlled var.

→ I want it to stay in between two limits...

{ But relation dead zone and amplitude of y is hard ! }

Idea 2: not suited to the problem, DZs on error are usefull to avoid undue small frequent actuator movements but NOT for our probeem (some controllers square the error → e^2... more $e\uparrow$ and greater gain of C, sliding mode control BANG BANG/LINEAR..)

Idea 1: can be usefull BUT it is NOT immediate to select the DZ limits (which in general could even NOT be symmmetric) given the allowed "free run" range for the controlled variable in the example

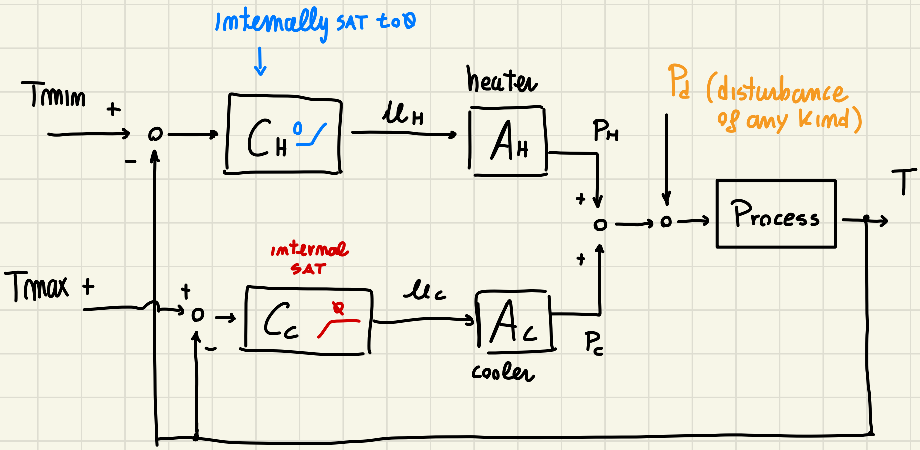
$(T_{min}, T_{max}) \xrightarrow{?} DZ$

relation hard to find...

{ It will depend also on disturbance type... }

• PLUS, with Idea 2 we may still have to equalize the actuators or set up the cascade structure seen before (1 control, 2 actuators)

Idea 3 & PREFERABLE : use two controllers and exploit saturation



When Temp on range none of A_H, A_c should act!

IF $T \sim T_{Max} \rightarrow A_c$ should act
IF $T \sim T_{min} \rightarrow A_H$ act

ask the Heater to maintain T_{min}! (NO SAT)
IF I try to go $T < T_{min}$ it act (>0 control)
if $T > T_{min}$ ↑ it try to cool down but it can't because SAT. (<0 NOT by A_H)

heater with its own set point, try to set point T_{MIN}! if
$T > T_{min}$ I wanna cool
but I can't → SAT → do NOTHING
IF $T < T_{min}$ I do a positive action and heat up!

IF I need to heat, C_H ACT... IF I need cool NOTHING happen, SAT to 0

equally for the cooler! IF $T < T_{max}$, cooler sat to 0 (NOTHING DONE)
IF $T > T_{max}$, cool down, neg action required ✓

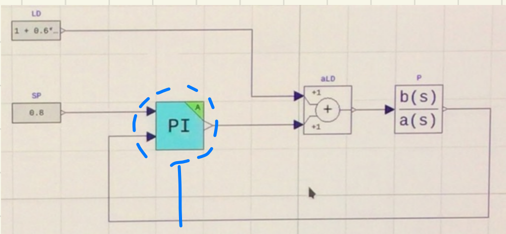
- heater will only act on T approaching T_{min}
- cooler will only act on T approaching T_{max}

PLUS: I can tune C_H for A_H.Process
and C_C for A_C.Process } no moore equalisation needed! because each actuator has its own controller tuned!

⇓

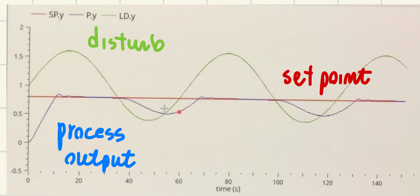
on Modelica
>Typical_control_structure >Keep_below_limit ($T < T_{max}$)

Load disturbance



controller
SAT on (-2,0)

⇒ simulation



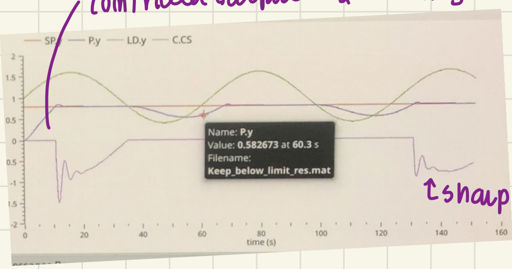
disturb

set point

process output

controller output: Q When y can fluctuate..

acts only when y near the limit



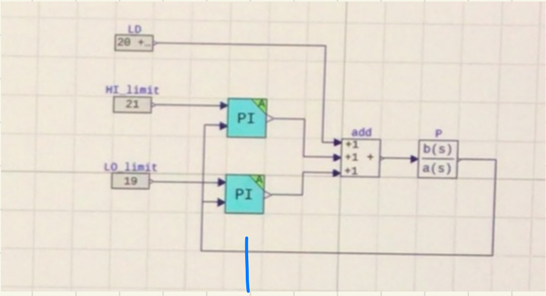
↑ sharp reaction

$T < T_{max}$ not heat up too much with comfort zoone

> Keep_within_two_limits

lower upper limit

$$19 \le T \le 21$$



two controllers

in open loop we have oscillating behaviour

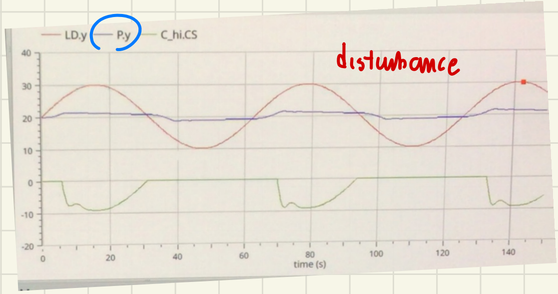
↓

closing the loop with high/low limit

⇓

process output y remain inside range!

↳ I can increase PI gain to be sharper inside the range...



disturbance

all related to your design...
IF critical control you can put a safety zone limitation, higher gain to guarantee..

{ so with idea 3 you don't need to properly design the dead zone amplitude... }

Thank you for your attention

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