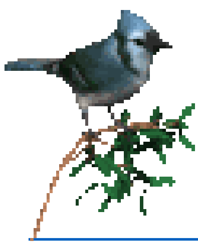
Sveučilište u Zagrebu

Fakultet elektrotehnike i računarstva

Zavod za automatiku i računalno inženjerstvo

Laboratorij za podvodne sustave i tehnologije

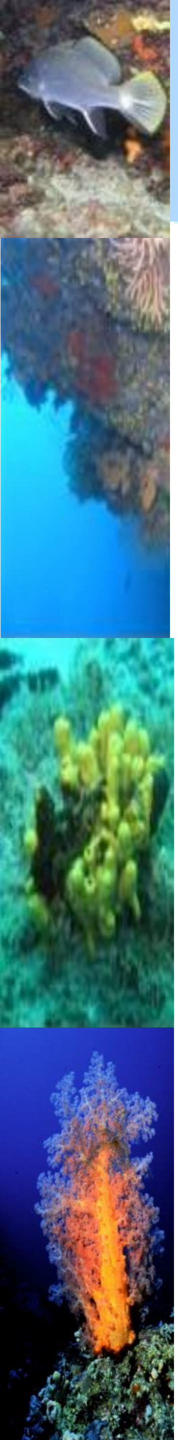
Lectures 1 & 2
Why adaptive or robust control?



Prof. dr.sc. Zoran Vukić

Evolution of control theory

- Classical control : 1940~1960
  - – Transfer function based methods
    - Time-domain design & analysis
    - Frequency-domain design & analysis
- Modern control : 1960~1980
  - – State-space-based methods (optimal and adaptive control)
- Robust control : 1980~2000 (QFT, H_{∞} , ...)
- Intelligent control : 1990~2000 (fuzzy and neural,..)
- Cooperative & Reconfigurable & Cognitive (present hot topic of research)



Semantics

<u>Adapt</u>:

1. Fit, adjust, make suitable.
2. To adjust behaviour to a new circumstances.
3. Alter or modify to fit for a new use, new conditions. Any alteration in structure or function of and organism to make it better fitted to survive and multiply its environment
4. Undergo modification to fit a new use, new conditions.

<u>Learn</u>:

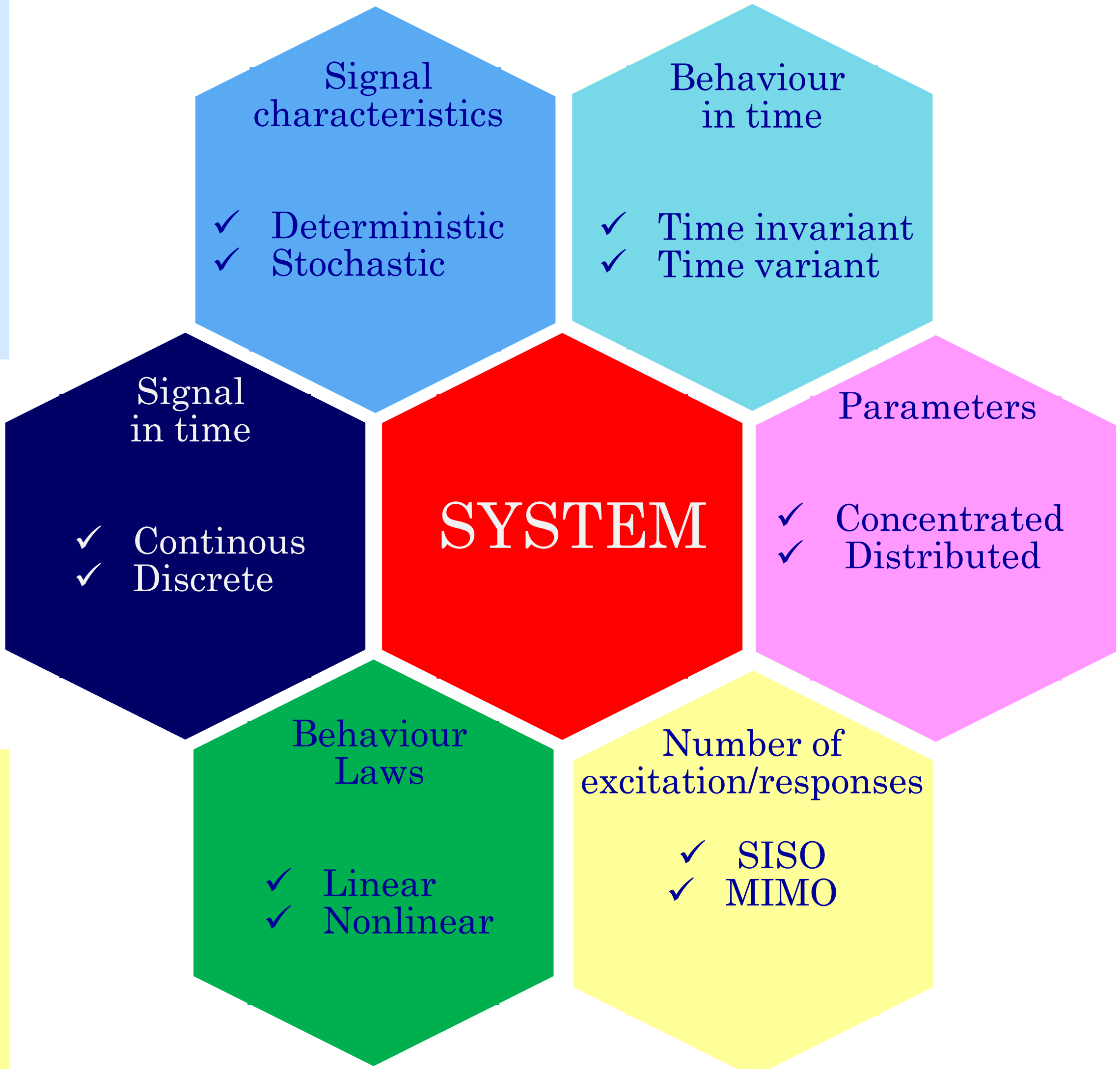
Acquire knowledge.

1. Acquire knowledge of (a subject) or skill in (an art etc…) as a result of study, experience or instruction; acquire or develop an ability to do.
2. Become acquainted with or informed of (a fact); hear (of), ascertain.

System classification

Students learned about:

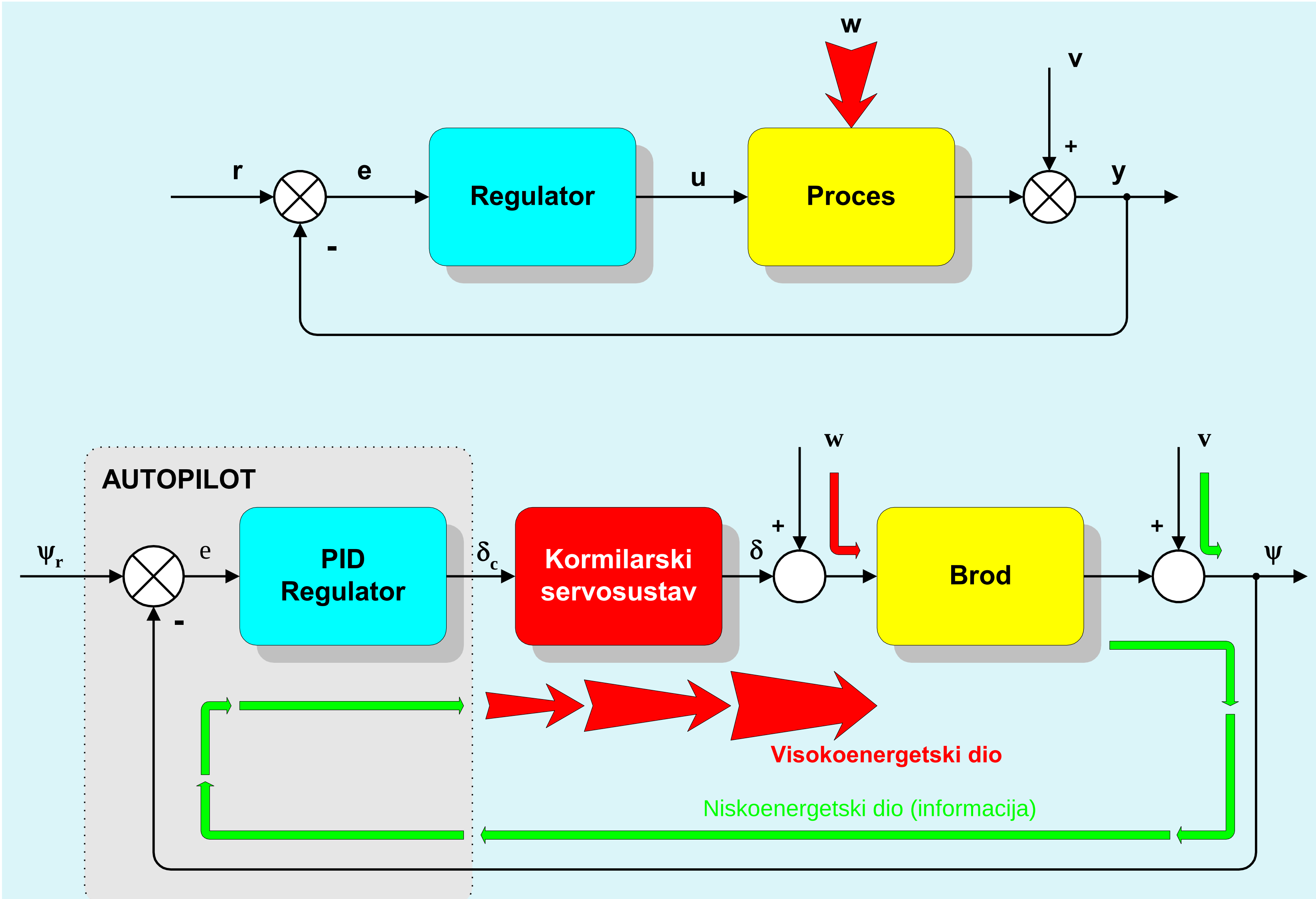
- ✓ Linear systems
- ✓ Deterministic
- ✓ Time invariant
- ✓ Concentrated parameters
- ✓ SISO
- ✓ Continous & discrete



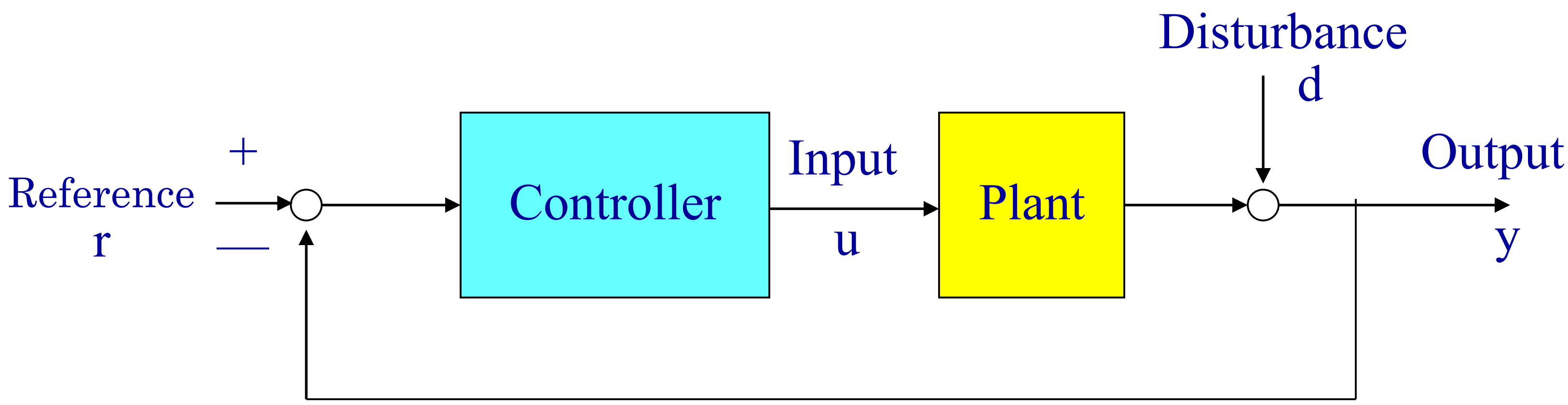
Nature is:

- ✓ Nonlinear
- ✓ Stochastic
- ✓ Time variant
- ✓ Distributed parameters
- ✓ SISO & MIMO
- ✓ Continous & discrete

Conventional control structure



Conventional Control

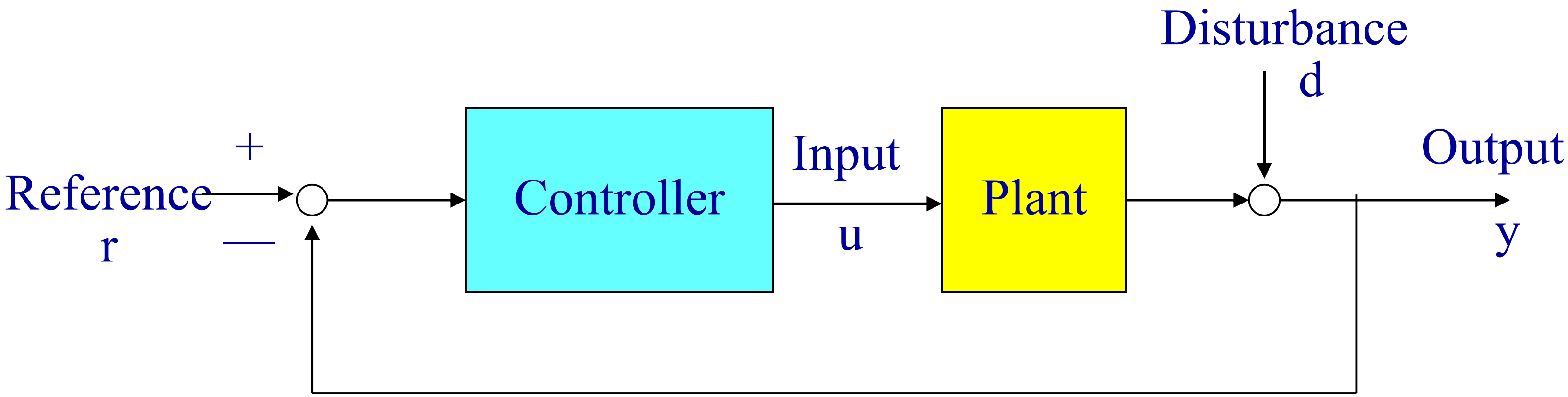


Plant is initially unknown or partially known, or is slowly varying.

There is an underlying performance index, *eg*

$$\text{minimize } J = \lim_{T\to\infty} \frac{1}{T}\int_0^T \left[u^2 + (y-r)^2\right]dt$$

Conventional Control (continued)



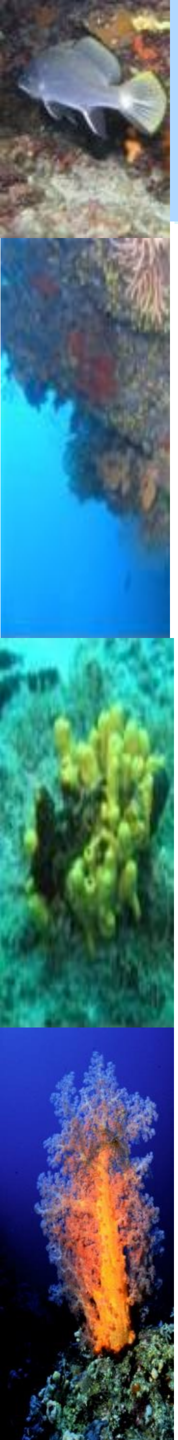
A non-adaptive (conventional) controller maps the error signal *r(t) – y(t)* into *u(t)* in a causal, time-invariant way:

$$\dot{x}_c = A_c x_c + b_c (r - y)$$

$$u = c_c x_c$$

$$\text{with } A_c, b_c, c_c, \text{ constant}, \; x_c^T = \begin{bmatrix} x_{c1} & x_{c2} & . & . & x_{cm} \end{bmatrix}$$

An adaptive controller is controller with possible adjustments on:
- Controller parameters and/or
- Structure and/or
- Signal injection



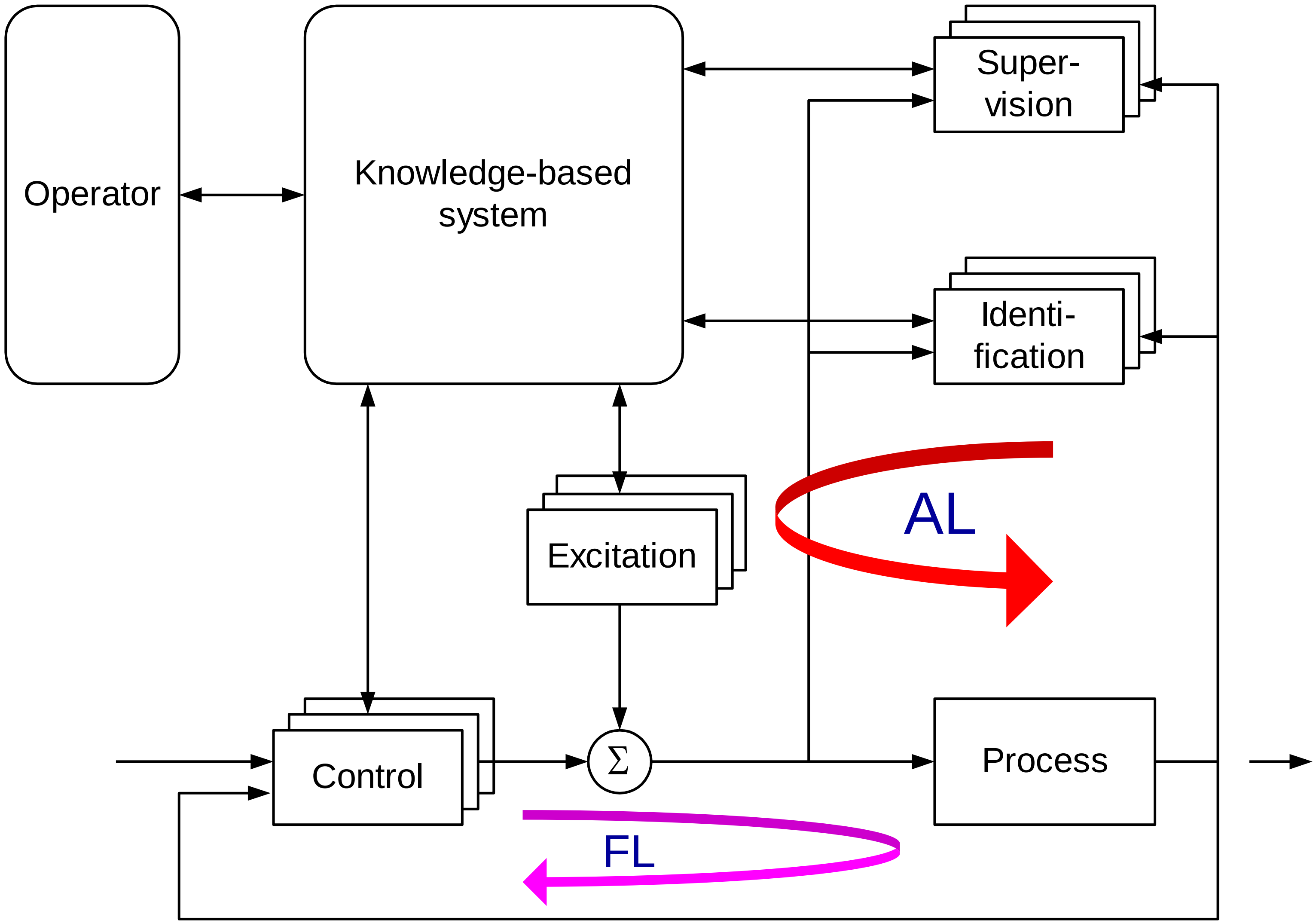
When to use adaptive and when robust control ?

- Both methods are used for time-variant systems. In general, systems are almost always time-variant. There are various causes for this, such as:
  - ➢ Components change with time (for instance capacitors detoriate with time),
  - ➢ Components change with temperature or humidity or ….
  - ➢ Components change with conditions in which they operate
- Use robust controllers when you know
  - ✓ Process structure
  - ✓ Bounds of the variations of the parameters
  - ✓ Operating conditions in which the system will operate
- Otherwise, use adaptive control. Adaptive control is used whenever we do not know in advance what changes our process will experience.

Adaptive control

- Interesting topic from
  - ✓ Theoretical standpoint
  - ✓ Practical standpoint
- Specific type of control with two hierarchically different parts:
  - ➢ feedback loop – as in conventional CL control (fast)
  - ➢ adaptive loop – hierarchically higher level (slower)
- Based upon refreshed knowledge obtained during normal operation
- Interventions in the control loop are made in order to fulfill the control goal

Structure



Operator
Knowledge-based system
Super-vision
Identi-fication
Excitation
AL
Control
Σ
Process
FL

Control Loop Performance
A Never Ending Cycle (re-tuning)

Evaluate if re-tuning is needed

Testing current process dynamics

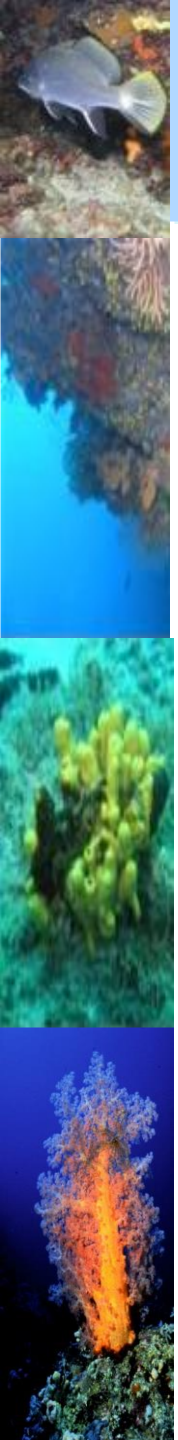
Degradation happens over time

The more often you tune, the better the performance!

Calculate i.e. re-tune

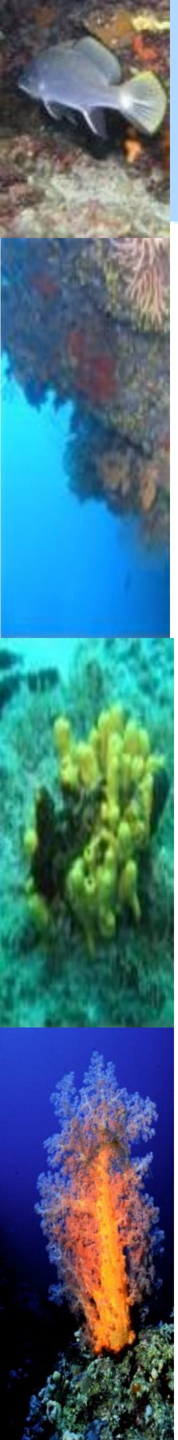
System is operating

Deploy system



There Must Be A Better Way

Wouldn't it be nice to have controllers that use optimal tuning parameters all the time (continually) while the process is operating, without having to re-tune from time to time?



What prerequisites are needed for dealing with adaptive control ?

- ✓ Linear systems
- ✓ Computer control
- ✓ Stability theory
- ✓ Control system design
- ✓ Estimation theory
- ✓ Nonlinear systems
- ✓ Optimal control
- ✓ Stochastic control
- ✓ Discrete (sampled-data) systems
- ✓ ....

What Is Adaptive Control?

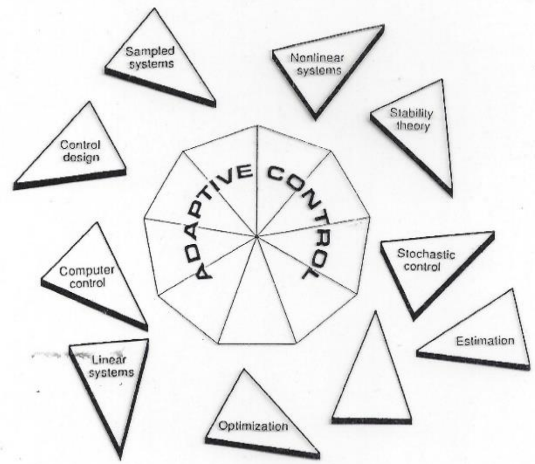
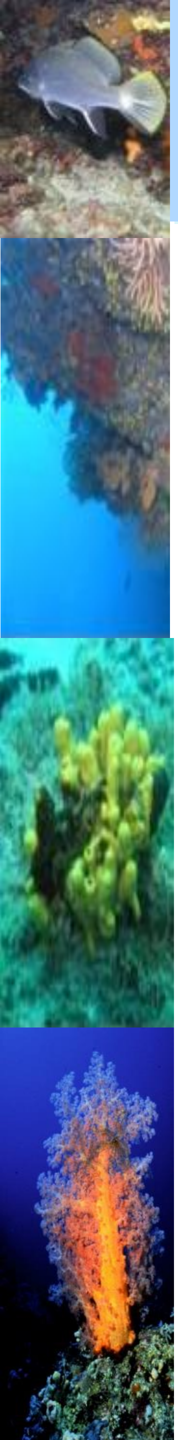


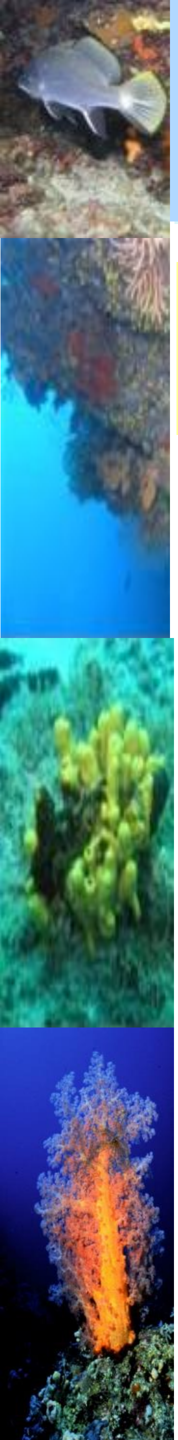
Figure 1.1 Relations of adaptive control to other subfields of automatic control.

Source: Åström and Wittenmark book



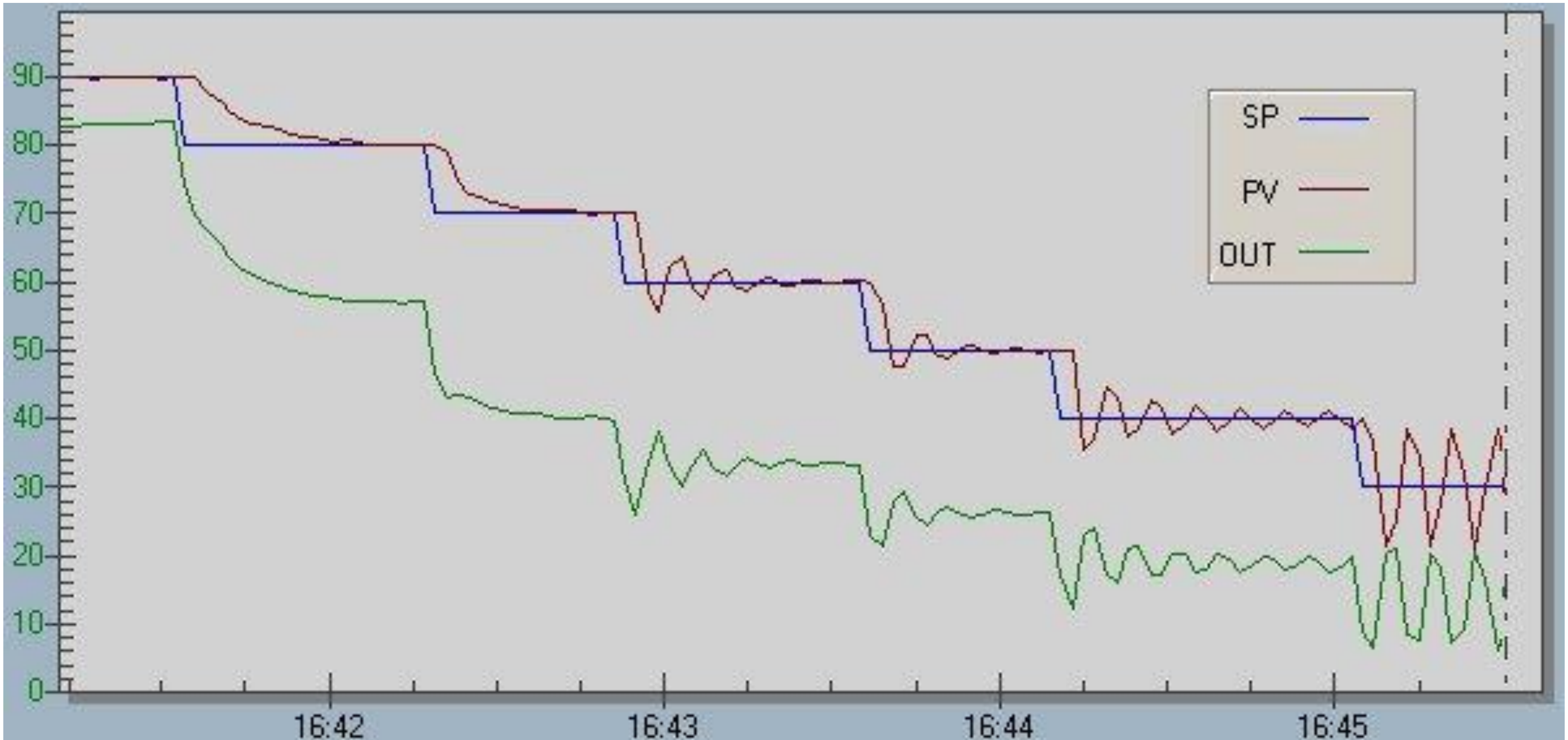
Adaptive control

- Interventions can be obtained by changing:
  - Signals – signal adaptation
  - Parameters – parameter adaptation
  - Structure – structure adaptation
- Reasons for using adaptive control are:
  - Variations in process dynamics
  - Variations in the character of disturbances
  - Engineering efficiency
- Why we need adaptive or robust control?
  - Process parameters may vary due to:
    - Nonlinear actuators
    - Changes of the operating conditions
    - Nonstationary disturbances

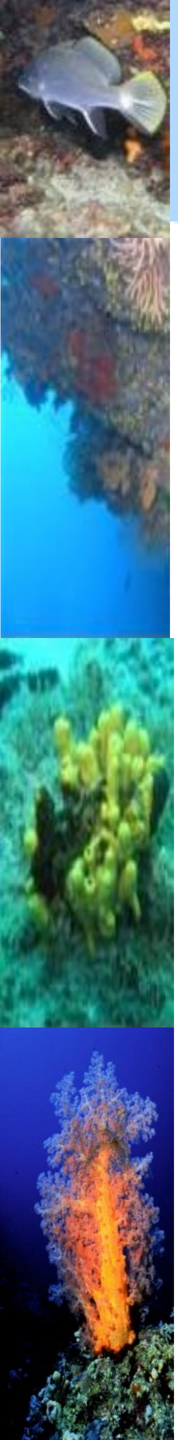


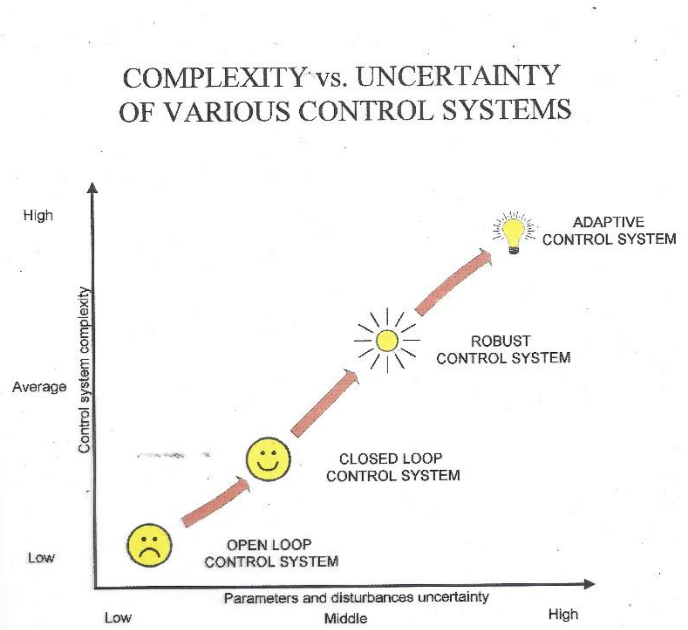
Operating Condition Impact

Process gain and dynamics may change as a function of operating condition (set point (SP) change the operating condition) as indicated by process value (PV), measured output signal (OUT) or other measured signal/parameters.



Complexity vs. Uncertainty in Control

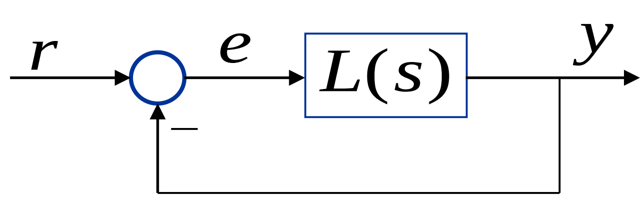




Because of uncertainty of our knowledge about the system the complexity of control system becomes higher and we need as much reliable information as possible to counteract this effect of not enough knowledge.

NOTE 1: Parameters may vary due to:
- Nonlinear actuators
- Change in the operating conditions
- Nonstationary disturbances

NOTE 2: The most common regulator is a feedback controller with fixed parameters. Through feedback it is possible to decrease the sensitivity to parameter variations by increasing the loop gain (L) of the system:

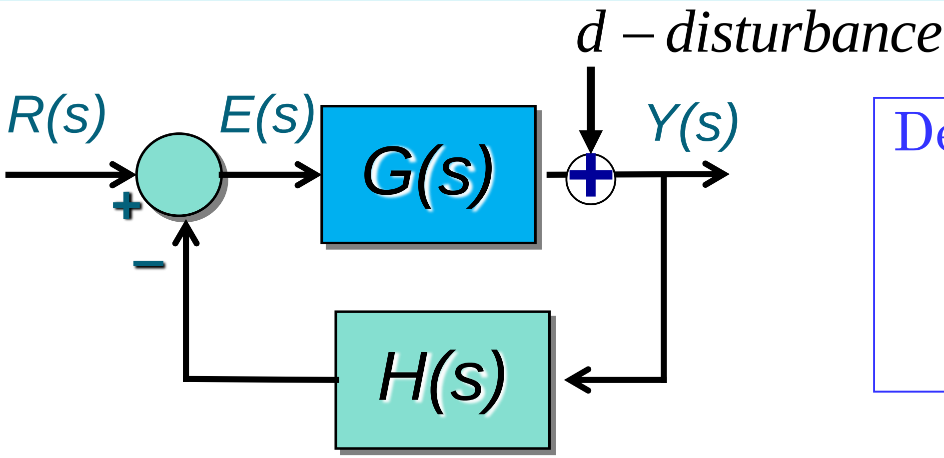


Transfer function from $r(t)$ to $e(t)$ is the sensitivity:

$$S(s) = \frac{1}{1+L(s)} \quad \text{where } |L(s)| \text{ is the loop gain .}$$

- If there are bounds on the uncertainties of the process parameters, it is possible to design the robust controllers by increasing the complexity of the controller.
- To use this approach it is necessary:
  - To know the structure of the process fairly accurately
  - To have bounds on the variations of the parameters

Through feedback it is possible to decrease the sensitivity to parameter variations of G by increasing the loop gain of the system



Design recipe:

- ✓ $1 >> H >> 1/G$
- ✓ $G >> 1/H >> 1$
- ✓ G maximally uncertain!
- ✓ H small, low uncertainty

$$G >> \frac{1}{H} > 1 \quad \Rightarrow \quad GH >> 1$$

$$\Rightarrow \quad S << 1 \quad \Rightarrow \quad y \approx \frac{1}{H} r$$

$$S = \frac{1}{1+GH} \; ; L = GH$$

$$\mathrm{Y}(s) = G(s)S(s)R(s) + S(s)d(s)$$

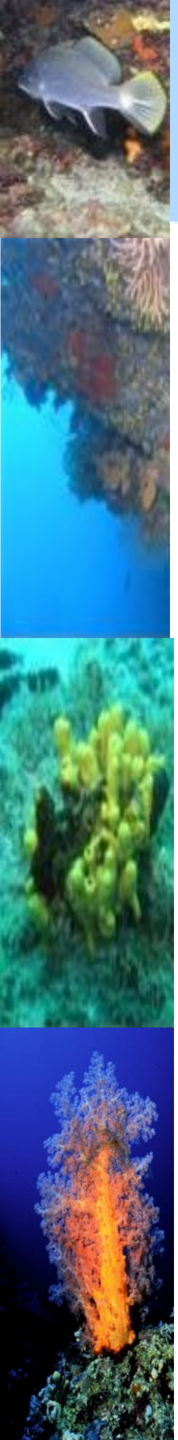
$$Y(s) = \frac{1}{H(s)}\left[1 - S(s)\right]R(s) + S(s)d(s)$$

Results for $y \approx (1/H)r$:

- ✓ high gain
- ✓ low uncertainty
- ✓ d attenuated

High-gain controllers introduce drawbacks:

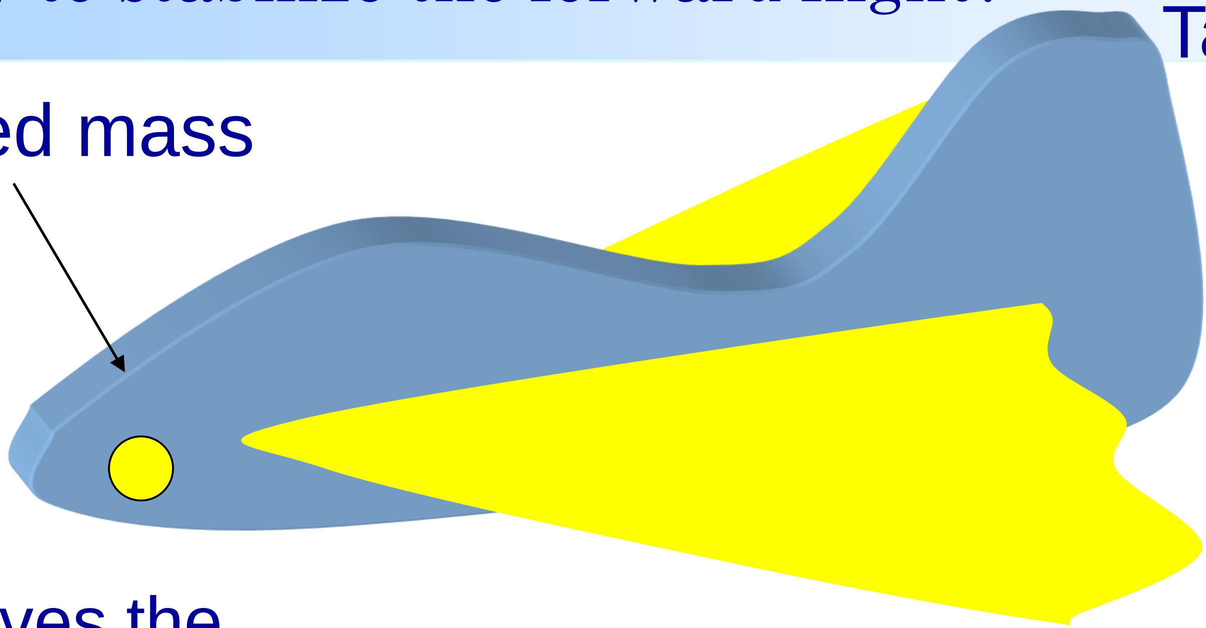
- high magnitude of control signal
- decreased stability of the closed-loop system
- saturation of actuators



Feedback and robustness

- Primitive technologies build fragile systems from precision components.
- Advanced technologies build robust systems from sloppy components.
- High gain negative feedback is the most powerful mechanism, and also the most dangerous.
- Negative feedback is both the most powerful and most dangerous mechanism for robustness.
- It is everywhere in engineering, but remains hidden as long as it works
- Biology seems to use it even more aggressively, but also uses other familiar mechanisms:
  - Positive feedback to create switches (digital systems)
  - Protocol stacks
  - Feedforward

Change of the body structure improves dynamics
How to stabilize the forward flight?

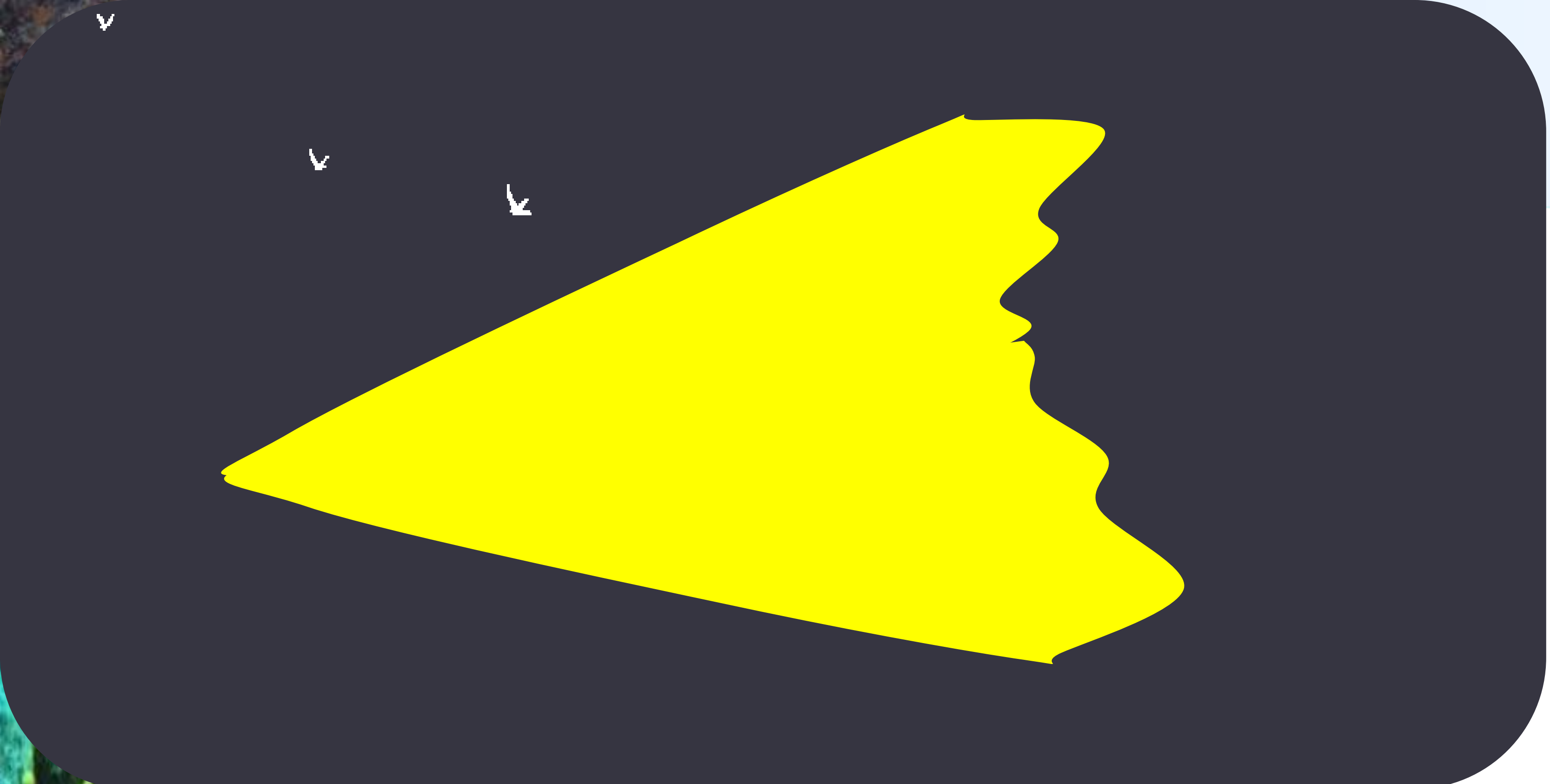


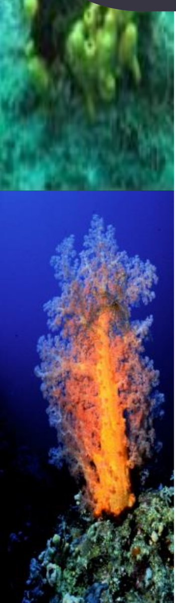
Moves the center of pressure aft.

Moves the center of mass forward.

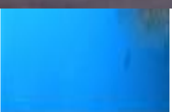
Thus stabilizing forward flight.

At the expense of extra weight and drag.

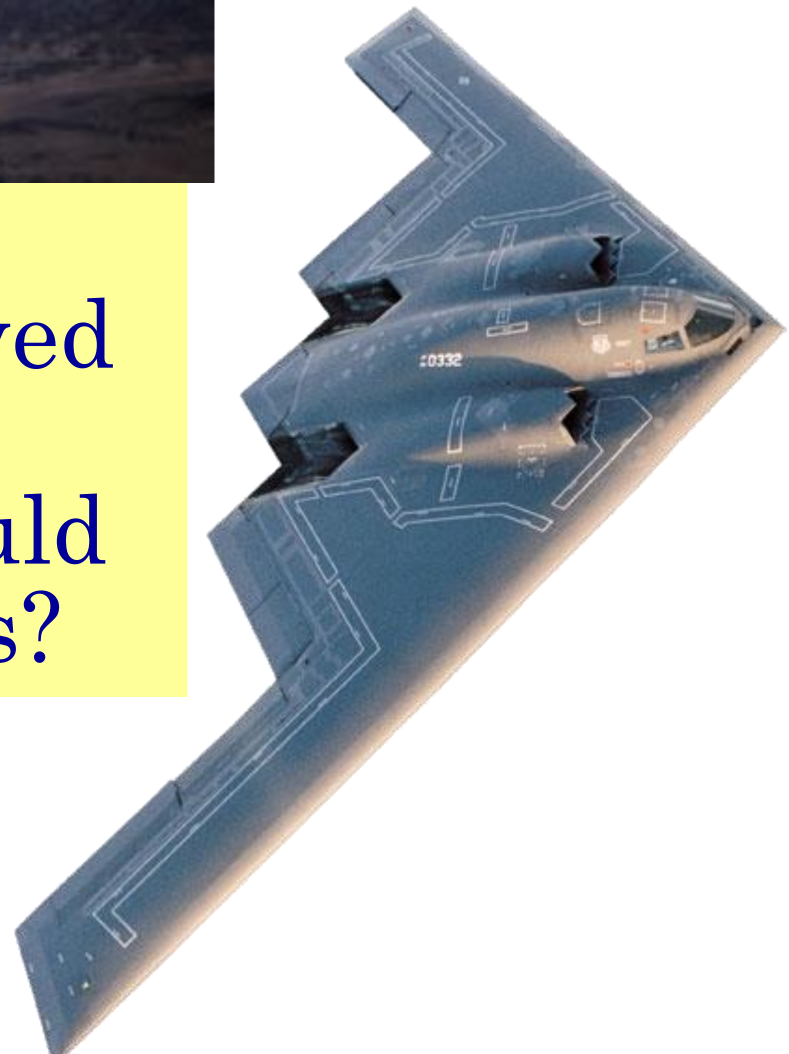


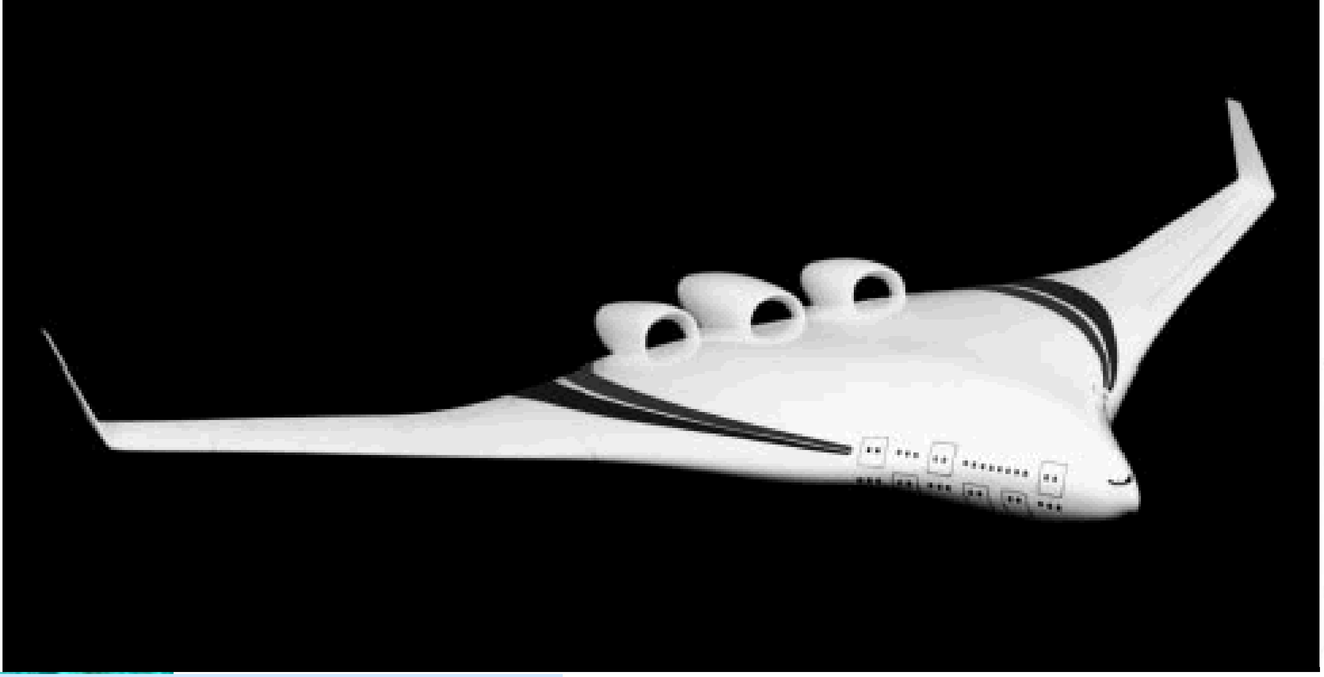


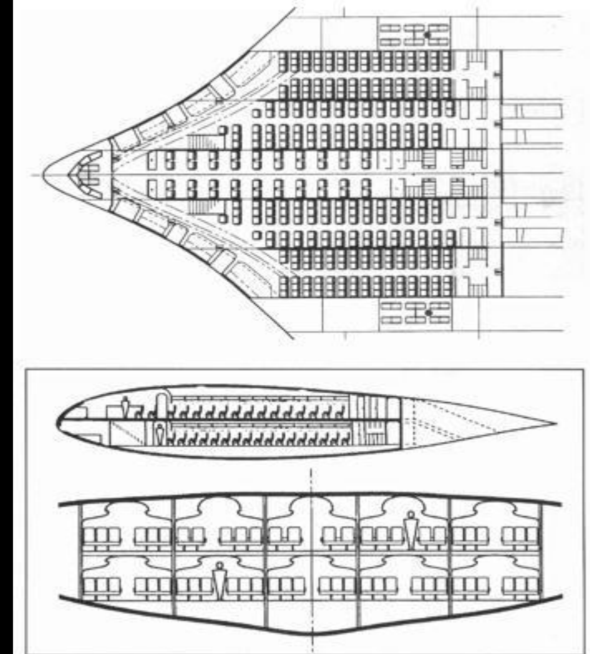
For minimum weight & drag, (and other performance issues) eliminate fuselage and tail.



- Can manoeuvering capability be improved during flight?
- How this change could influence robustness?

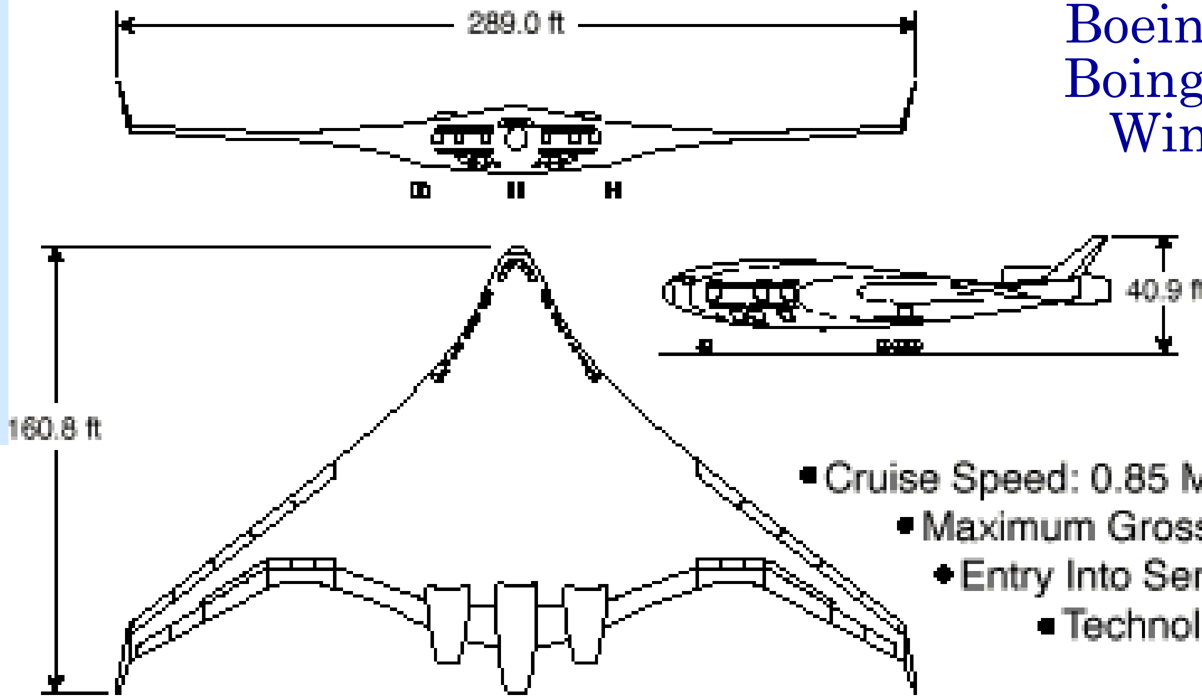






Boeing BWB – Boing Blended Wing Body

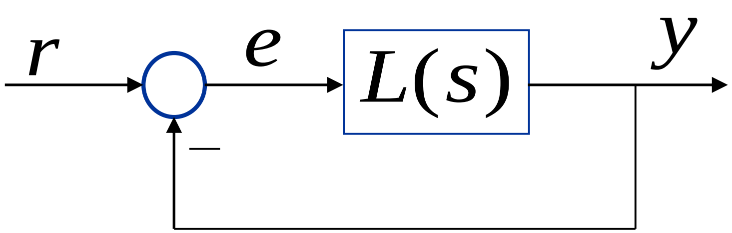
This is the most promising future airliner both aesthetically and in terms of economical operation.
Cleaner, less expensive to build, stronger, quieter, easier to handle and still within the parameters of the 90 meter (295 ft) box.



BWB

- Cruise Speed: 0.85 Mach (1040 km/h)
- Maximum Gross Wt: 373306 kg
- Entry Into Service Date: 2020
- Technology Level: 2015

Tracking of constant reference signal



Transfer function from $R(s)$ to $E(s)$ is:

$$S(s) = \frac{E(s)}{R(s)} = \frac{1}{1+L(s)}$$

and consequently $E(s) = S(s)R(s)$.

$S(s)$ is called system sensitivity function.

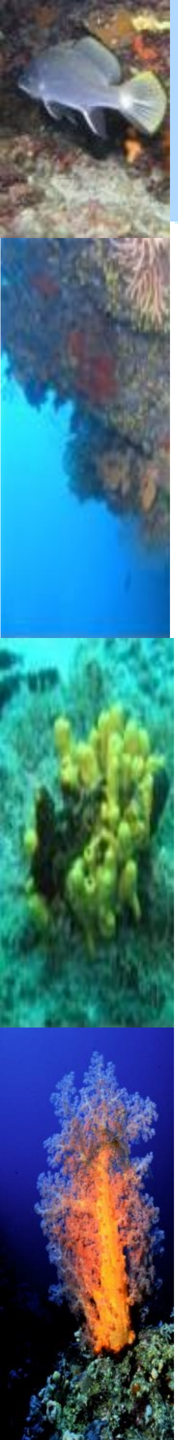
System is stable iff $S(s)$ have no poles with $\mathrm{Re}[s] \geq 0$.

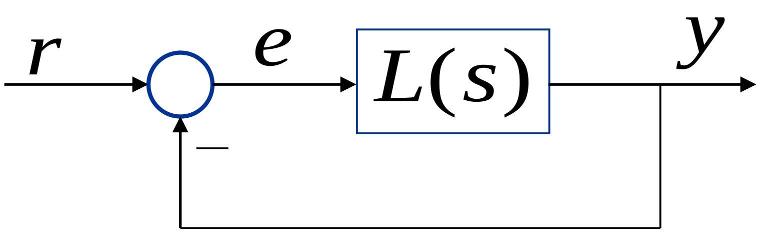
Then for $r(t) \equiv r_0$, we have $e(\infty) = S(0)r_0 = \dfrac{1}{1+L(0)} r_0$

Good tracking of constant reference signal in steady state asks for:

$S(0)$ small $\leftrightarrow$ $L(0)$ large.

Tracking of the LF reference signal





Transfer function from $r(t)$ to $e(t)$ is the sensitivity $S(s) = \dfrac{1}{1+L(s)}$.

For $s = j\omega$ the sensitivity is: $S(j\omega) = |S(j\omega)|\, e^{j\phi_S(\omega)}$.

Iff the control system is stable: then in the steady-state the error to harmonic reference $r(t) = r_0 \cos(\omega_0 t)$ is given by:

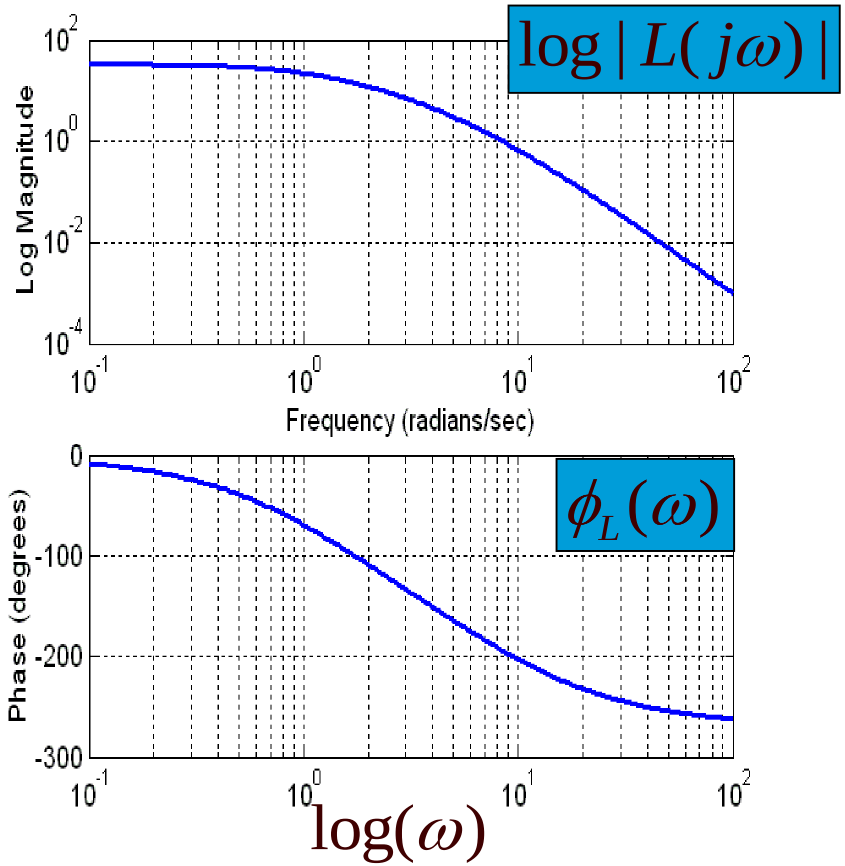
$$e(t) = r_0\, |S(j\omega_0)| \cos(\omega_0 t + \phi_S(\omega_0)).$$

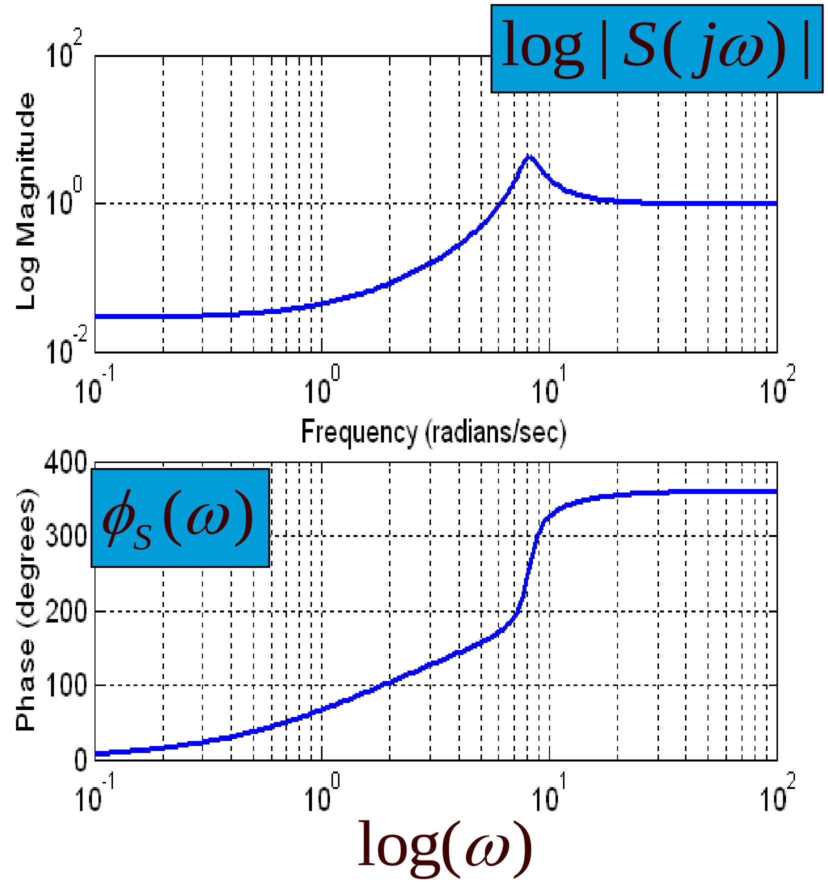
Good tracking in the steady-state asks for:

$|S(j\omega_0)|$ small $\xleftrightarrow{\approx}$ $|L(j\omega_0)|$ large.

Bode

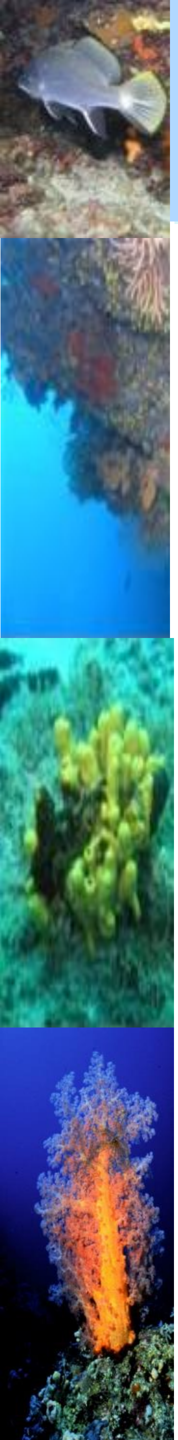
$L(j\omega)$ $S(j\omega)$





Good tracking $\leftrightarrow$ large $|L(j\omega)| \leftrightarrow$ small $|S(j\omega)|$

in the frequency domain of interest.



Algebraic constraints on performances

$$G_{er}(s) = \frac{1}{1+P(s)C(s)} = S(s) \quad \text{sensitivity}$$

$$G_{yn}(s) = \frac{P(s)C(s)}{1+P(s)C(s)} = T(s) \quad \text{complementary sensitivity}$$

GOAL:

- Keep S(s) small if good tracking is needed
- Keep T(s) small if noise rejection and robustness is needed

Problem: ***S(s) + T(s) = 1***

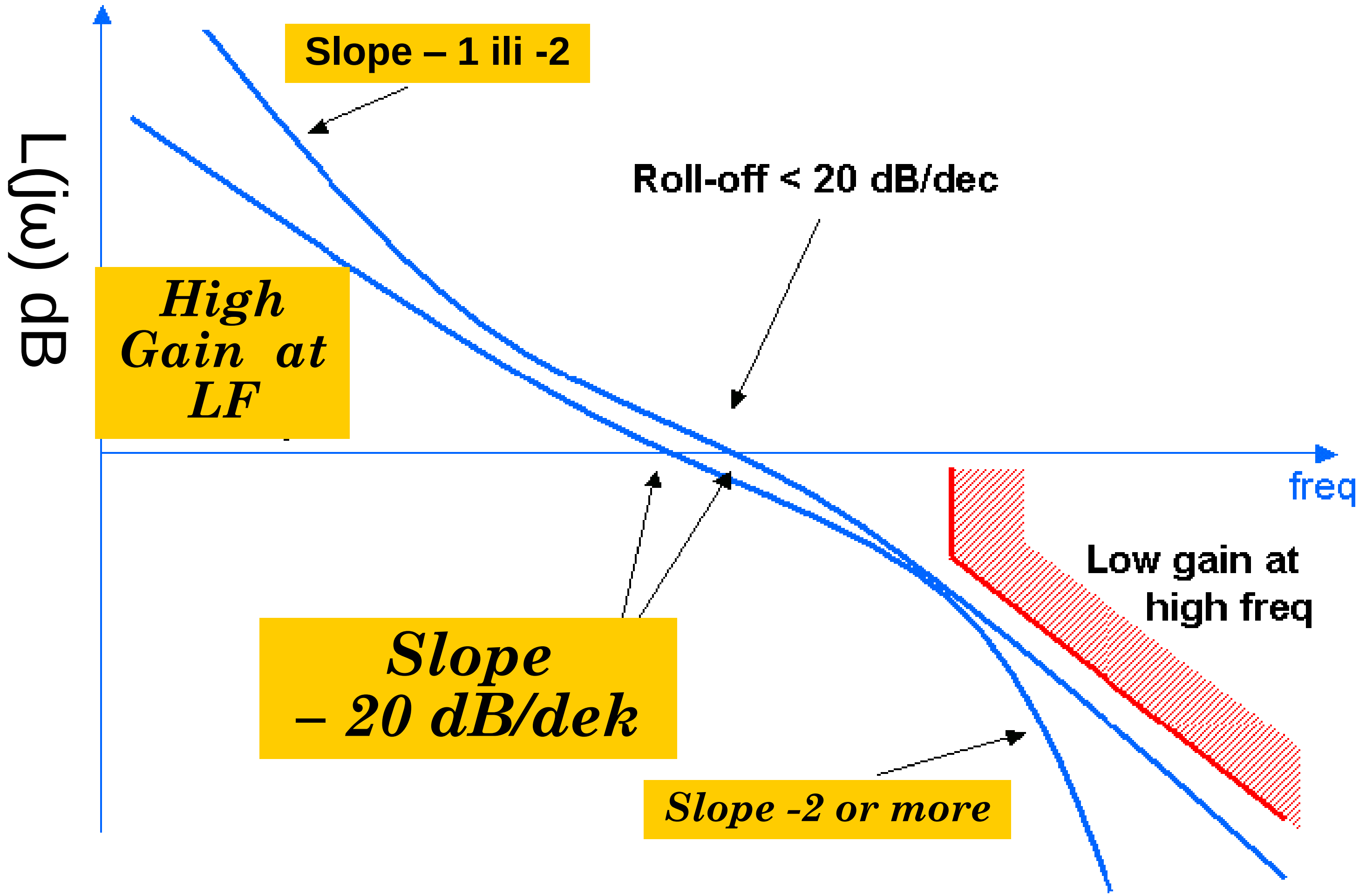
It is not possible to ensure both: S and T small in the same frequency domain

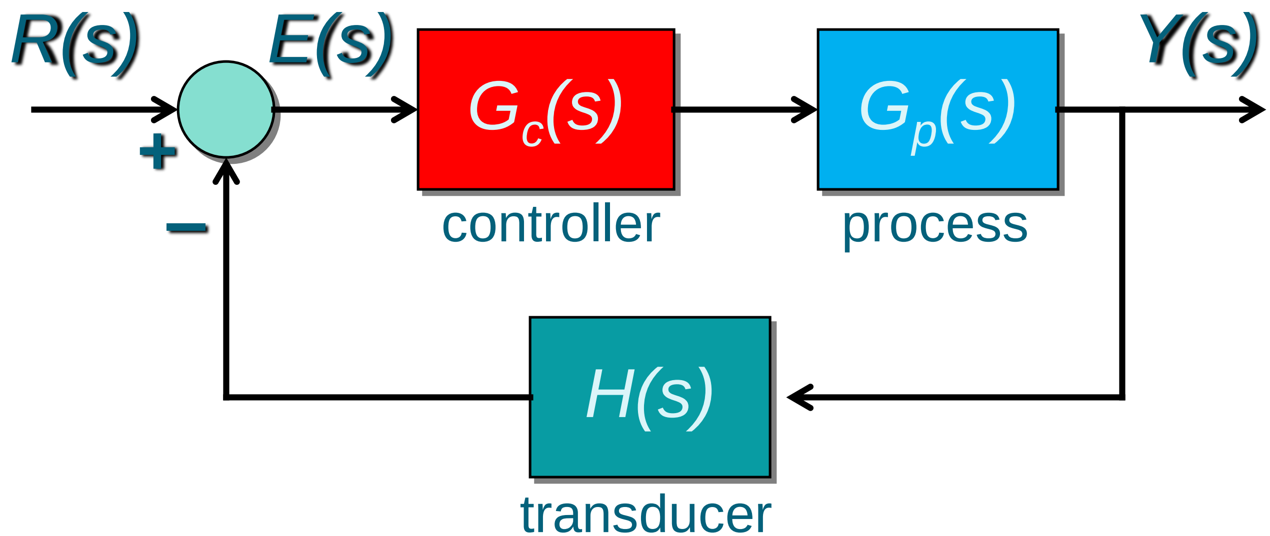
Solution: Keep S small at LF and T at HF

Interpretation through L = PC: L large at LF i L small at HF

Robust loop shaping (contd.)

Open loop frequency characteristic L(jω) should obey

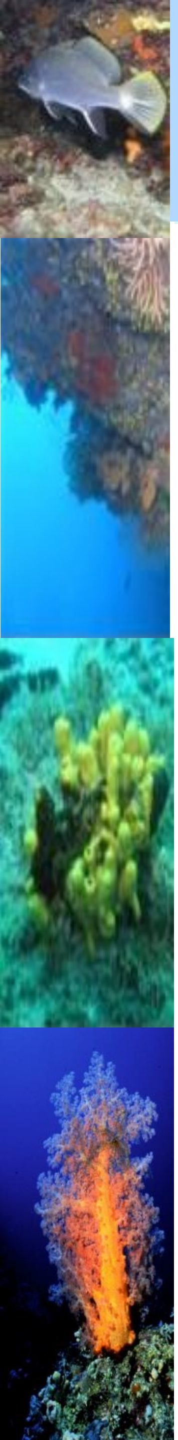




$$Y(s) = \frac{G_c(s)G_p(s)}{1 + G_c(s)G_p(s)H(s)} R(s)$$

What if process parameters change with time?
Controller is not any more appropriate !!
It must change accordingly !!

What is adaptive control ?

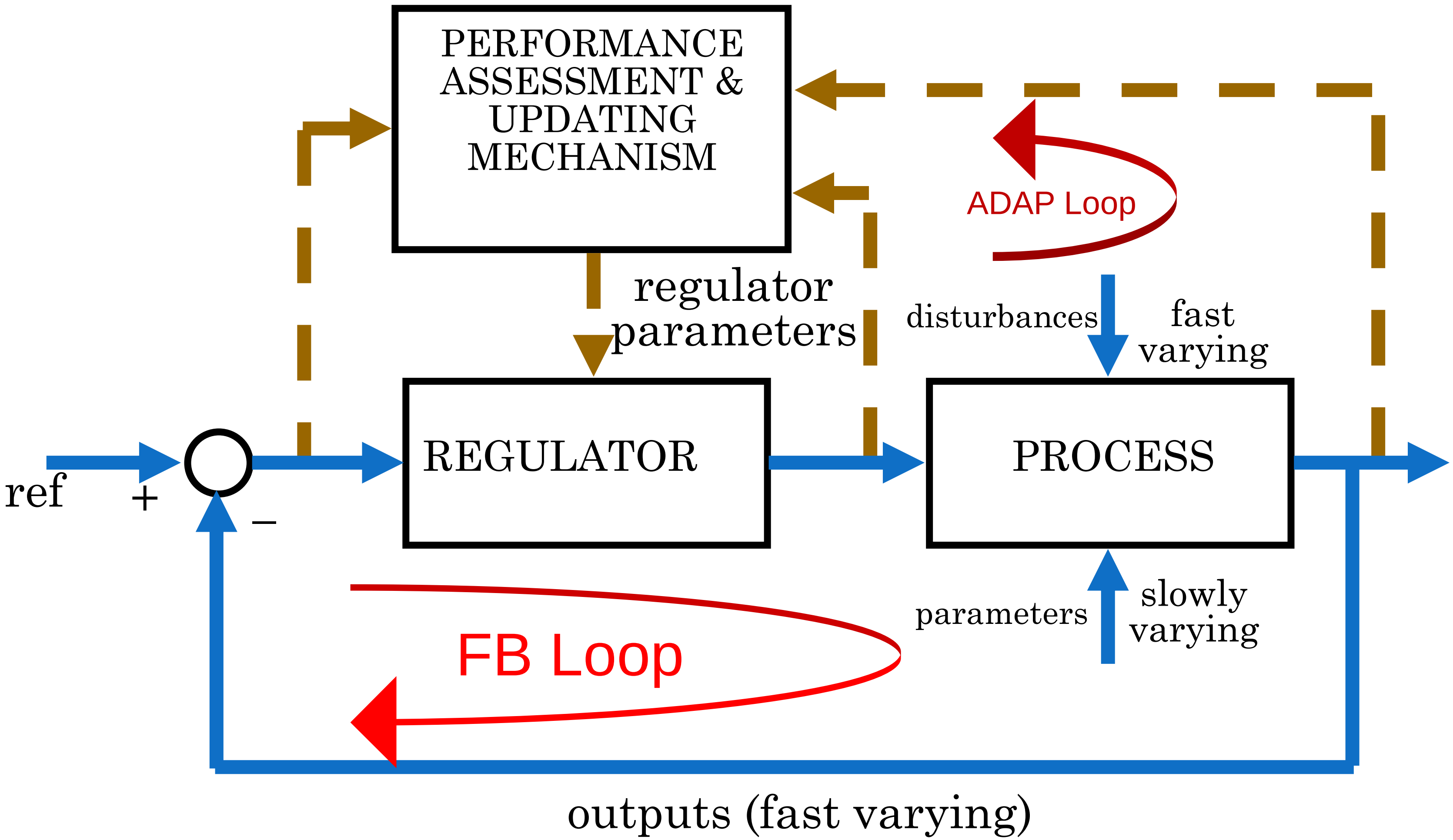


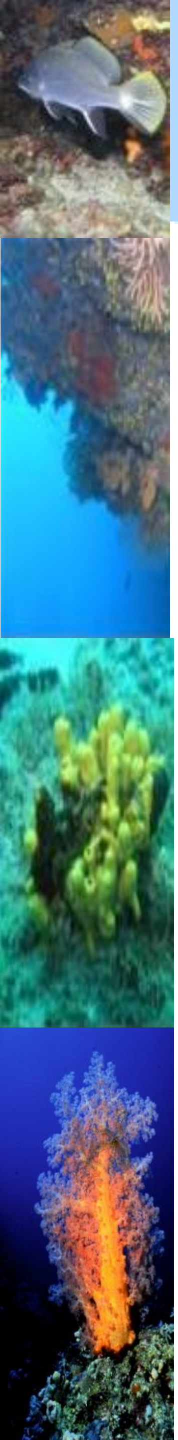
Adaptive control is a special type of nonlinear control in which the states of the process can be separated into two categories:-

1. *slowly varying states* -viewed as parameters
2. *fast varying states* - compensated by standard feedback

In adaptive control it is assumed that there is feedback (*adaptation loop*) from the system performance which adjusts the regulator parameters to compensate for the slowly varying process parameters.

ADAPTIVE CONTROL





Methods of adaptation

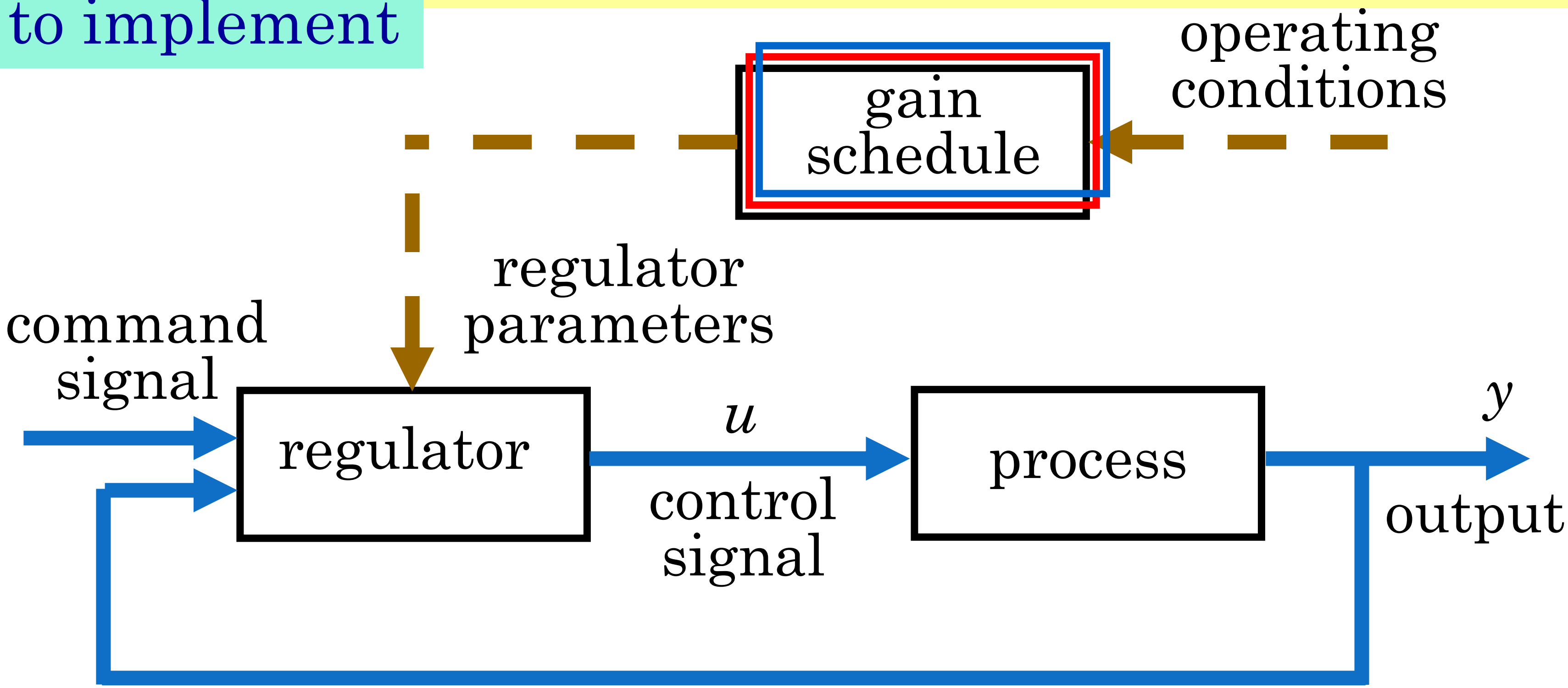
Parameter adaptive control is usually implemented as:

- ✓ Gain scheduling adaptive control
- ✓ Model reference adaptive control
- ✓ Self-tuning adaptive control

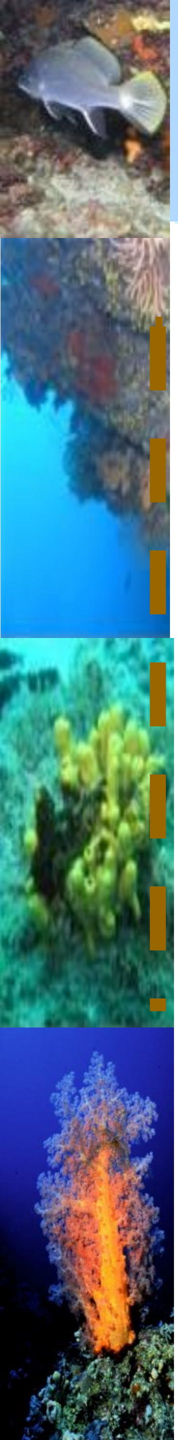
Adaptive control – Gain scheduling

Advantages:
- ✓ Fast in adaptation
- ✓ Easy to implement

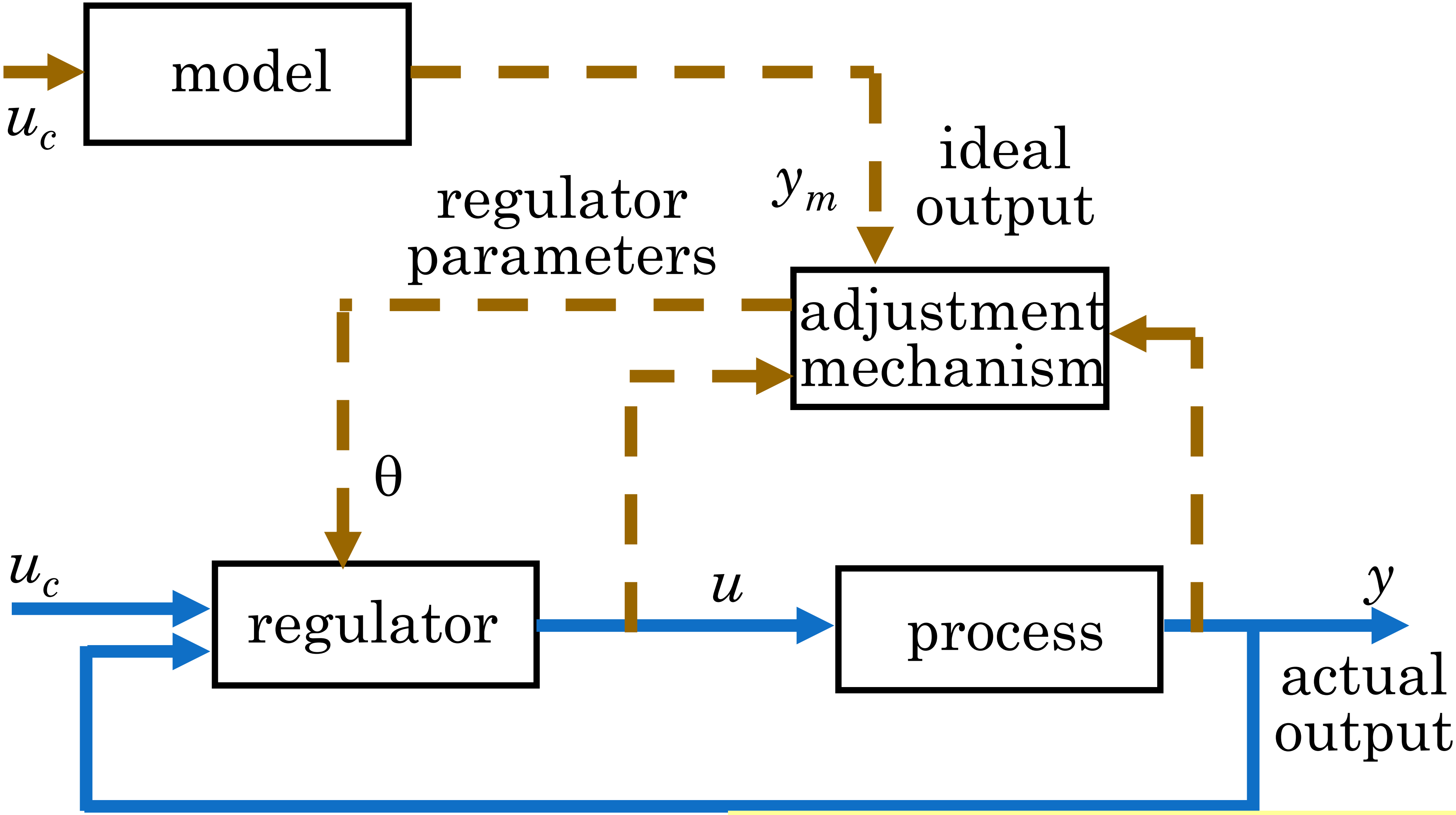
Disadvantage:
The process may experience some unexpected change not previously memorized in the table of gains



The regulator parameters are adjusted to suit different operating conditions. Gain scheduling is an *open-loop compensation*. No adaptation loop!



Model Reference Adaptive Systems (MRAS)



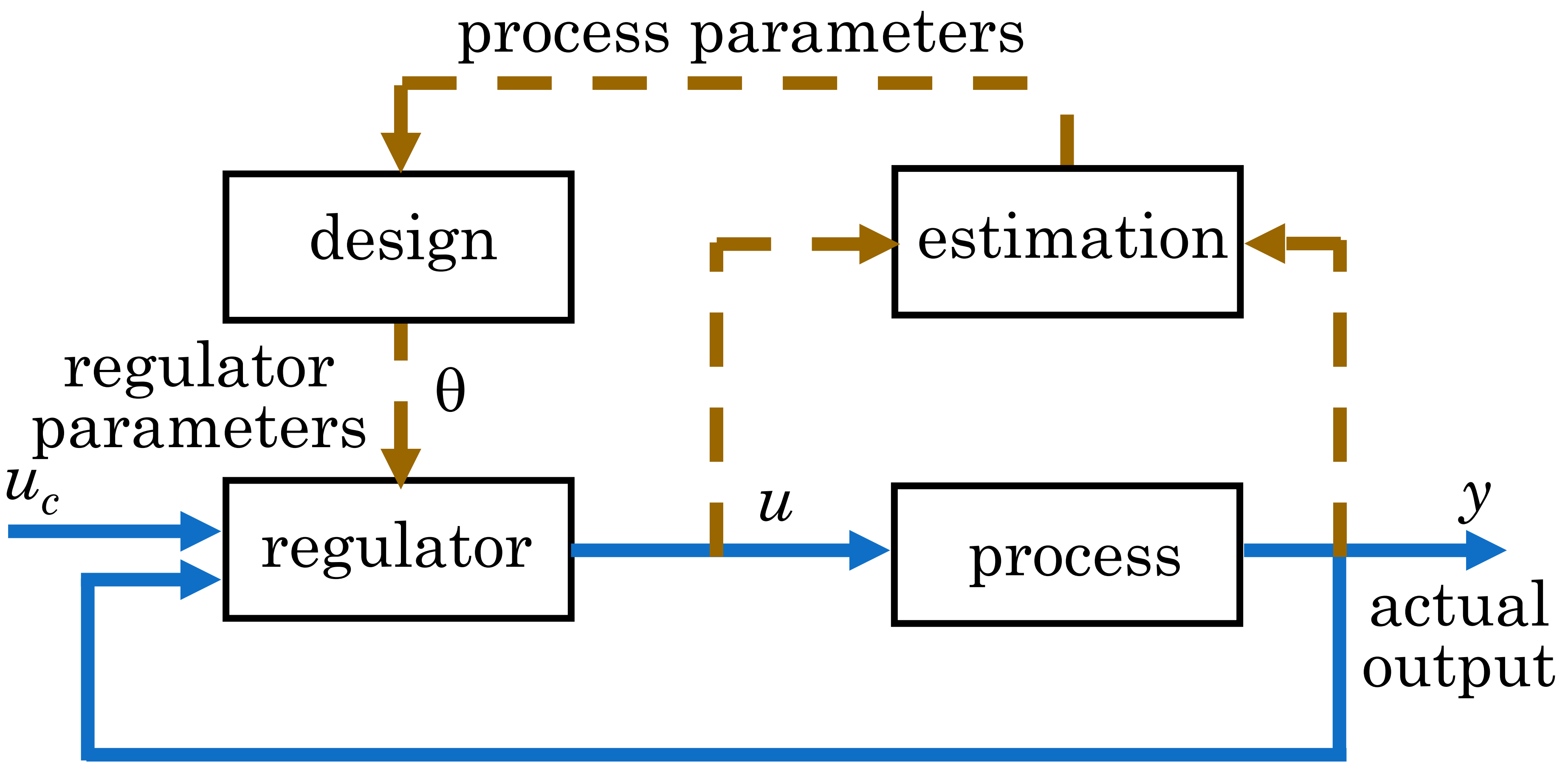
Advantage:
- ✓ Analog and digital technique is possible
- ✓ Stability ensured

Disadvantages:
- ✓ Model must be carefully chosen
- ✓ This type of control can give large control signals
- ✓ Not reccomended for stochastic systems

Self-tuning regulator (STR)

Advantages:
- ✓ Applicable in the stochastic setting
- ✓ Capable of resolving many practical situations

Disadvantages:
- ✓ Slower than the MRAS control
- ✓ Can not be realized in analog technique

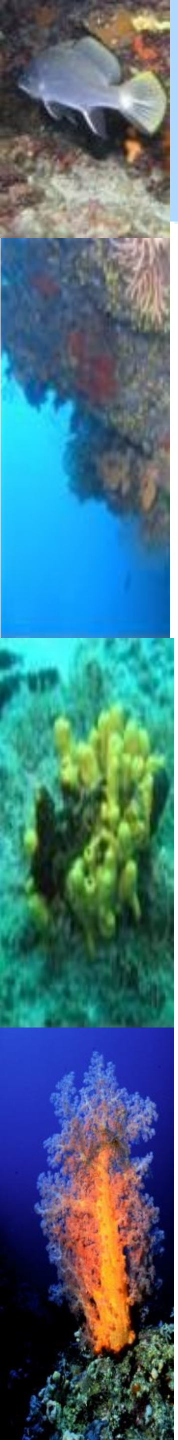


The self-tuning control is exclusively realized by use of a digital technique (DSP, PC, ...) so all the advantages and disadvantages of this technique is carried over to this type of control.

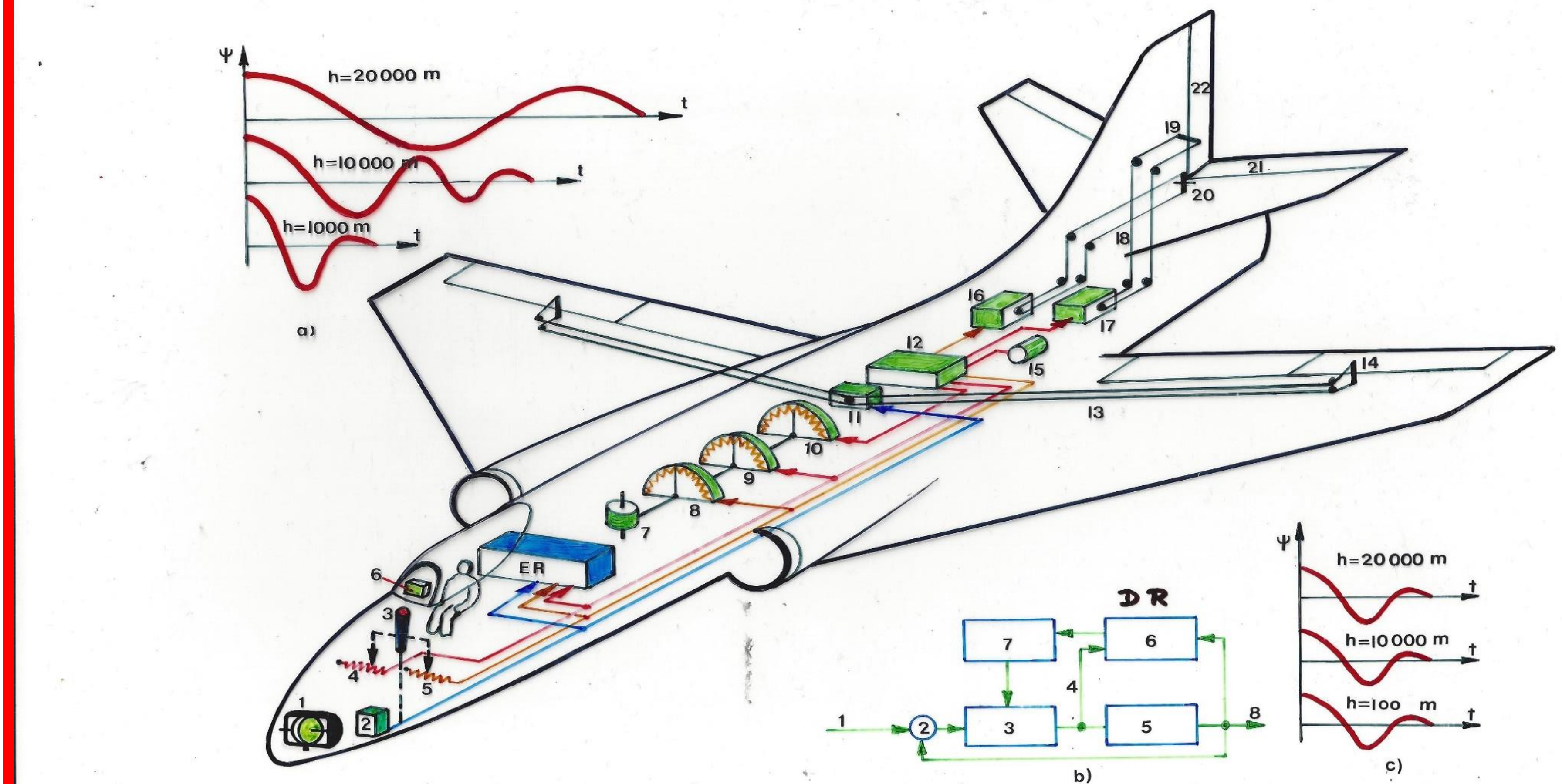
LTI aproximation is not satisfactory when operating conditions change

Example 1: Guidance and control of the airplane

- Airplane dynamics change depending on
  - Speed (V)
  - Altitude (h)
  - Angle of attack (α)
- First adaptive control was applied in 1950-ies to airplanes (fighter jets)
- From then adaptive control theory developed over the years to become a viable option for controlling the time variant systems



Airplane dynamics change with the
- speed (v)
- altitude (h)
- angle of attack (α)

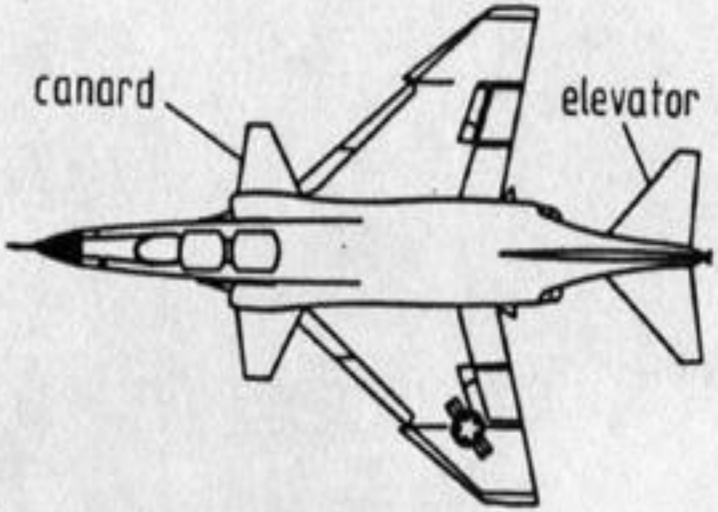


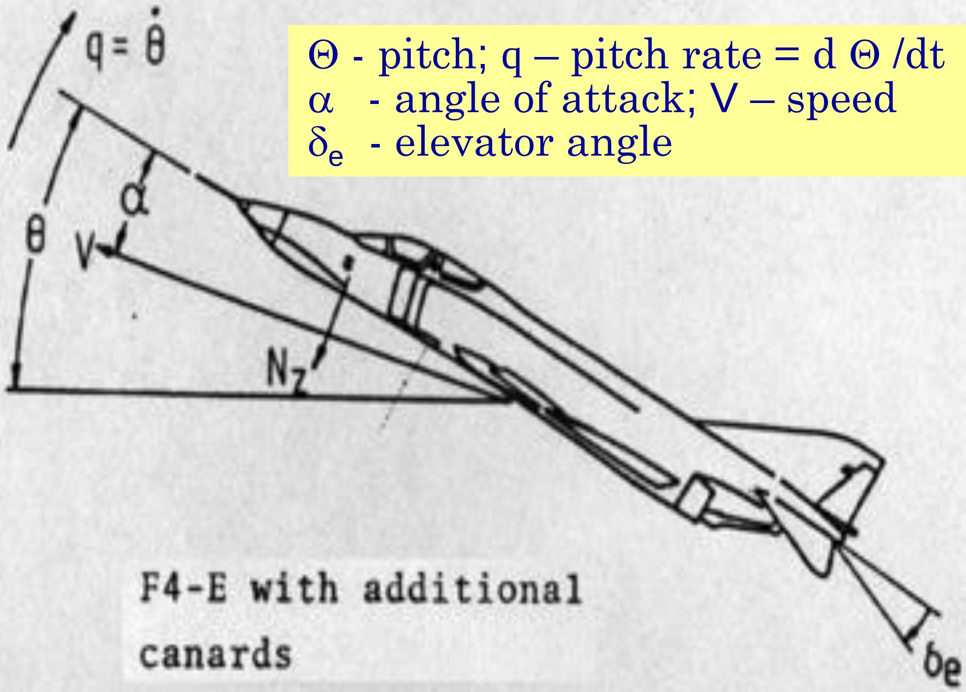
For time-variant systems robust or adaptive control is the answer

Example: F4-E airplane with canards

Source: Åström and Wittenmark book

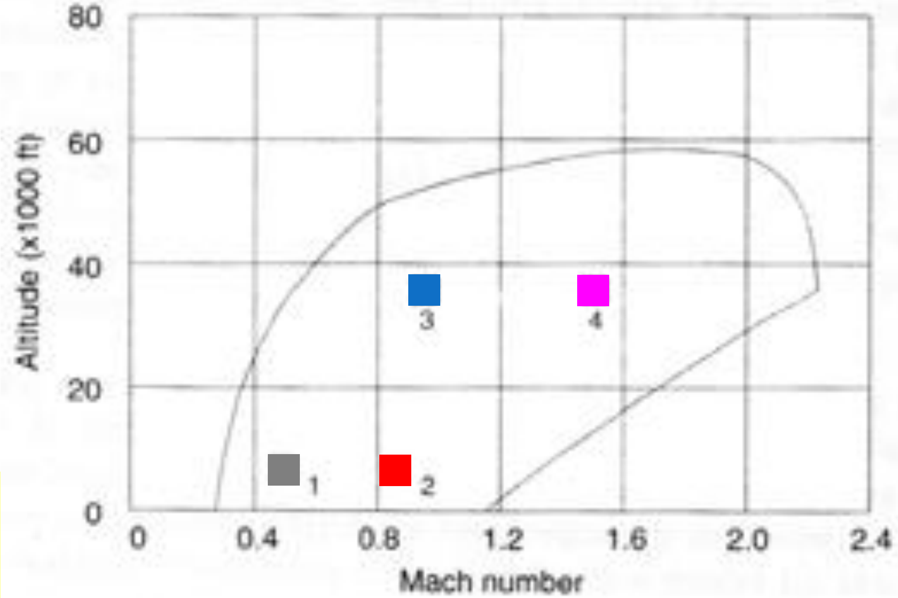
Canards make it easier to manoeuver the airplane, at the cost of decreased stability





Θ - pitch; q – pitch rate = d Θ /dt
α - angle of attack; V – speed
δ_e - elevator angle

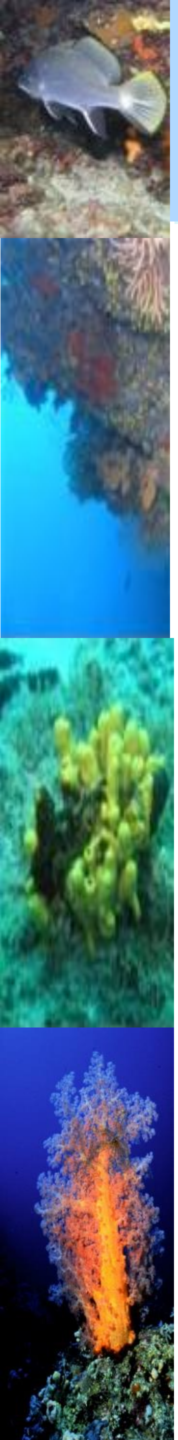
F4-E flight envelope



60000 ft = 18288 m
1 Mach = 340 m/s = 1225 km/h

Flight conditions (FC)

- FC1
- FC2
- FC3
- FC4



Mathematical model (rigid body dynamics) - short period dynamics

Airplane dynamics can be linearized around stationary flight conditions (i.e. V = const. h = const. & small α)

State variables are:
$x_1 = N_z$ – *acceleration*
$x_2 = q = d\Theta/dt$ - *pitch rate*
$x_3 = \delta_e$ - *elevon angles*

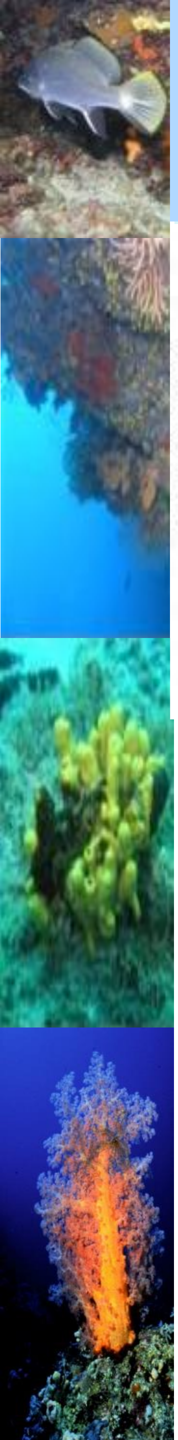
Dynamics of the servo of the elevons and the canards have the transfer function:

$$\boxed{\begin{array}{l} \dfrac{\delta_e(s)}{u(s)} = \dfrac{a}{s+a}\text{; where } a = 14 \\ \textit{or} \text{ in the time domain:} \\ \dot{\delta}_e(t) = -a\delta_e(t) + au(t) \text{ where } \tau = \dfrac{1}{a} \end{array}}$$

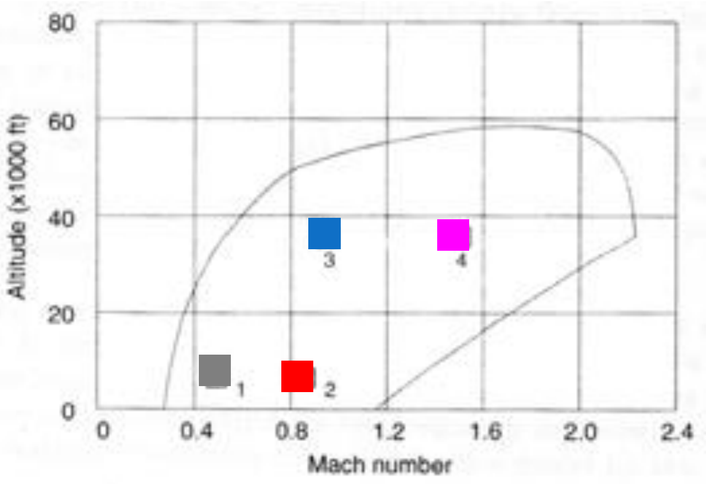
***NOTE**: It is very important that the controller not excite the bending modes of the airplane. The bending modes are not included in the model. The first bending mode has the frequency 85 s^{-1}*

The linearized state-space model is then:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \end{bmatrix} = \begin{bmatrix} \dot{N}_z(t) \\ \dot{q}(t) \\ \dot{\delta}_e(t) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & -a \end{bmatrix} \cdot \begin{bmatrix} N_z(t) \\ q(t) \\ \delta_e(t) \end{bmatrix} + \begin{bmatrix} b \\ 0 \\ a \end{bmatrix} u(t)$$



Example: F4-E airplane - continued



$$
\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \end{bmatrix} = \begin{bmatrix} \dot{N}_z(t) \\ \dot{q}(t) \\ \dot{\delta}_e(t) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ 0 & 0 & -a \end{bmatrix} \cdot \begin{bmatrix} N_z(t) \\ q(t) \\ \delta_e(t) \end{bmatrix} + \begin{bmatrix} b \\ 0 \\ a \end{bmatrix} u(t)
$$

Unstable for subsonic speed < 1 Mach (FC1, FC2, FC3)

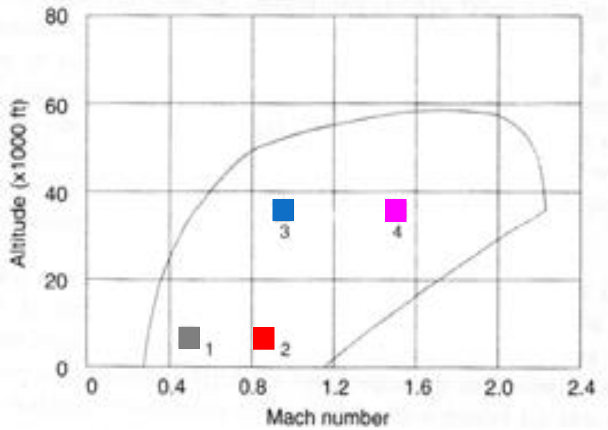
Stable for supersonic speed > 1 Mach (FC4)

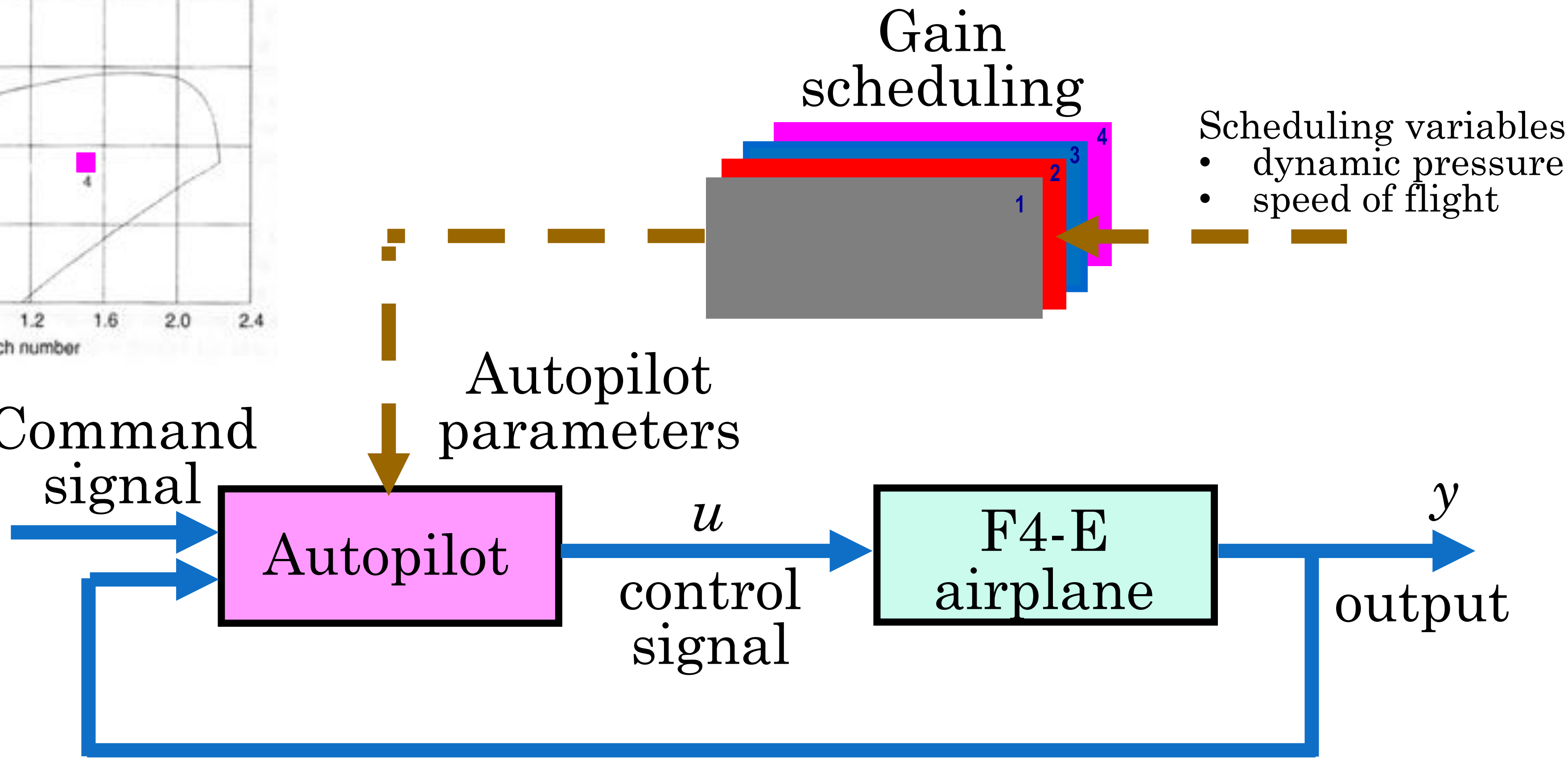
Flight cond.	**FC1**	**FC2**	**FC3**	**FC4**
Mach (km/h)	0,5 (600)	0,85 (1041)	0,9 (1102)	1,6 (1960)
Altitude (m)	1524	1524	10668	10668
a_{11}	-0,9896	-1,702	-0,667	-0,5162
a_{12}	17,41	50,72	18,11	26,96
a_{13}	96,15	263,5	84,34	178,90
a_{21}	0,2648	0,2201	0,08201	-0,6896
a_{22}	-0,8512	-1,418	-0,6587	-1,225
a_{23}	-11,39	-31,99	-10,81	-30,38
b	-97,78	-272,2	-85,09	-175,60
λ_1	-3,07	-4,90	-1,87	-0,87+j4,3
λ_2	1,23	1,78	0,56	-0,87-j4.3

Autopilot with fixed parameters can not resolve this problem !!

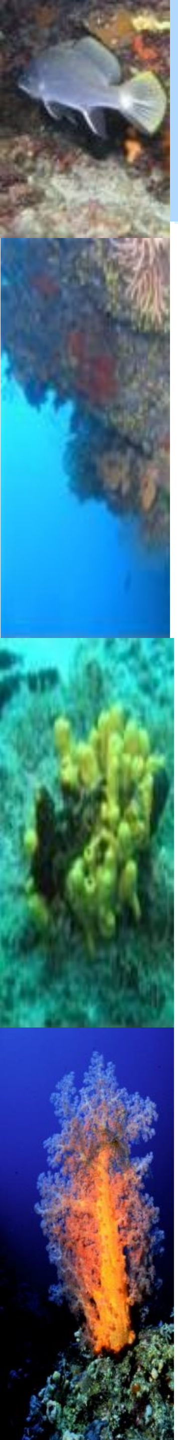
Short period dynamics eigenvalues

Adaptive control – Gain scheduling





The autopilot for F4-E airplane is designed for different flight conditions, and the parameters are changed using gain scheduling. Dynamic pressure and speed of flight are used as scheduling variables. Prefilters are used on the command signal to ensure that bending modes of the airplane will not be excited



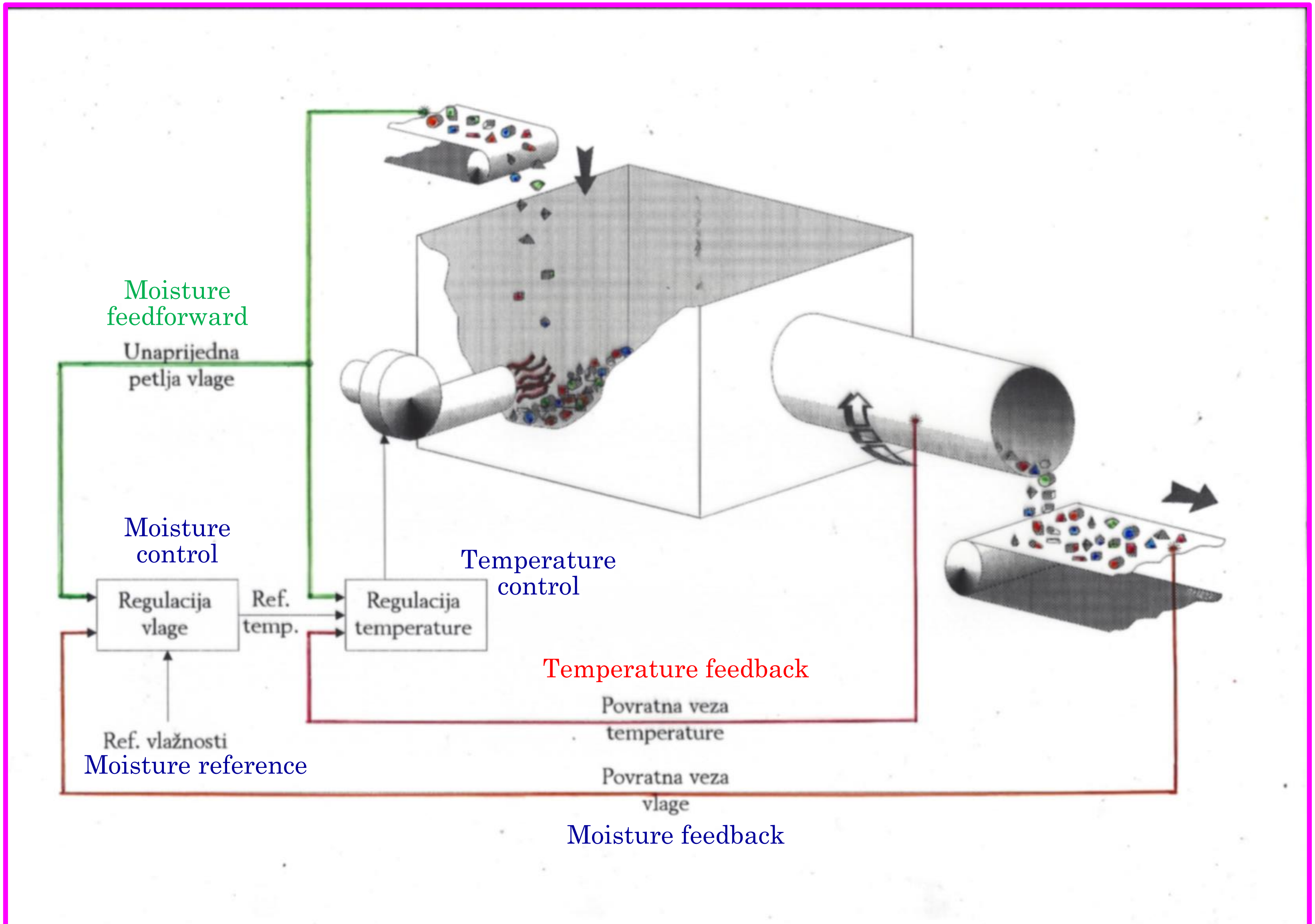
Example 2: Rotary dryer – common in many industries (paper, cement, grain, ...)

1. It can be very difficult to derive a good process model because:
   - dynamics depend on many variables,
   - physics of rotary dryer is not yet fully understood

   This makes the process difficult to control using conventional controllers

2. Dynamics will change with:
   - ✓ The speed of the material transit through the dryer
   - ✓ The moisture content of the incoming material (could change drastically from one to another batch)
   - ✓ The production rate (dead time will vary with the production rate)

Example 2: Rotary dryer – common in many industries (paper, cement, grain, ...)

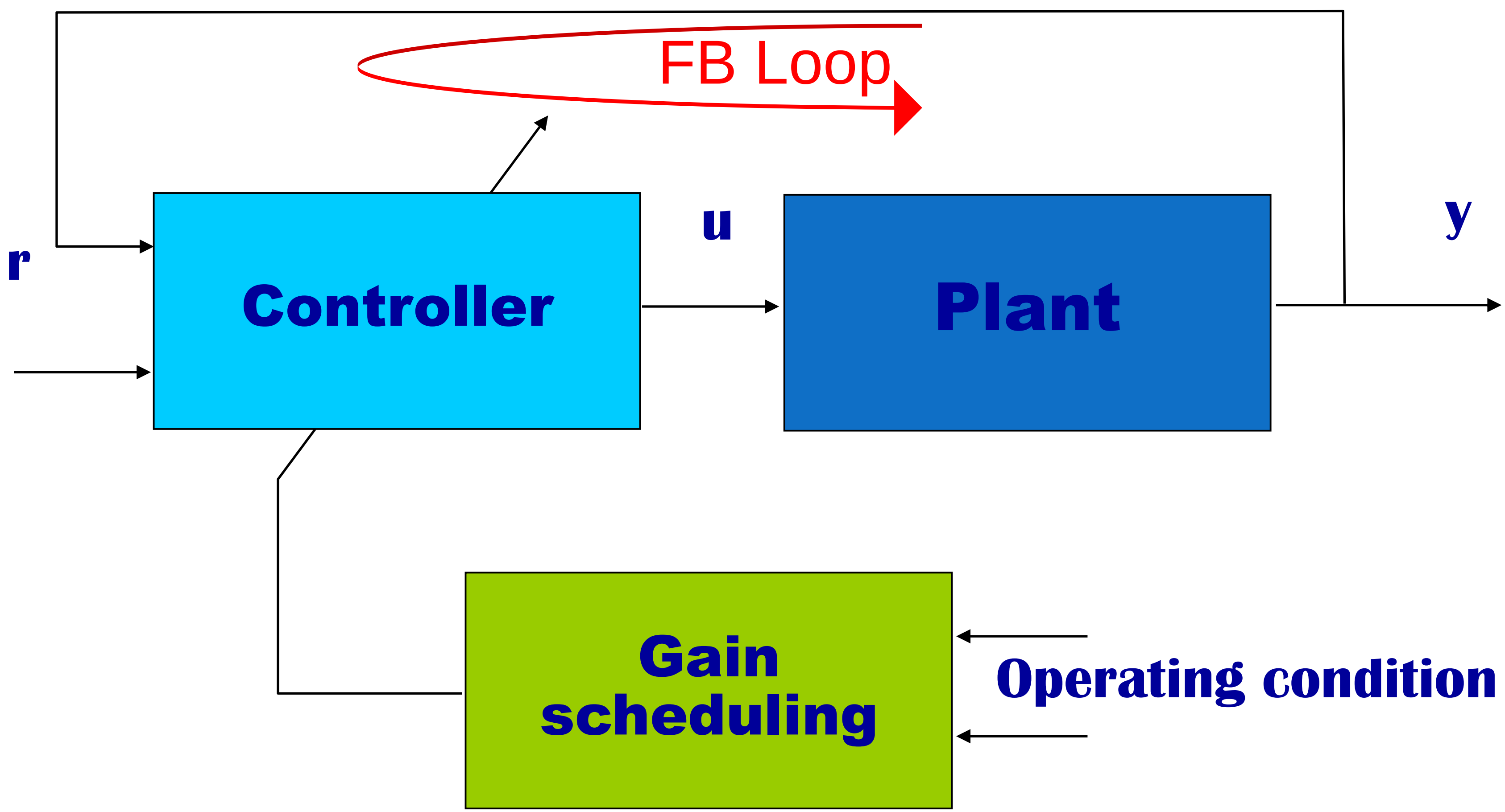


Source: Åström and Wittenmark book

Tuning rotary dryer controllers

- ✓ Constant gain controller has to be conservatively tuned to the longest time delay (worst stability case)
- ✓ Control becomes slugish for shorter delays (higher speed or production rate)
- ✓ In drying it is important to combine feedback and feedforward loops. To achieve good feedforward control it is essential to have good knowledge of the influence of measurable disturbance to dynamics of the process
- ✓ Here adaptive controller can be very useful, since it can adapt to the changing dynamics and variations in disturbances!

Gain sheduling (Adaptive control ?)



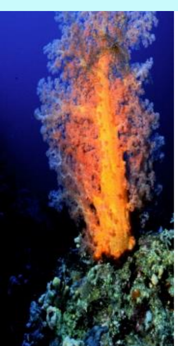
We need measurable variables that can give us information about the operating conditions

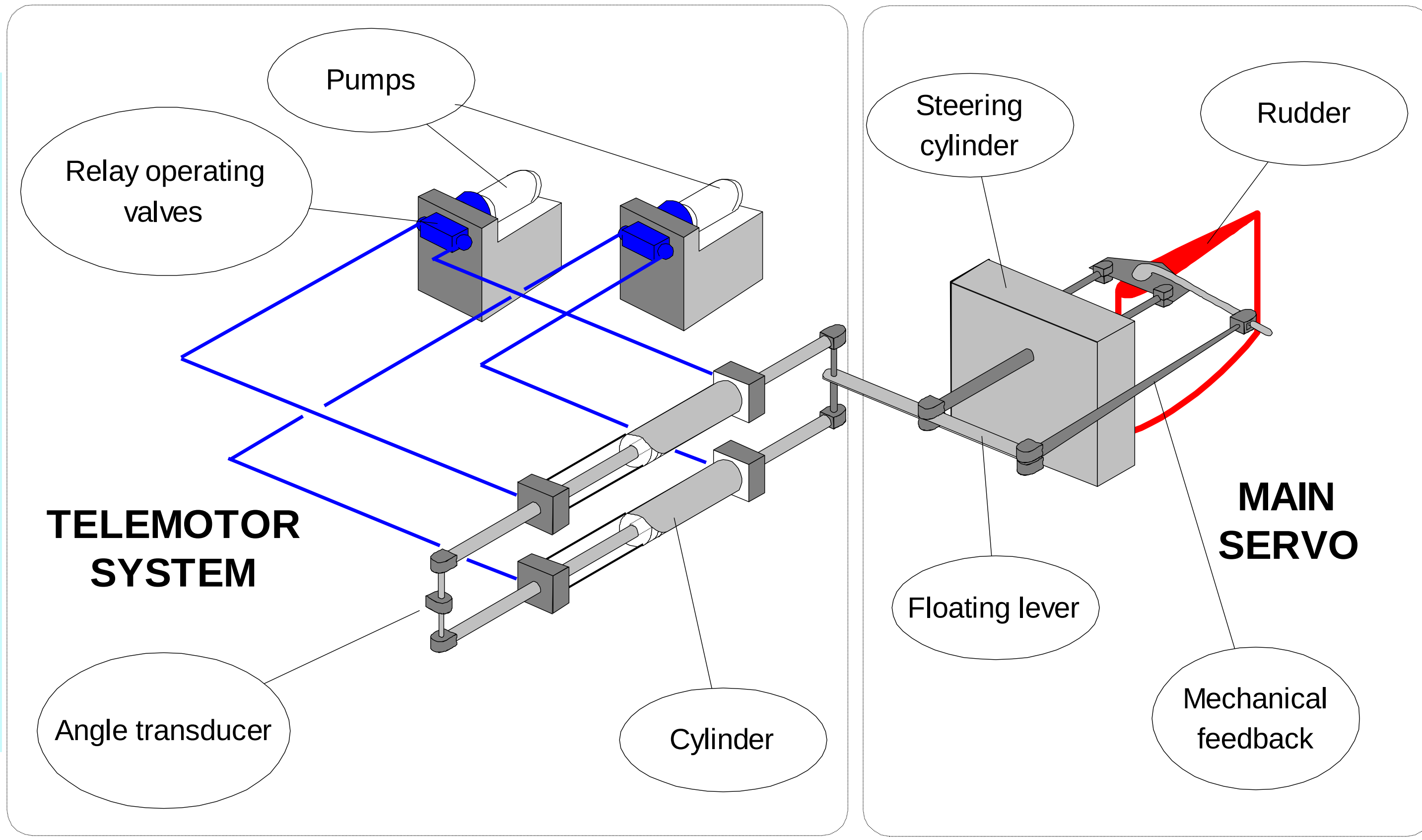
In case of the rotary dryer the batch moisture is measurable !

Nonlinear actuators – source of variations when operating conditions change

HYDRAULIC RUDDER SERVO SYSTEM

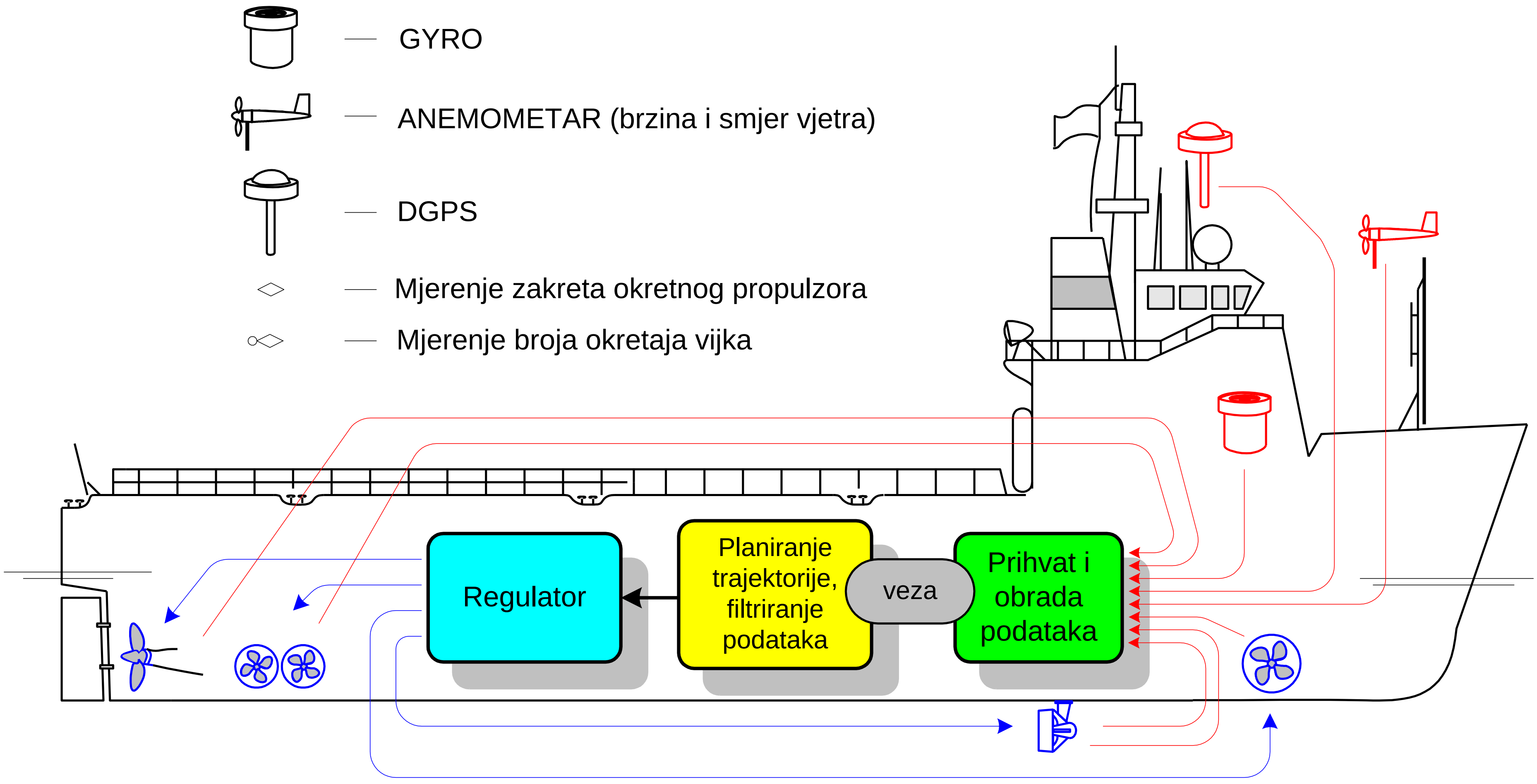
- Change of the dynamics can be caused by:
  - Leakage of fluid
  - Intrusion of the air somewhere in the system
  - Uneven wear of the pumps
  - Sensor failure
  - etc.





BLOCK DIAGRAM OF HYDRAULIC RUDDER SERVOSYSTEM

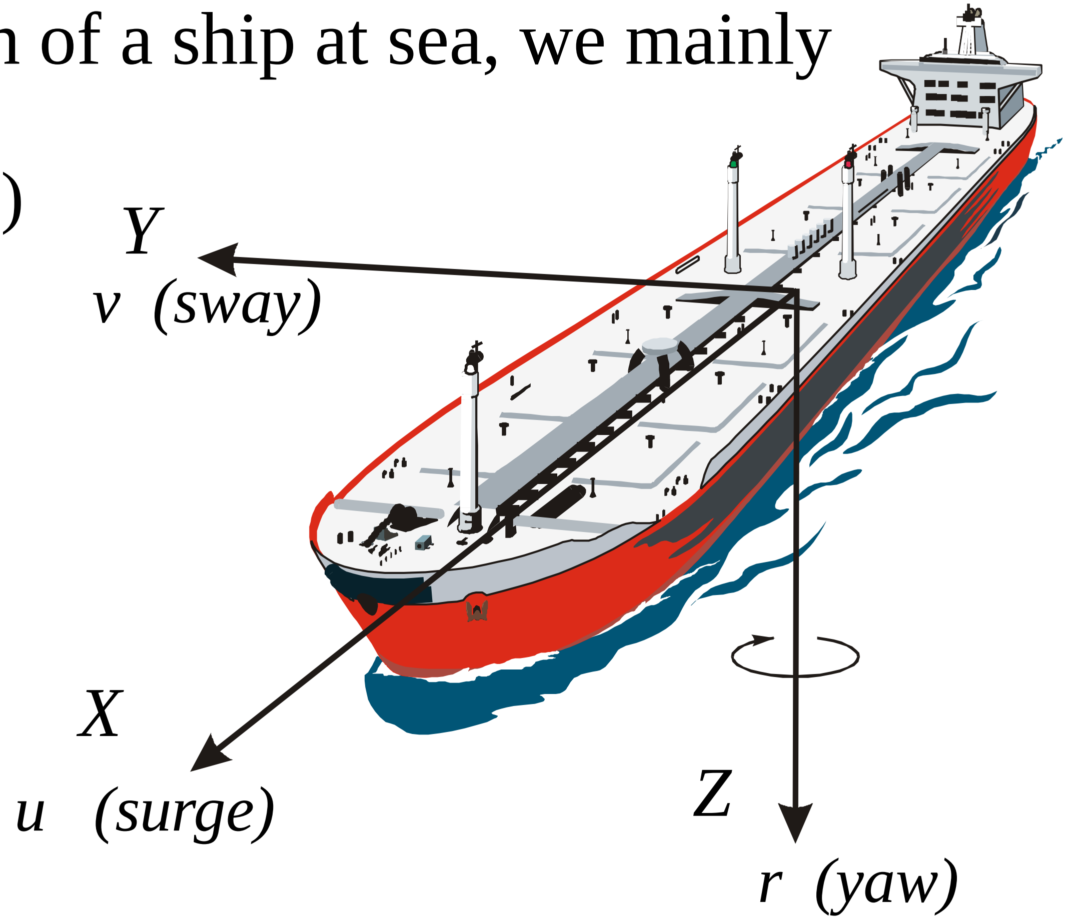
Croatian mine hunter



Reference frames (6DOF)

To describe the local motion of a ship at sea, we mainly use two reference frames:

- North-East-Down (*n*-frame)
- Body-fixed (*b*-frame)

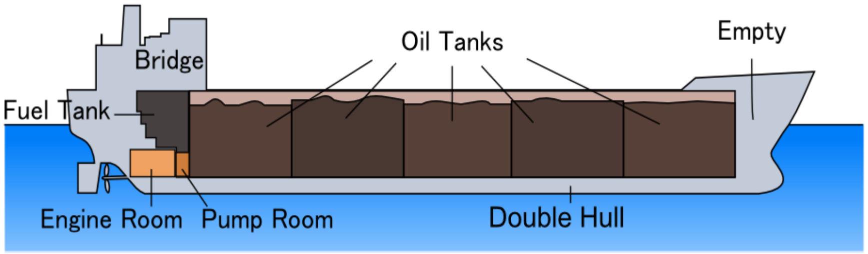


- The n-frame is used to define the position of the vessel on the earth, and the direction of wind and current.

- The b-frame is the frame to which all the velocity and acceleration measurements on board are referred. This frame is also used to formulate the equations of motion and to define some ship motion performance indices.

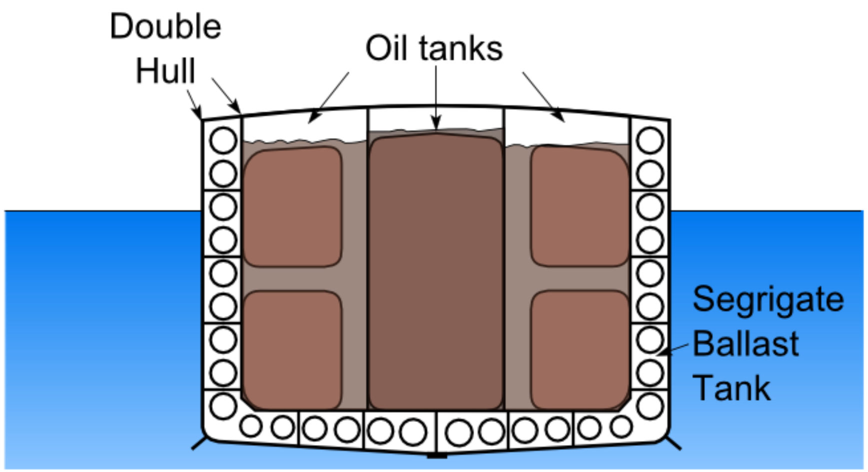
Ship dynamics change with depth under keel

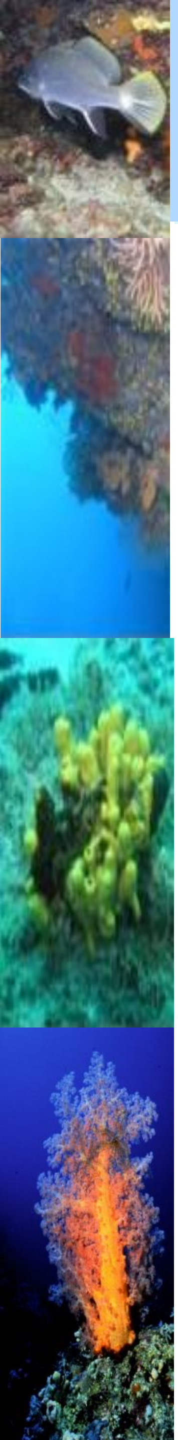
Oil tanker (side view)



Oil tanker (front view)

Center cut view





Fujino, conducted planar motion mechanism (PMM) and oblique tests of two ship models at various water depth-to-draft ratio H/T

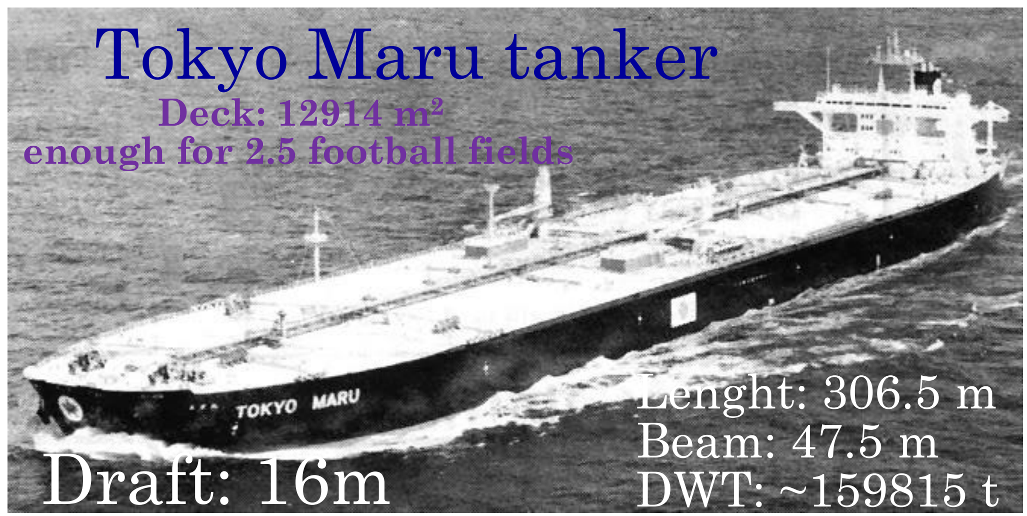
$$
\begin{bmatrix} \dot{\psi}(t) \\ \dot{r}(t) \\ \dot{\beta}(t) \\ \dot{\eta}(t) \\ \dot{\delta}(t) \end{bmatrix} =
\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & a_{22} & a_{23} & 0 & a_{25} \\ 0 & a_{32} & a_{33} & 0 & a_{35} \\ 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\dfrac{1}{\tau} \end{bmatrix}
\begin{bmatrix} \psi(t) \\ r(t) \\ \beta(t) \\ \eta(t) \\ \delta(t) \end{bmatrix} +
\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \dfrac{1}{\tau} \end{bmatrix} \delta_c(t) +
\begin{bmatrix} 0 & 0 \\ \gamma_{21} & \gamma_{22} \\ \gamma_{31} & \gamma_{32} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}
\begin{bmatrix} N \\ Y \end{bmatrix}
$$

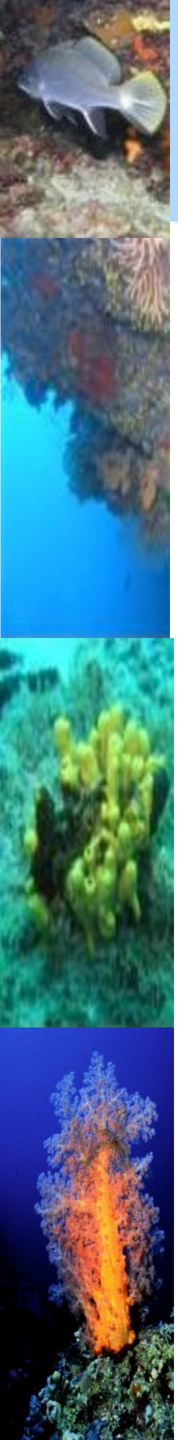
$\beta -$ ship's drift angle

$\eta -$ lateral offset from desired path

$\delta -$ rudder angle; $\delta_c -$ rudder command

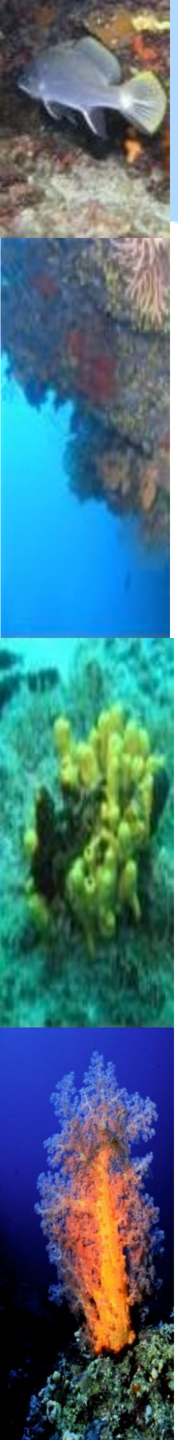
Largest tanker in the World in 1970-ties (launched 1965)





Ship model particulars

Model particulars	Mariner	Tokyo Maru
λ Linear scale ratio	64.37	145.00
L_{pp} [mm]	2,500.00	2,000.00
B Breadth [mm]	359.8	327.6
T_{fore} Draft fore [mm]	106.5	110.3
T_{aft} Draft aft [mm]	125.5	110.3
T_{mean} Draft mean [mm]	116.0	110.3
Displacement [kg]	61.44	58.44
Block coefficient, C_B	0.5888	0.8054
Rudder area [mm^2]	-	3,390.9
Propeller diameter [mm]	104.2	53.8
Propeller pitch [mm]	108.1	39.8
Number of blades	4	5
Direction of rotation	right	right

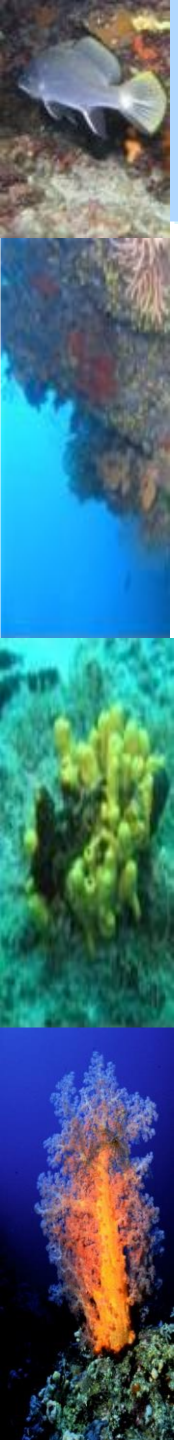


Coefficients of Mariner class ship model versus H/T at $F_n = 0.0905$ (7 knots full-scale)

Rudder servo system has: $\tau = 0.223$
(corresponds to a 10 seconds rudder constant)

H/T	1.21	1.50	1.93	2.50	∞
a_{22}	-4.439	-2.696	-2.3764	-2.1962	-2.1939
a_{23}	10.413	7.5634	5.6534	4.2852	3.3658
a_{25}	-0.96338	-1.3331	-1.4537	-1.5947	-1.4609
γ_{21}	712.14	822.90	909.93	963.51	971.78
γ_{22}	17.386	14.392	-2.8014	-4.6587	-4.4228
a_{32}	-0.58224	0.01253	0.15168	0.18097	0.28585
a_{33}	-1.5734	-0.98808	-0.80288	-0.72058	-0.89059
a_{35}	-0.26338	-0.19531	-0.23307	-0.20998	-0.20813
γ_{31}	75.829	30.465	23.556	23.294	13.082
γ_{32}	-29.013	-42.020	-50.808	-55.058	-64.162

NOTE: Typically, oceangoing ships have a maximum rudder capability of ± 35 [^{0}] and are required to have rudder rate capability of at least 2.33 [^{0}/s].
For a first order system this means that the rudder time constant should be τ = 10 [s]



Coefficients of Tokyo Maru ship model versus H/T at F_n = 0.103 (10.7 knots full-scale)

Rudder servo system has: τ =0.189
(corresponds to a 10 seconds rudder constant)

H/T	1.30	1.50	1.89	2.50	∞
a_{22}	-1.6508	-1.7136	-1.7657	-1.8177	-1.9515
a_{23}	9.3157	6.6235	5.7359	4.6112	3.1591
a_{25}	-0.55543	-0.79235	-0.88074	-1.0416	-1.0410
γ_{21}	346.69	385.98	477.68	536.00	567.13
γ_{22}	4.8040	-2.2145	-5.0043	-5.8625	2.3365
a_{32}	0.02974	0.01389	0.17199	0.23621	0.31507
a_{33}	-1.0388	-0.71895	-0.52766	-0.5456	-0.63651
a_{35}	-0.09995	-0.12092	-0.15607	-0.16639	-0.16163
γ_{31}	11.825	14.230	21.141	21.942	16.844
γ_{32}	-19.216	-23.123	-28.233	-31.49	-37.384

NOTE: Typically, oceangoing ships have a maximum rudder capability of ± 35 [^{0}] and are required to have rudder rate capability of at least 2.33 [^{0}/s].
For a first order system this means that the rudder time constant should be τ = 10 [s]




Test results

Mariner class ship is dynamicaly stable on any depth under keel

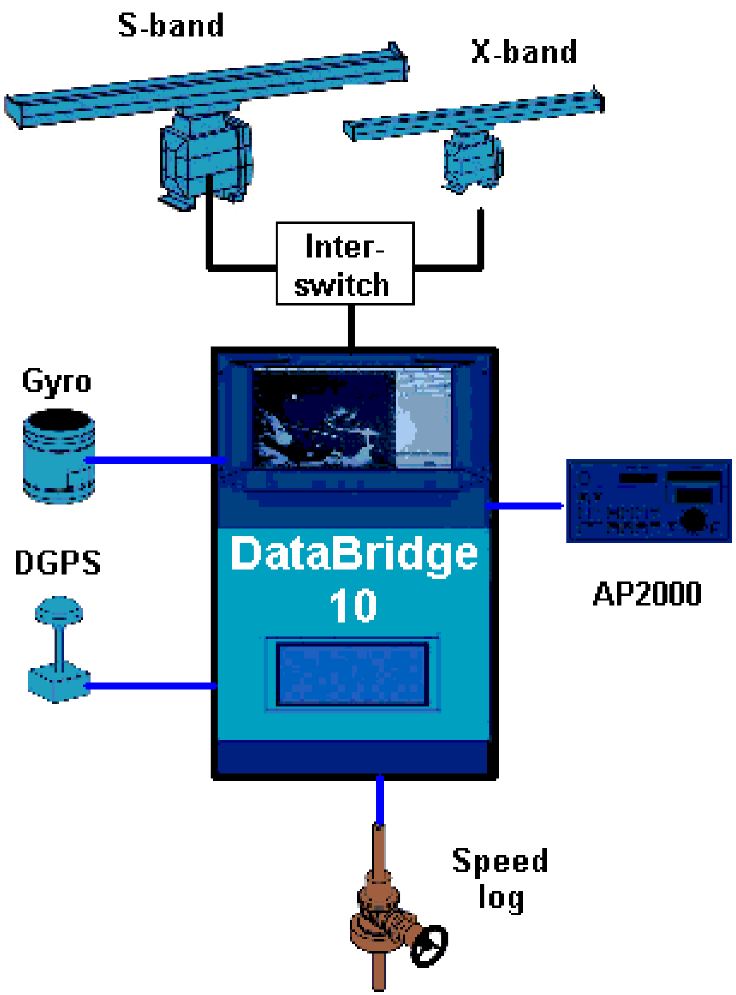
MARINER	$F_n = 0.0905$	
$\lambda_1 = \lambda_2$ $\lambda_3 = -1/\tau$	0.0 -4.478	
H/T	λ_4	λ_5
∞	-0.3446	-2.720
2.50	-0.3095	-2.607
1.93	-0.3745	-2.805
1.50	-0.9343	-2.750
1.21	-0.9343	-2.750

Toky Maru tanker is not stable for H/T = 2.5 and 1.89

TOKYO MARU	$F_n = 0.103$	
$\lambda_1 = \lambda_2$ $\lambda_3 = -1/\tau$	0.0 -5.281	
H/T	λ_4	λ_5
∞	-0.0992	-2.489
2.50	0.0405	-2.404
1.89	0.0237	-2.317
1.50	-0.1358	-2.297
1.30	-0.7360	-1.954

T – draft (gaz)
H – depth under keel

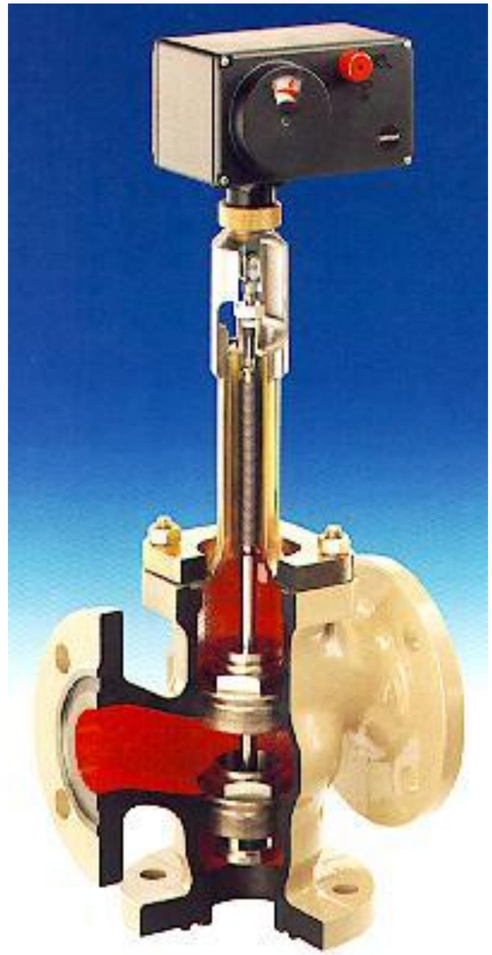
Kongsberg - Norcontrol – adaptive autopilot AP2000



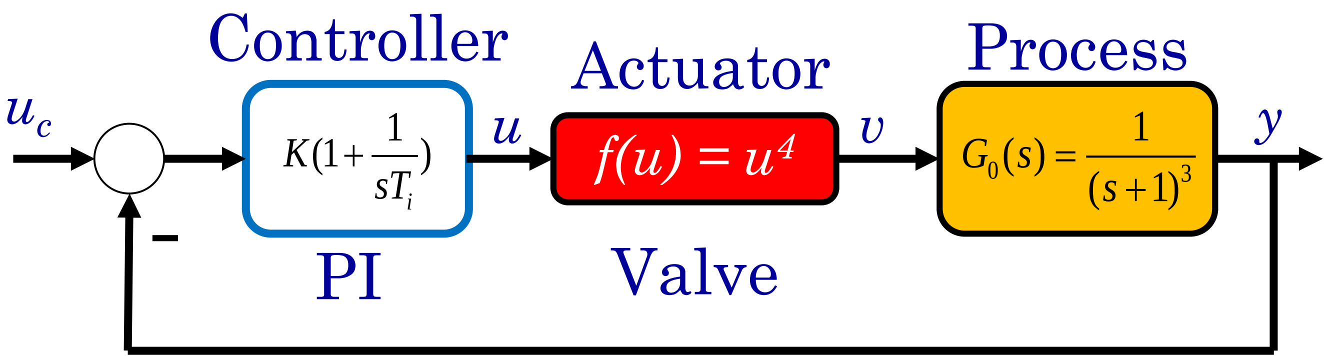
Sperry Marine ADG 3000 autopilot

Sperry Marine News (2000): Litton Marine Systems has introduced a new adaptive autopilot system with self-tuning software. The new auto-tuning software has been extensively tested in sea trials over the last nine months, and is available in the Sperry Marine ADG 3000 autopilot system.

Valves are most common actuators in industry



Example 3: Nonlinear actuators



$v(t) = f(u) = u^4(t)$; $u(t) \geq 0$

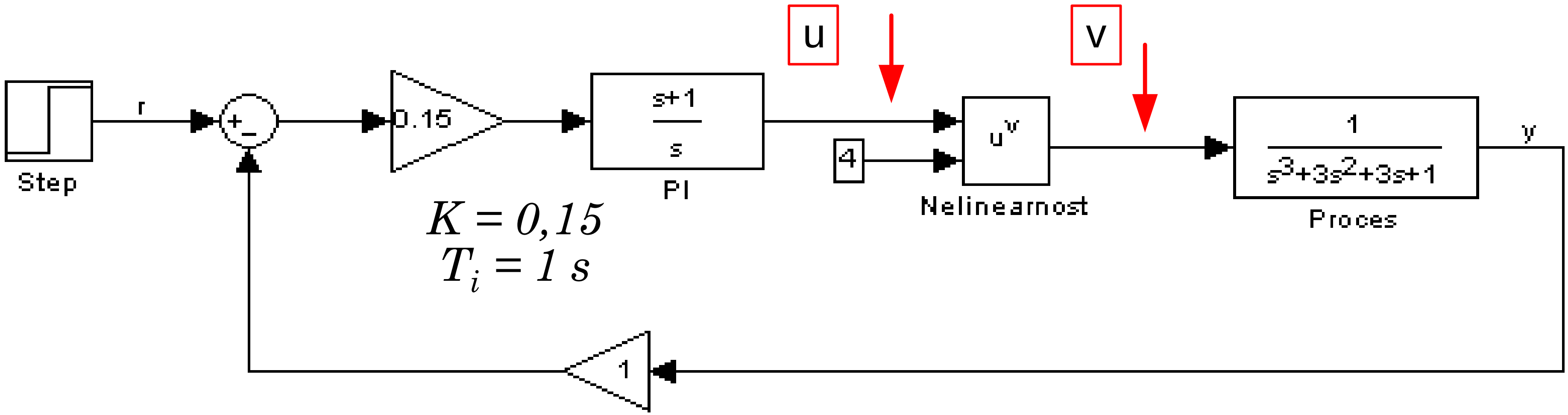
$$G_0(s) = \frac{1}{(s+1)^3}$$

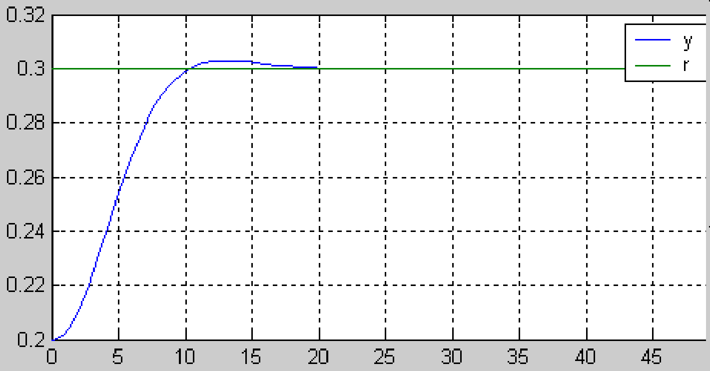
$K = 0,15$
$T_i = 1\ s$

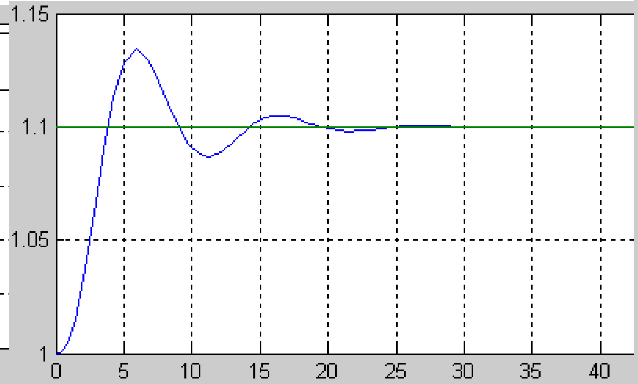
- ✓ A very common source of variations is nonlinearity of actuators (like valves).
- ✓ Block diagram represents control loop with PI regulator, actuator (valve) and a process.
- ✓ Linearizing this system around a steady-state operating condition shows that the incremental gain of the valve is *f(u)* and hence the loop gain is proportional to *df(u)/dt* i.e. the slope of the tangent at valve nonlinear static characteristic.

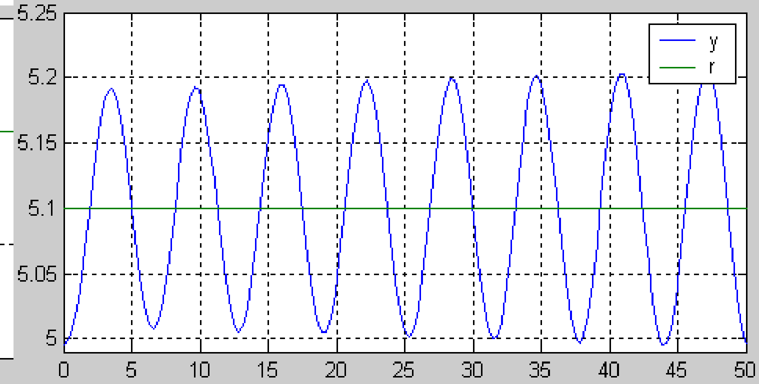
Source: Åström and Wittenmark book

Simulink block diagram – step responses to $\Delta u_c = 0.1$ for different operating conditions





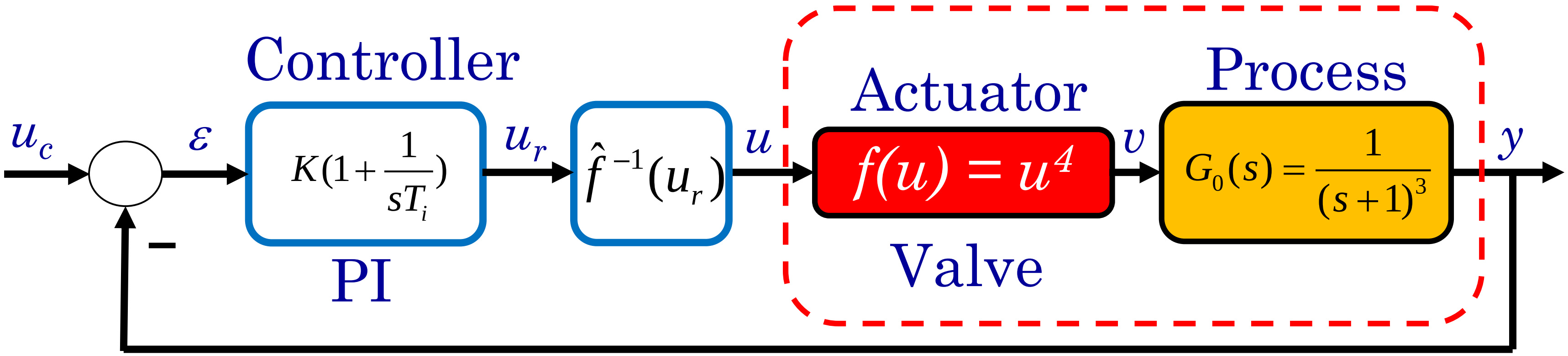




- The controller is tuned to give a good response at low levels of operating level (u = 0.2).
- For operating point $u_c = 1.0$ response to $\Delta\ u_c = 0.1$ detoriates
- For higher values of operating level, $u_c = 5.0$ the closed loop system even becomes unstable as can be seen in fig.3.

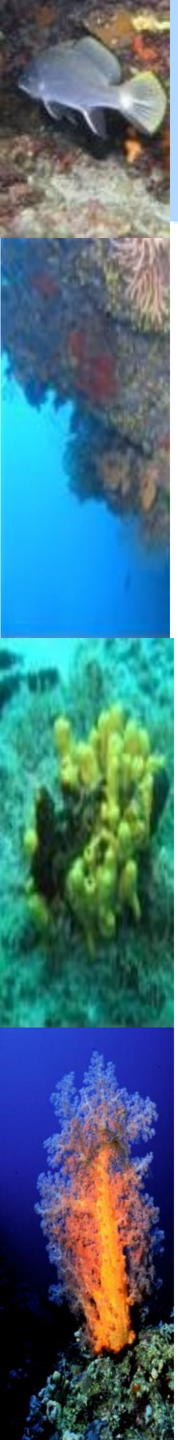
Discussion

- ✓ The system can perform well at one operating level and poorly at another.
- ✓ One way to handle this type of problem is to feed the control signal $u_r(t)$ through an inverse of the nonlinearity (crude approximation is sometimes sufficient) before it is applied to the valve.

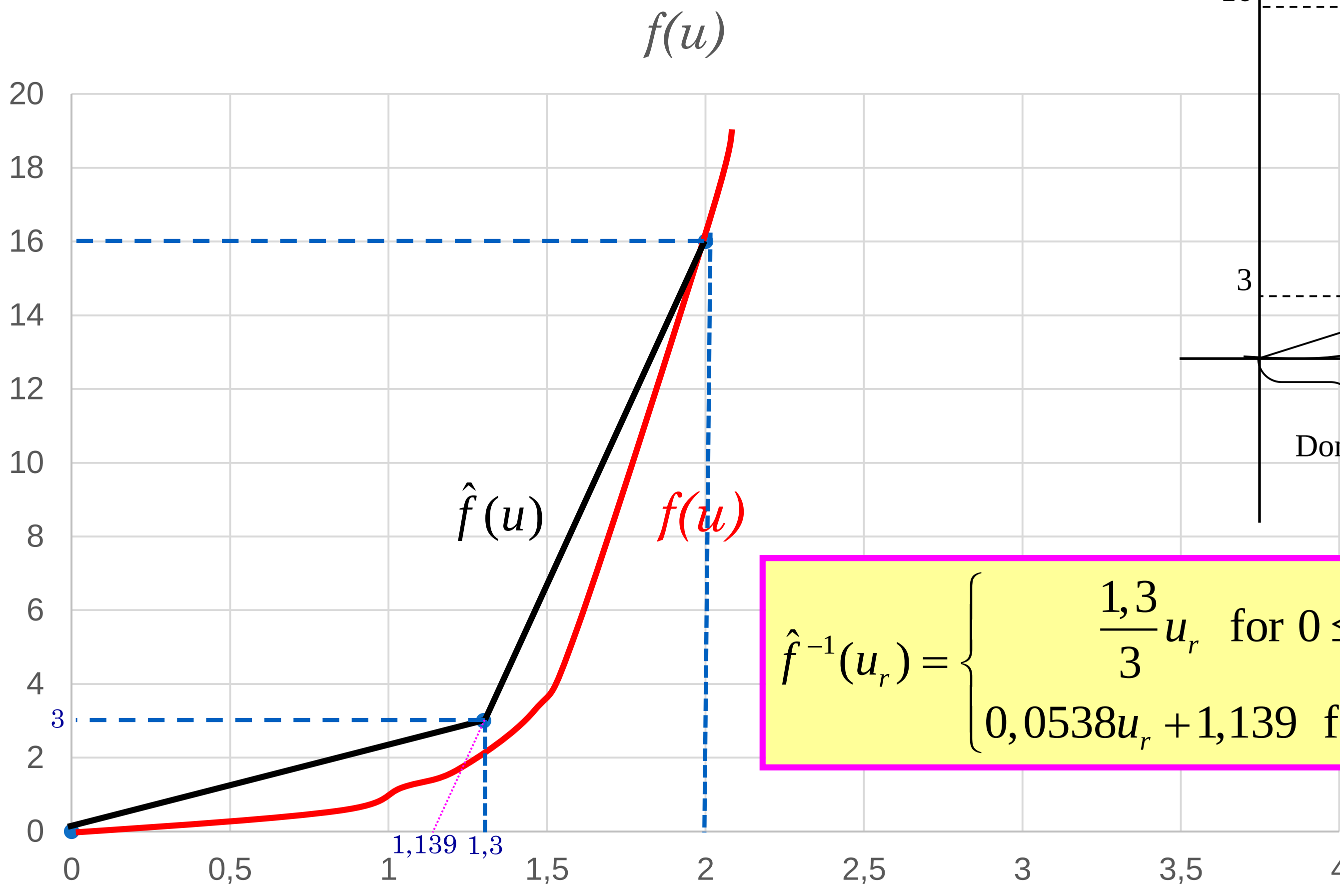


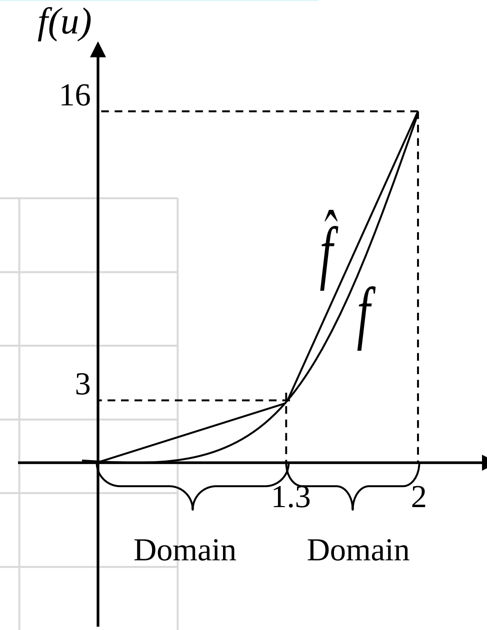
$$v = f(u) = f\underbrace{\left[\hat{f}^{-1}(u_r)\right]}_{\text{This function should have less variation in gain than f(u)}}$$

iff $\hat{f}^{-1}(u_r)$ is exact inverse, then $v = u_r$



***f(u)* is approximated by two straight lines**
- one conecting (0.0,0.0) and (1.3, 3.0)
- the other connecting (1.3, 3.0) and (2.0, 16.0)



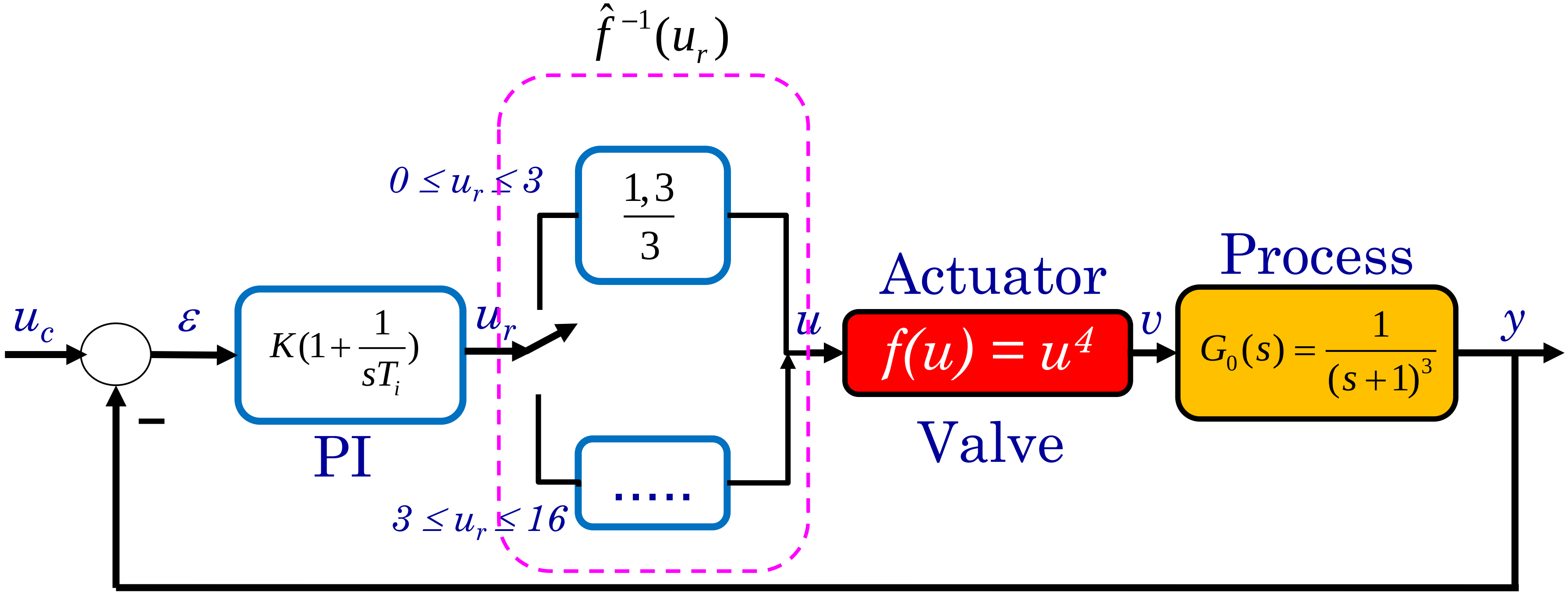


$$\hat{f}^{-1}(u_r) = \begin{cases} \dfrac{1,3}{3} u_r & \text{for } 0 \le u_r \le 3 \\ 0,0538 u_r + 1,139 & \text{for } 3 \le u_r \le 16 \end{cases}$$

We end-up with variable structure system – sort of gain scheduling

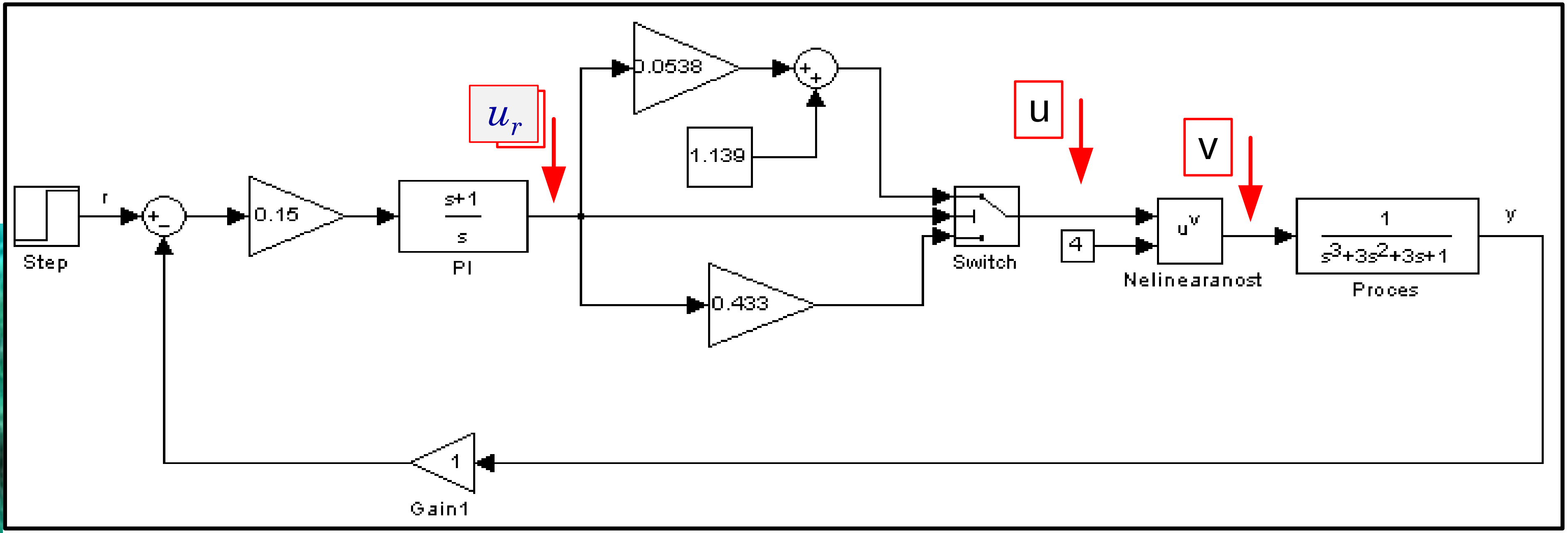
Variable structure system – possible solution to actuator nonlinearity effects

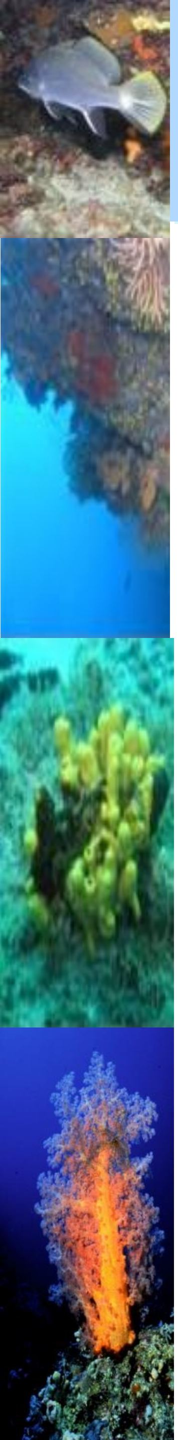
$$\hat{f}^{-1}(u_r) = \begin{cases} \dfrac{1,3}{3} u_r & \text{for } 0 \le u_r \le 3 \\ 0,0538 u_r + 1,139 & \text{for } 3 \le u_r \le 16 \end{cases}$$



We end-up with variable structure system – sort of gain scheduling

Simulink block diagram





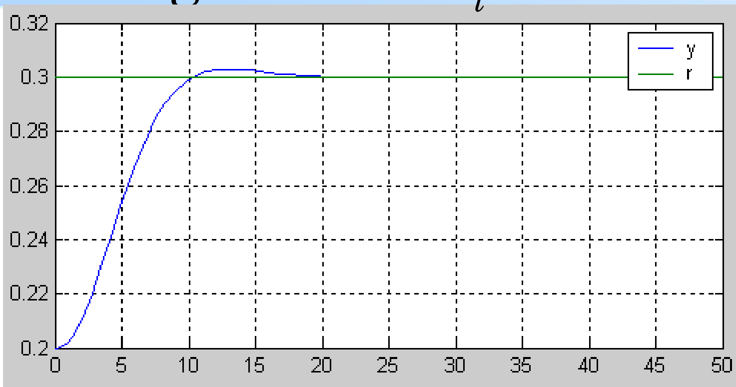
Step responses to $\Delta u_c = 0.1$

$K = 0,15$

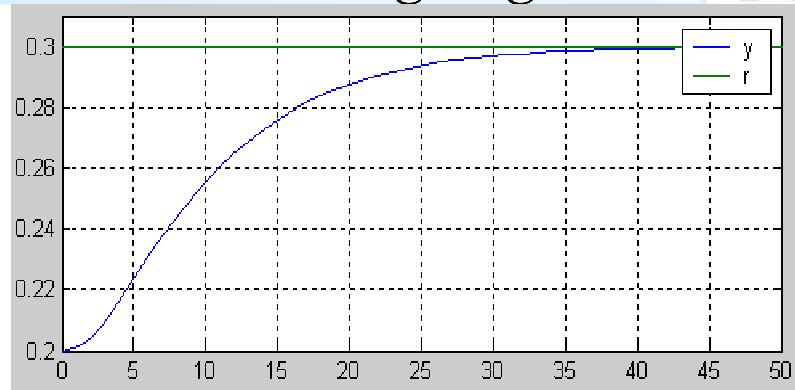
$T_i = 1\ s$

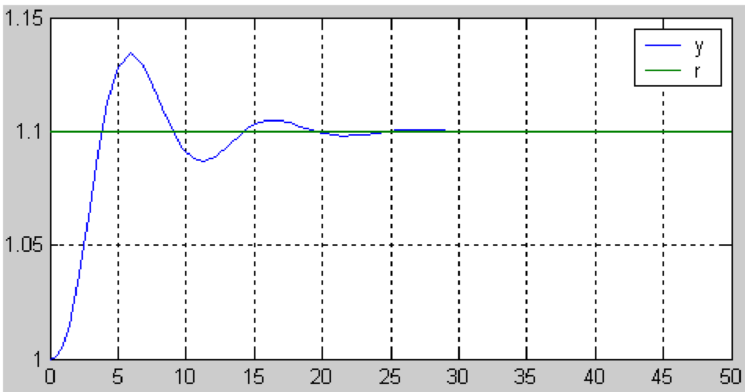
PI regulator

Gain scheduling regulator

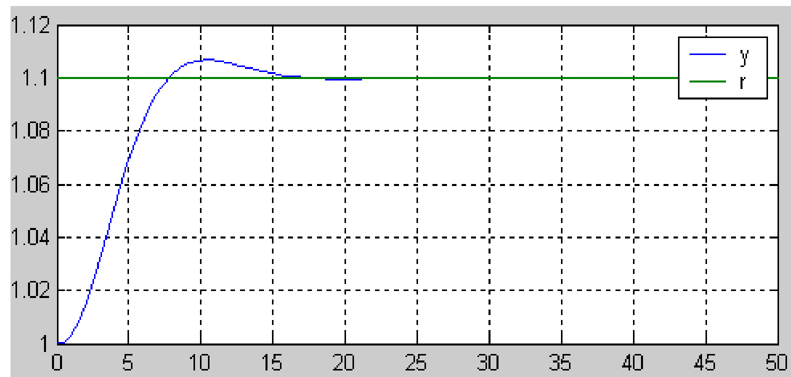


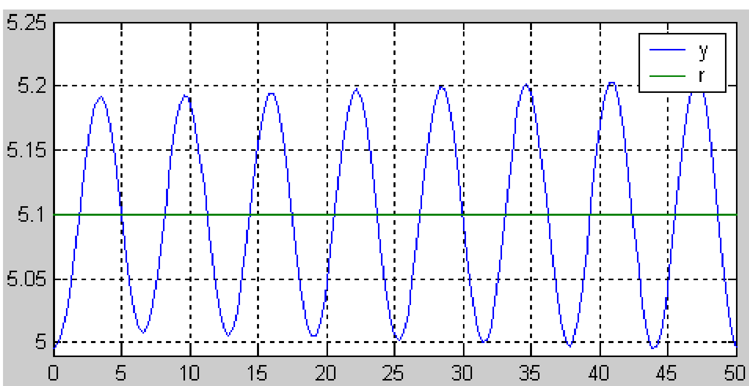
Y=0.2



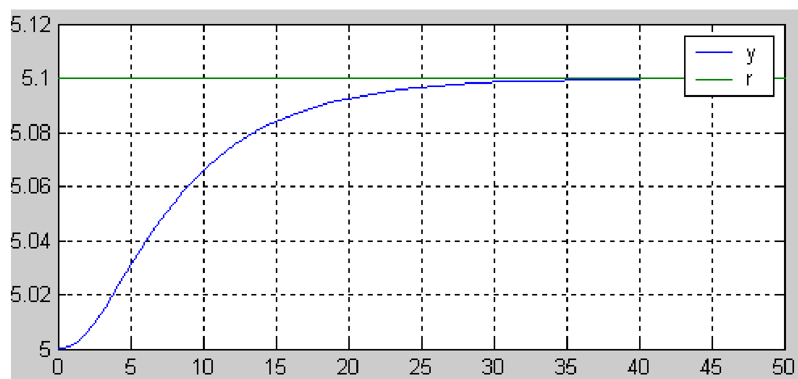


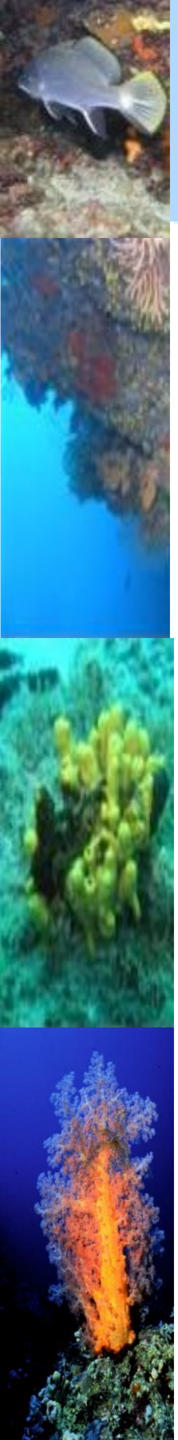
Y=1





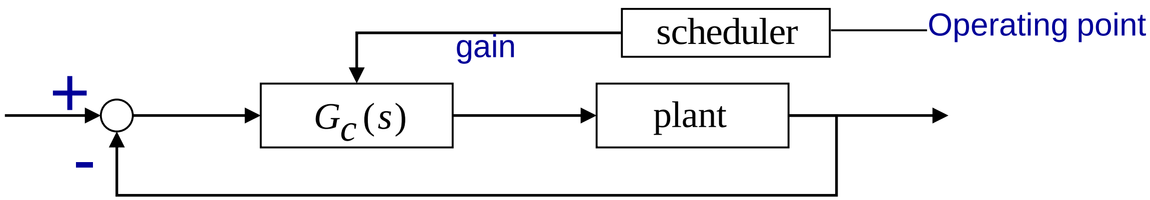
Y=5



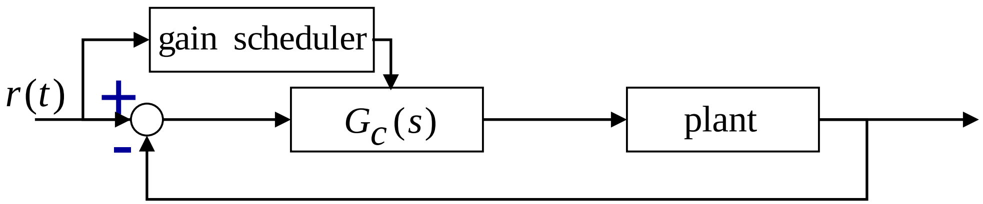


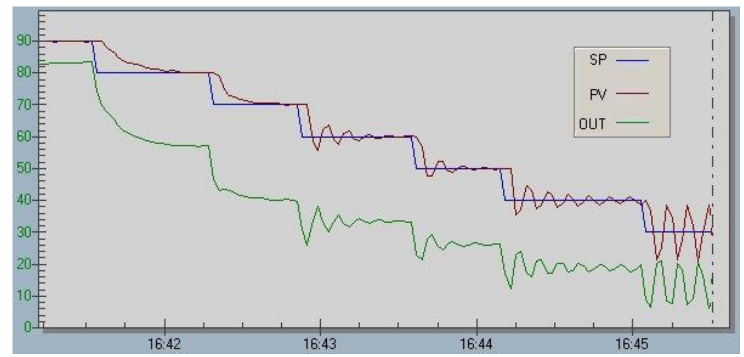
Classification of gain scheduling structures

Scheduling based upon operating conditions

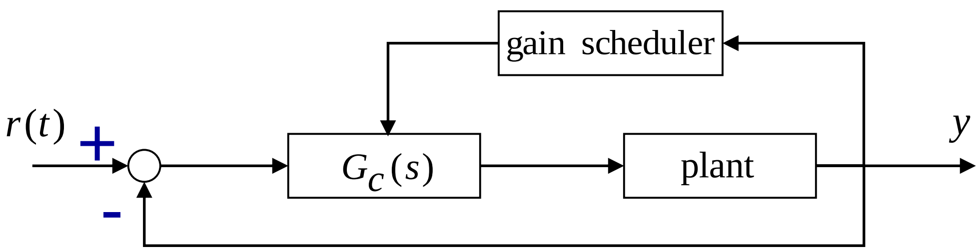


Scheduling based upon the reference signal





Scheduling based upon plant output



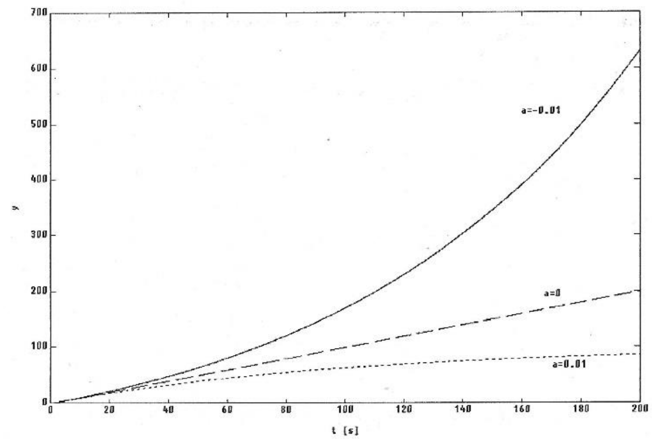
Gain-scheduling is perhaps one of the most popular approaches to nonlinear control design and has been widely and successfully applied in fields ranging from aerospace to process control.

Judging the need for adaptation

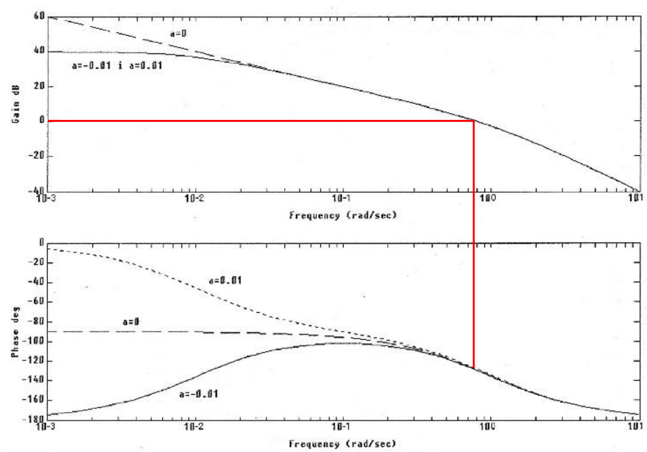
- ✓ The fact that there are significant variations in open-loop step responses (as a parameter variations effect) does not necessarily mean that adaptive control is needed
- ✓ **<u>Example 1</u>**. – change of parameters cause different open-loop step responses but small changes in closed loop step responses

$$u \longrightarrow \boxed{\frac{1}{(s+1)(s+a)}} \longrightarrow y \qquad a = \begin{cases} -0,01 \\ 0,0 \\ 0,01 \end{cases}$$

Example 1 - step response and frequency response of open-loop system



Open loop step response



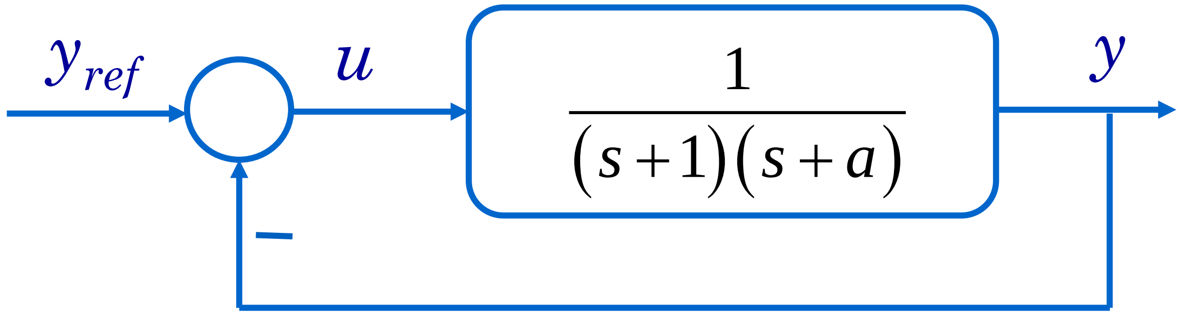
Open loop frequency response

Discussion:

- ✓ Quite different step responses
- ✓ Similar behaviour of the frequency response around ω_c

Does unity feedback robustifies this system?

Closing the loop

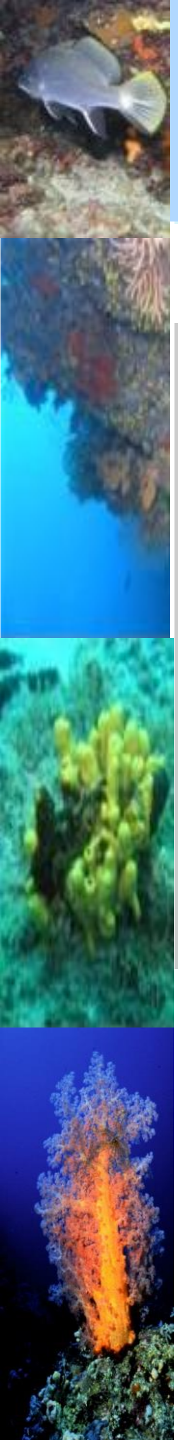


$$G_{cl}(s) = \frac{G_o(s)}{1+G_o(s)} = \frac{1}{s^2 + \underbrace{(1+a)}_{2\zeta\omega_n} s + \underbrace{1+a}_{\omega_n^2}}$$

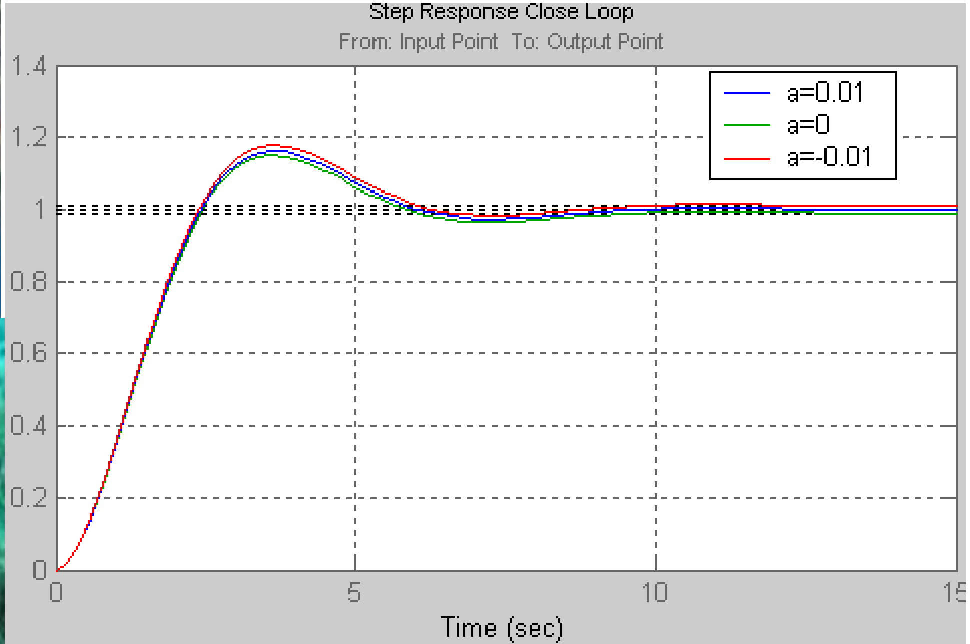
$$4\zeta^2\omega_n^2 = (1+a)^2 \rightarrow 4\zeta^2(1+a) = (1+a)^2 \rightarrow \zeta^2 = \frac{1+a}{4} \rightarrow \zeta = \frac{\sqrt{1+a}}{2}$$

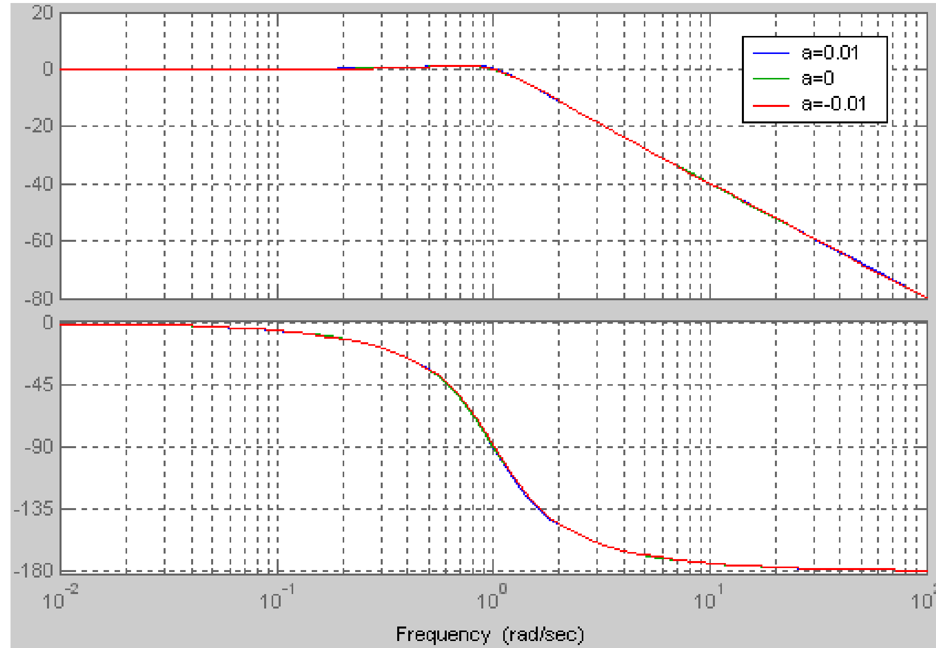
$$\omega_n^2 = (1+a) \rightarrow \omega_n = \sqrt{1+a}$$

$$\boxed{\zeta = \frac{\omega_n}{2}}$$



Closed-loop step and frequency responses





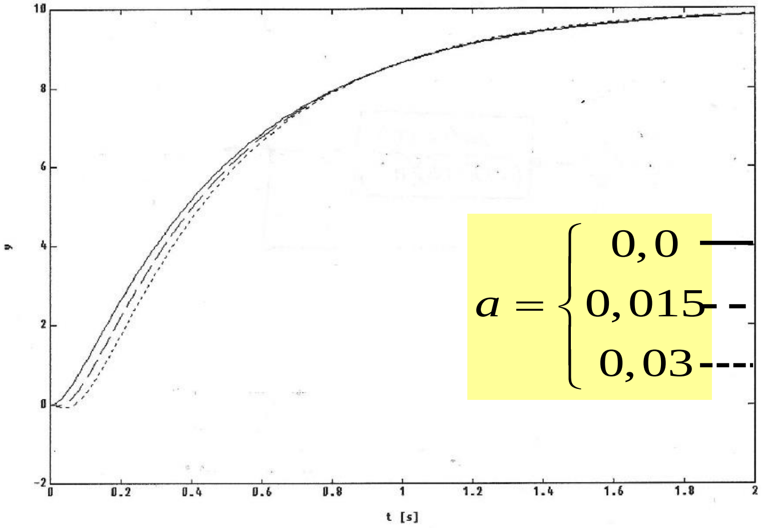
Step response of the closed-loop system

Closed-loop frequency characteristic

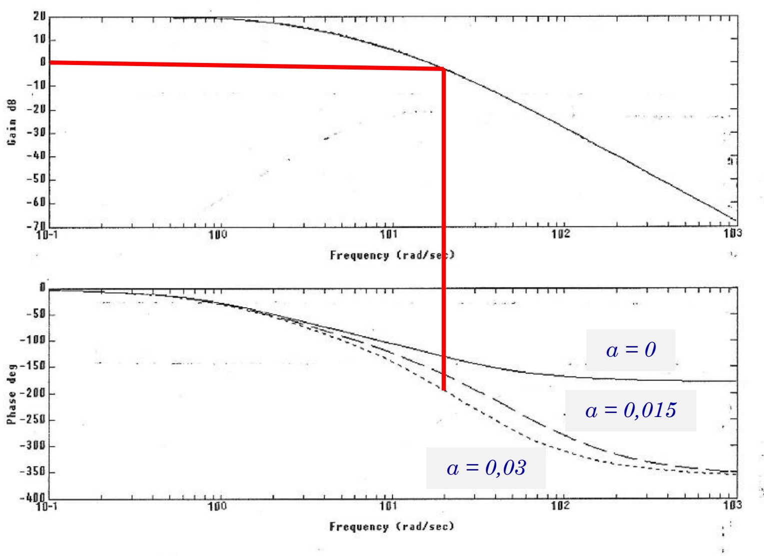
Step responses of a closed-loop system are almost indistinguishable !

The reason for that is that the open-loop and closed-loop frequency characteristic are very close at crossover frequency (ω_c) although their open-loop low frequency behaviours are different.

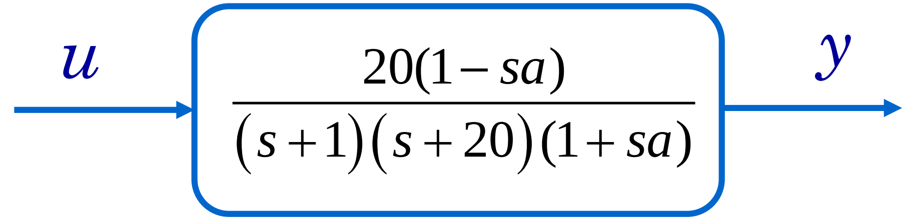
Example 2 – similar open-loop responses



Open loop step response



Open loop frequency response

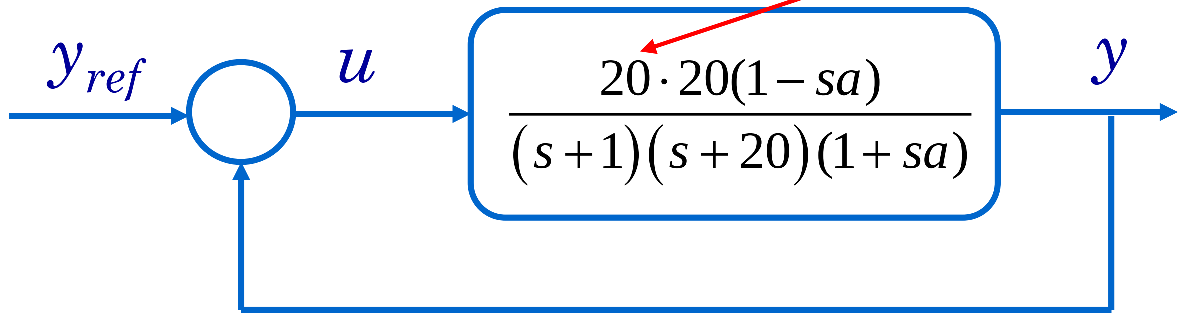


$$G_0(s) = \frac{20(1-sa)}{(s+1)(s+20)(1+sa)} \quad \text{where } a = \begin{cases} 0,0 \\ 0,015 \\ 0,03 \end{cases}$$

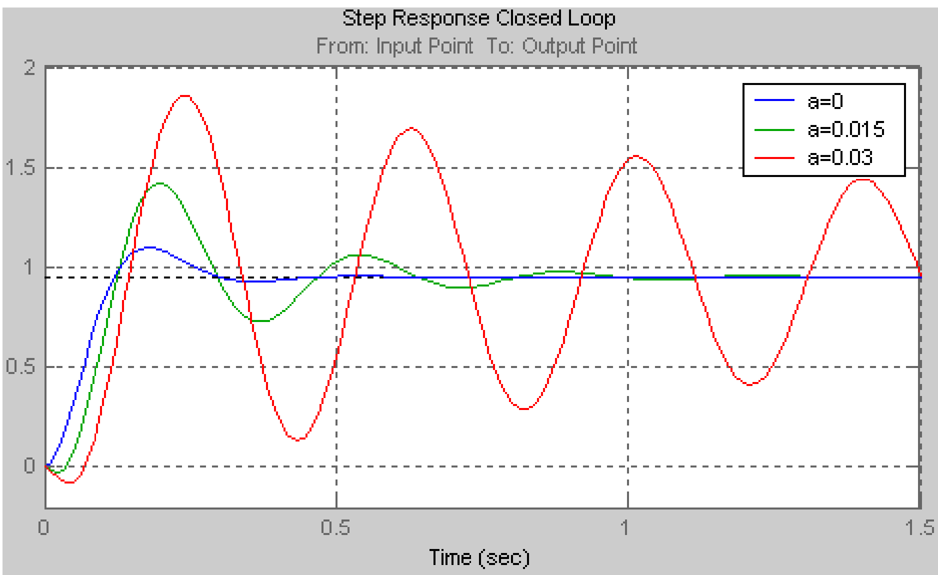
Discussion:

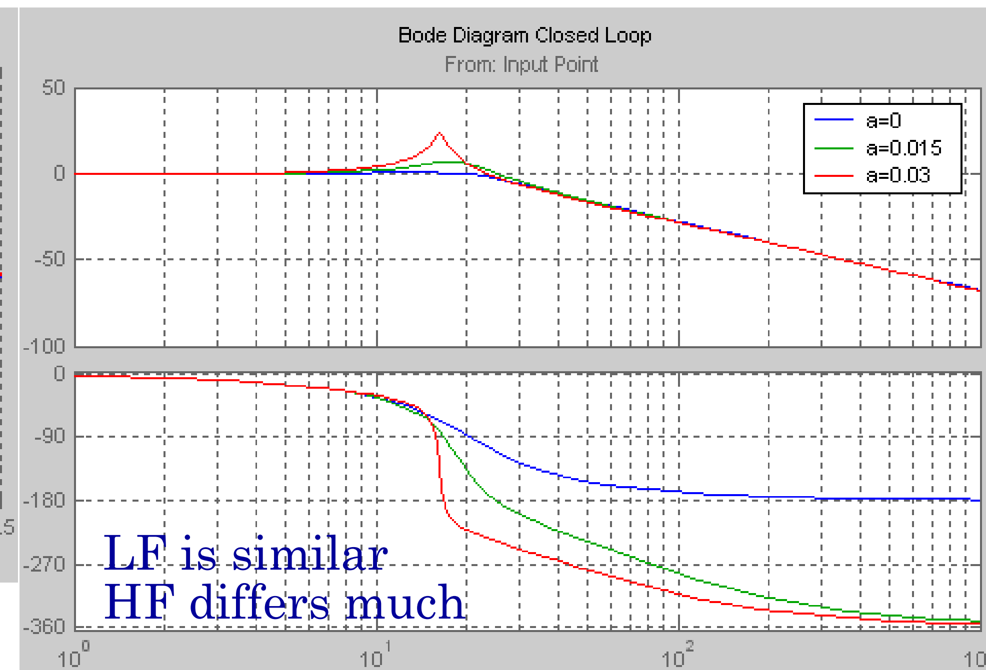
- ✓ Open-loop step responses are similar
- ✓ Open-loop frequency responses differ at ω_c.
- ✓ From step responses it seems that we do not need adaptation

Closing the loop and adding gain 20 in OL



$$G_{cl}(s) = \frac{G_0(s)}{1+G_0(s)} \quad ; \text{ where } G_o(s) = \frac{400(1-sa)}{(s+1)(s+20)(1+sa)}$$





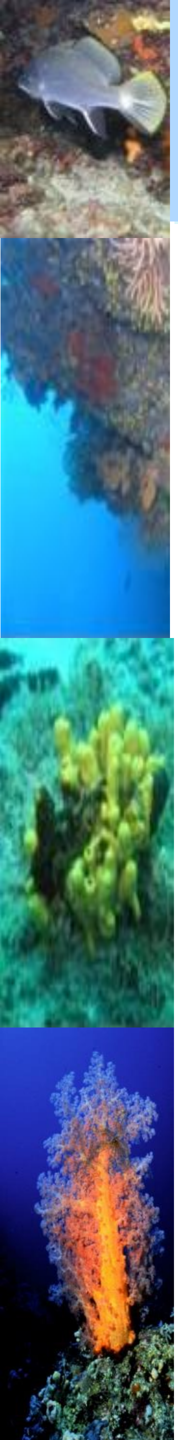
Closed-loop step and frequency response

Judging the need for adaptation Lessons to be learned from Example 1 & 2

1. It is essential to know the frequency response at the desired crossover frequency (ω_c) in order to judge whether parameter variations will have any effect on the closed-loop system properties
2. Step responses are poor guides! It is much better to look at the frequency responses!!
3. Presented examples and discussions indicate why adaptive or robust control is needed

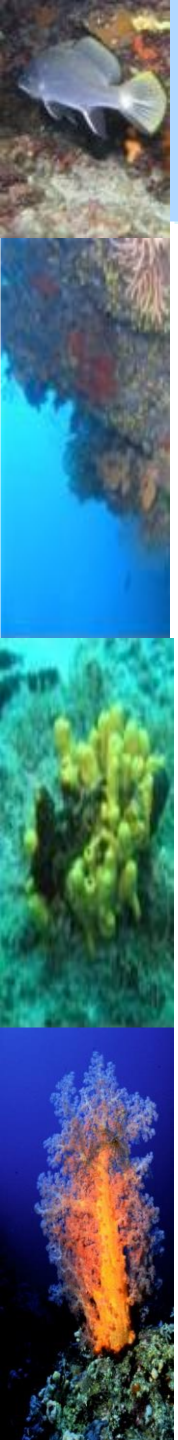
Adaptive control problem

- In typical industrial processes, which are often very complex, the parameter variations can not be determined from first principles
- It can therefore be advantageous to trade engineering efforts against more „intelligence” in the controller
- Use of the adaptive controller will not replace good process knowledge, which is still needed to choose:
  - The specifications
  - The structure of the controller
  - The design method



What contains the adaptive controller?

1. Control law with adjustable:
   - Parameters or signals
   - Regulator structure
2. Characterisation of the closed-loop response:
   - ✓ Reference model
   - ✓ Specification for design
3. Design procedure which must be convenient for on-line calculation
4. Parameter (signal) or structure updating based on measurements
5. Implementation of the control law



Conclusions

- Reasons for using adaptive control:
  - variations in process dynamics
  - variations in the character of the disturbances
  - engineering efficiency
- How to deal with variations
  - ✓ Gain scheduling control
  - ✓ Robust control
  - ✓ Adaptive control (MRAS and ST)
- In adaptive control we end-up with time-variant regulators
- In robust control we end-up with time-invariant regulators