Biomechatronics

Delft University of Technology
Course 2006-2007
(Wb 2432)

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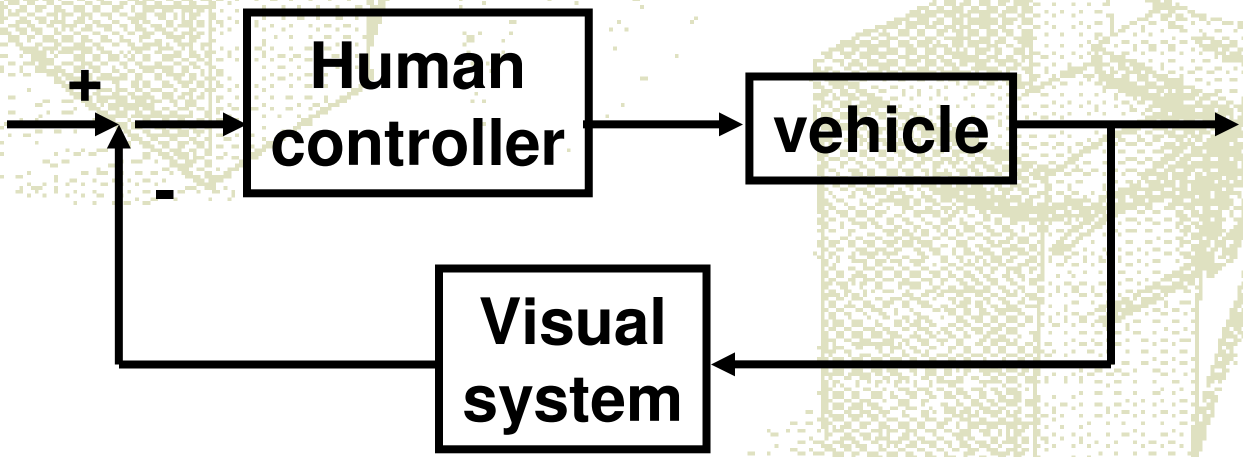
Lecture 13
Artificial motion control

Contents

- Introduction
- Definitions from control engineering
  - dynamical systems
  - stability
  - Phase-margin and gain margin
- Model of human controller
  - stability analyis
  - limitations and adaptation
- Supervisory control situations
  - supervisor over automated control loops

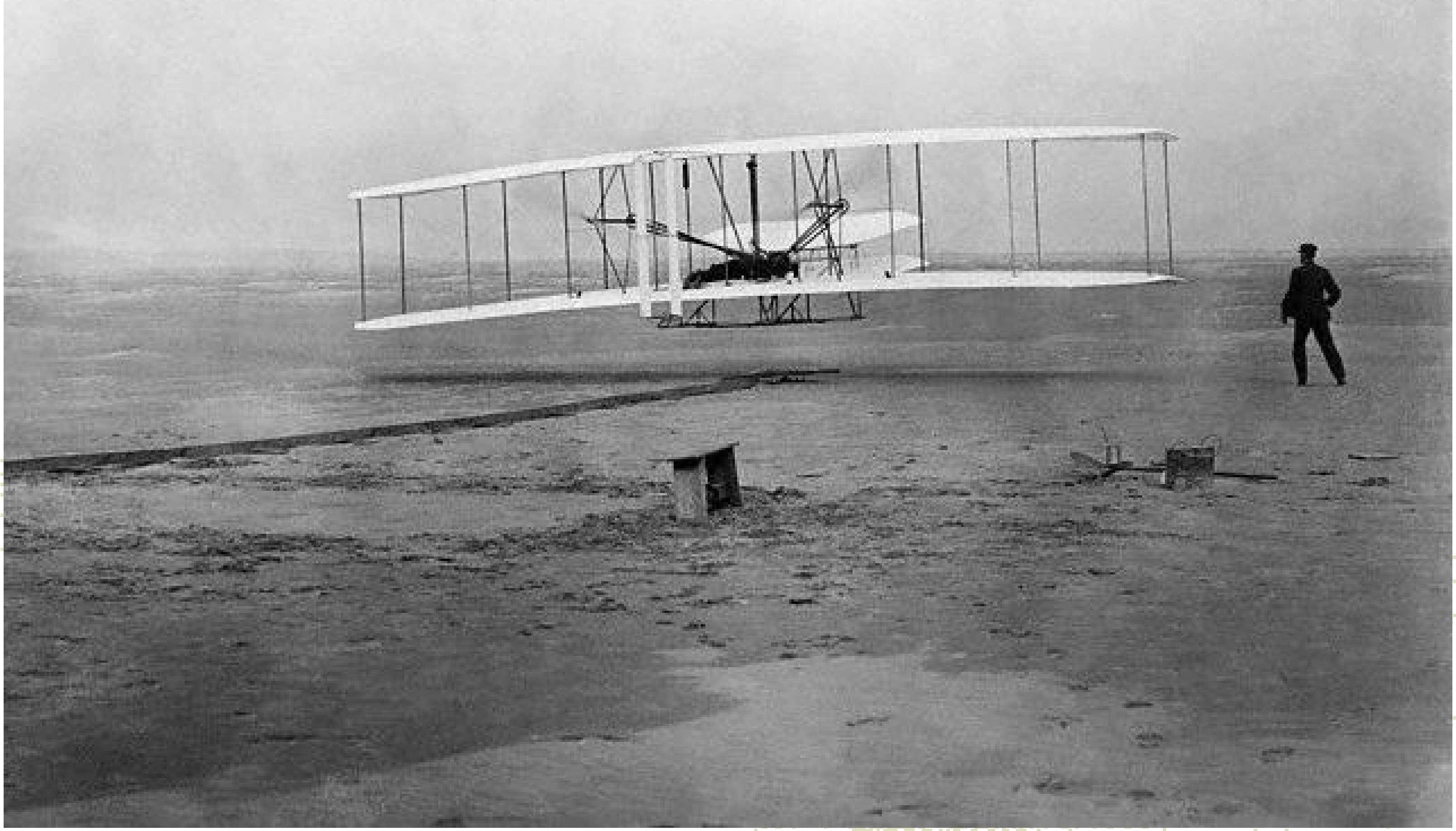
The human as controller

- Marine vessels
- Vehicles
- Airplanes
- ….

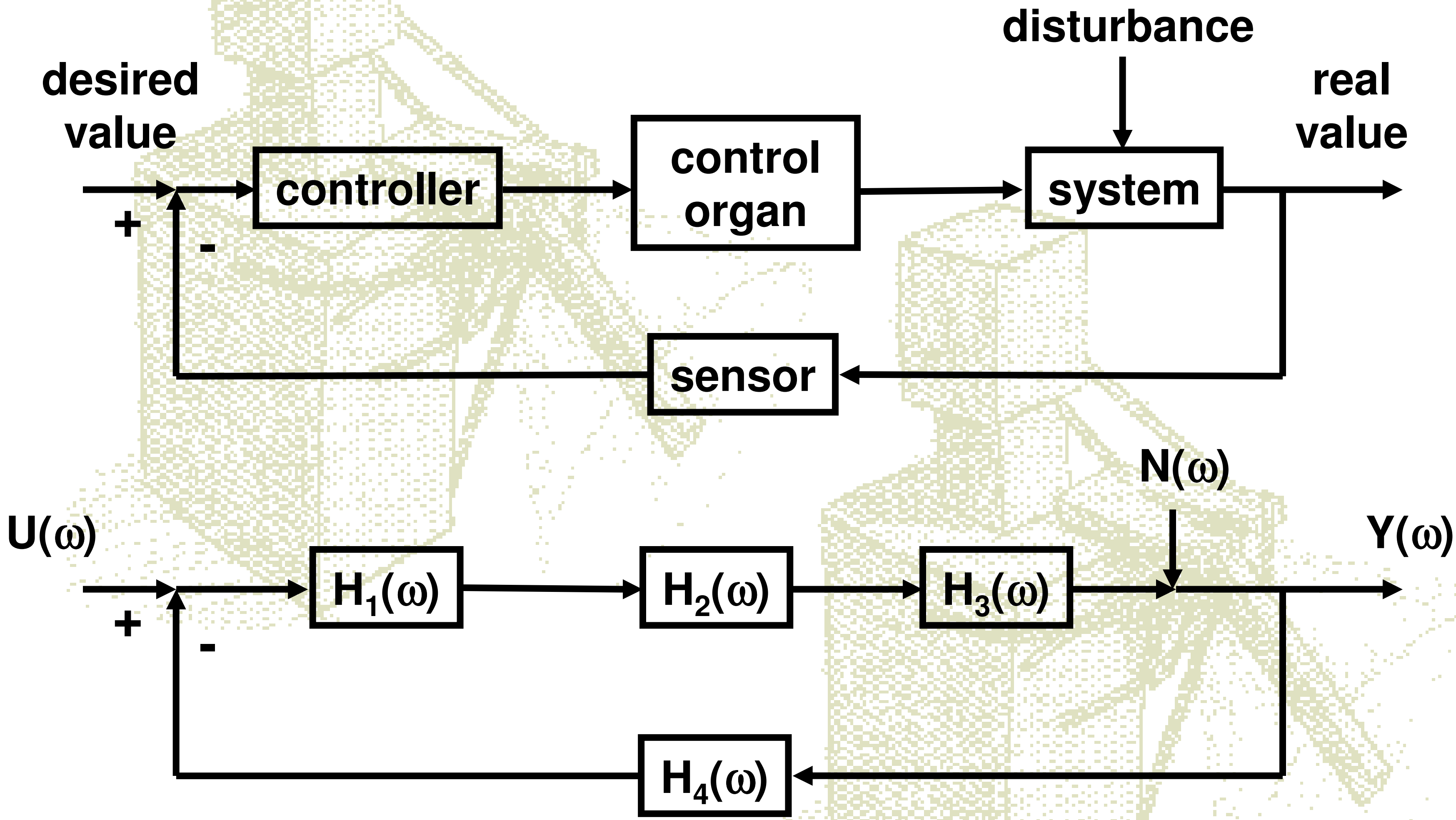


Closed-loop systeem

Why modeling a human controller?

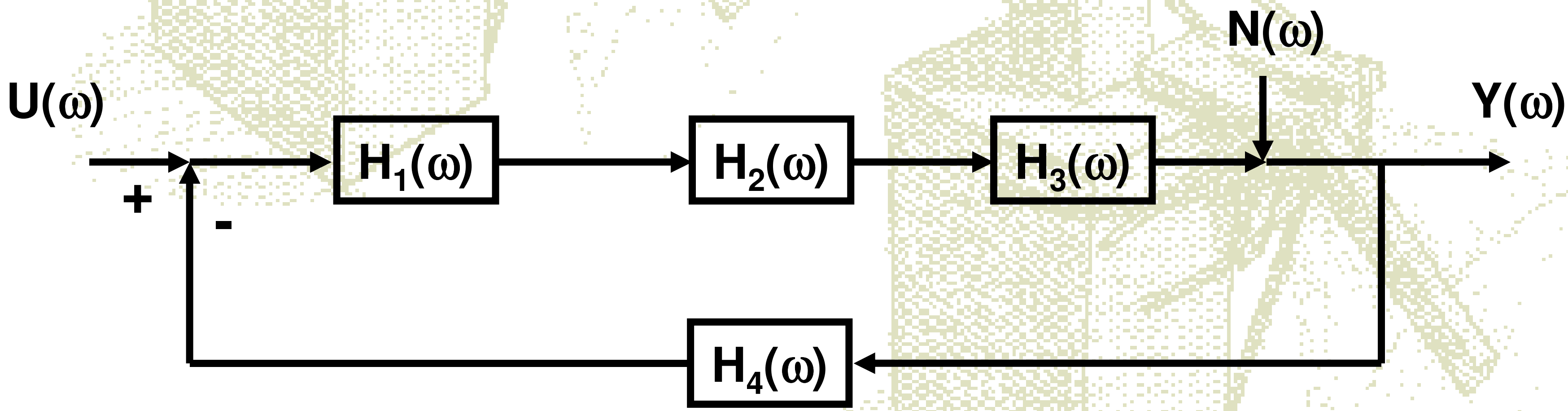


Block diagram of a control loop

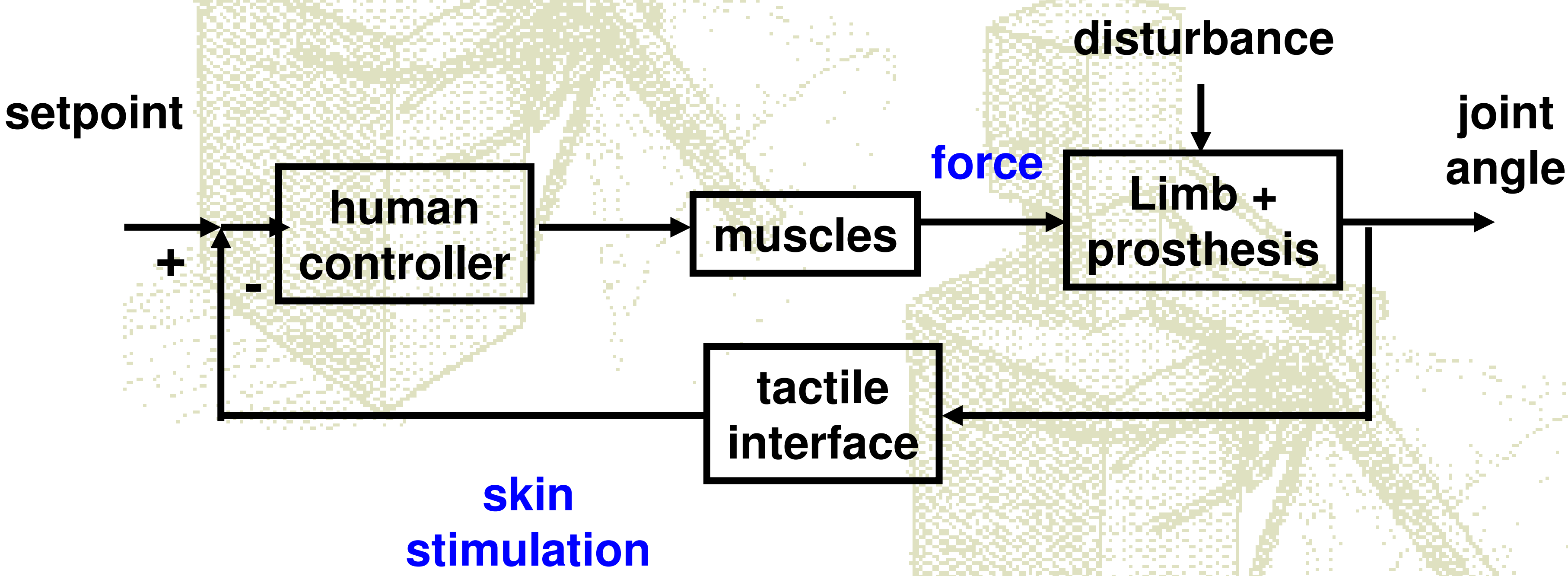


Block diagram of a control loop

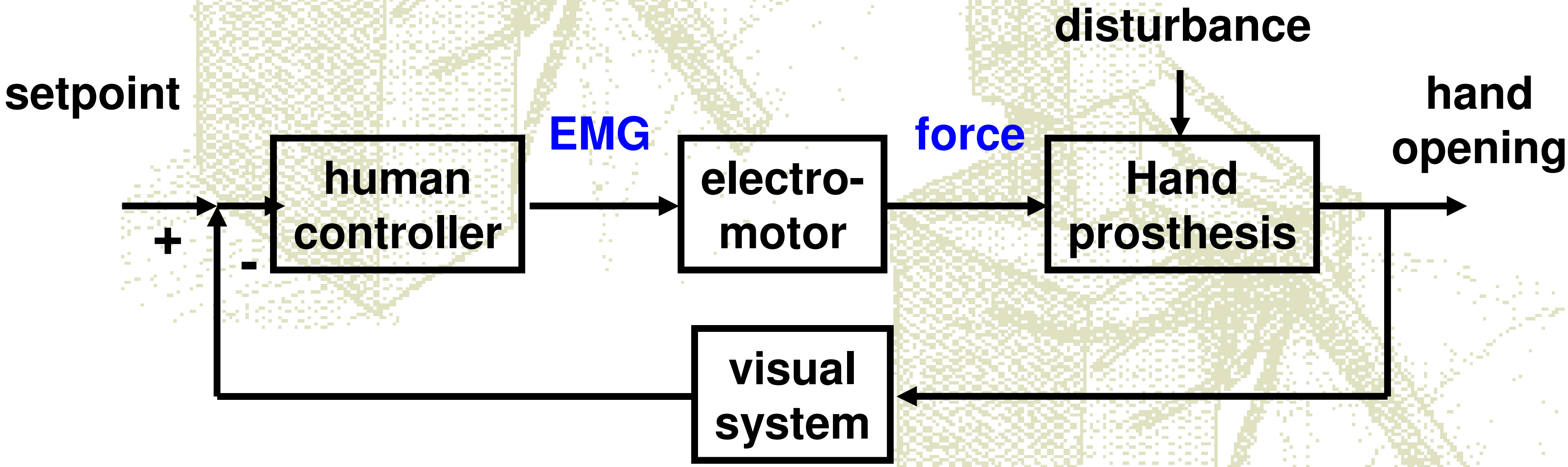
$$Y = \frac{H_1 H_2 H_3}{1 + H_1 H_2 H_3 H_4} U + \frac{1}{1 + H_1 H_2 H_3 H_4} N$$



Examples in biomechatronics



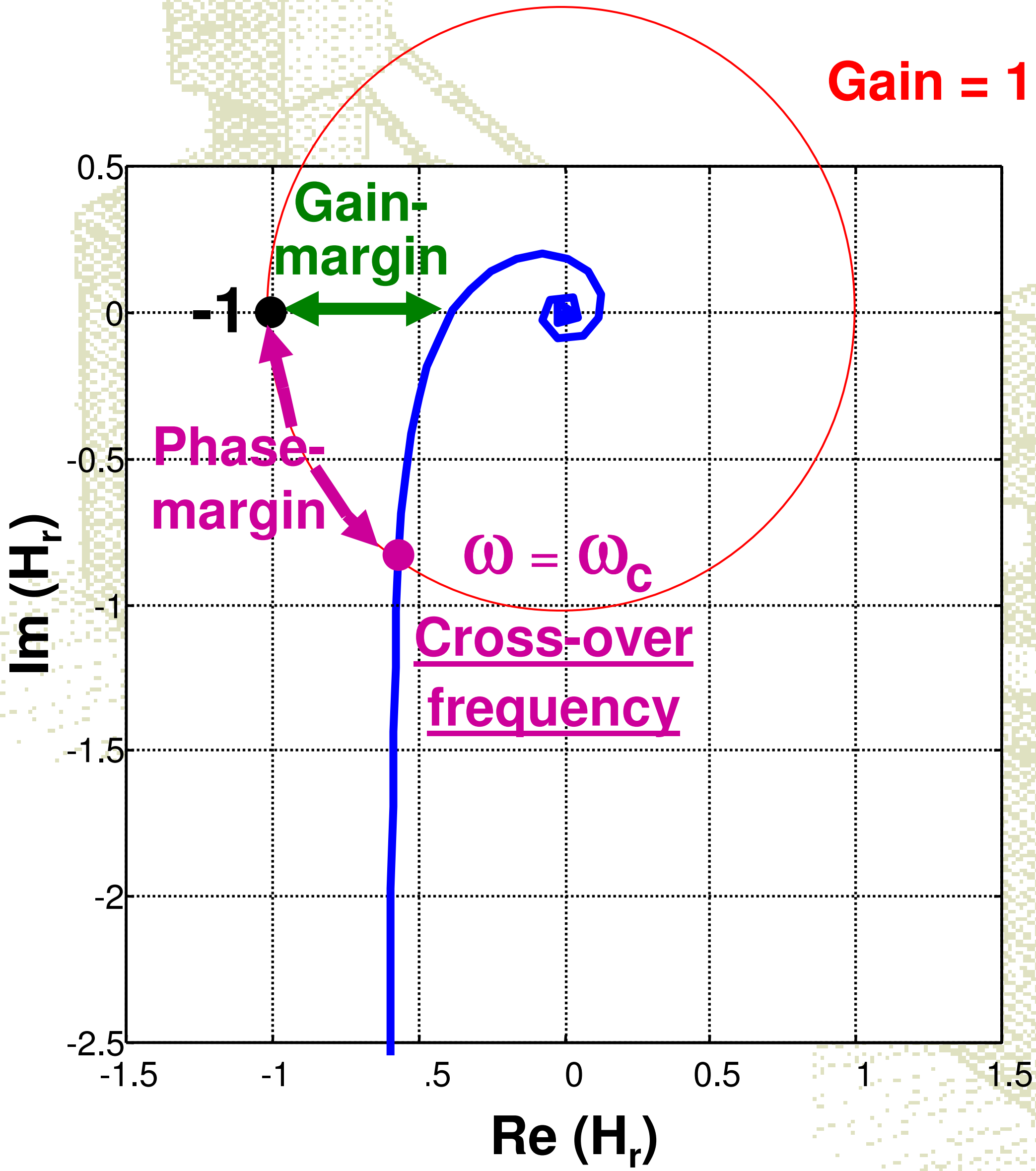
Examples in biomechatronics



Stability of a control loop

- Stability: Analyze loop gain function
  $H_r = H_1 . H_2 . H_3 . H_4$
- $H_r(\omega)$ is complex:
  mod $H_r(\omega)$ = gain, arg $H_r(\omega)$ = phase
- Phase-margin:
  If mod $H_r(\omega) = 1$ then arg $H_r(\omega) > -180^o$
- Gain-margin:
  If arg $H_r(\omega) = -180^o$ then mod $H_r(\omega) < 1$

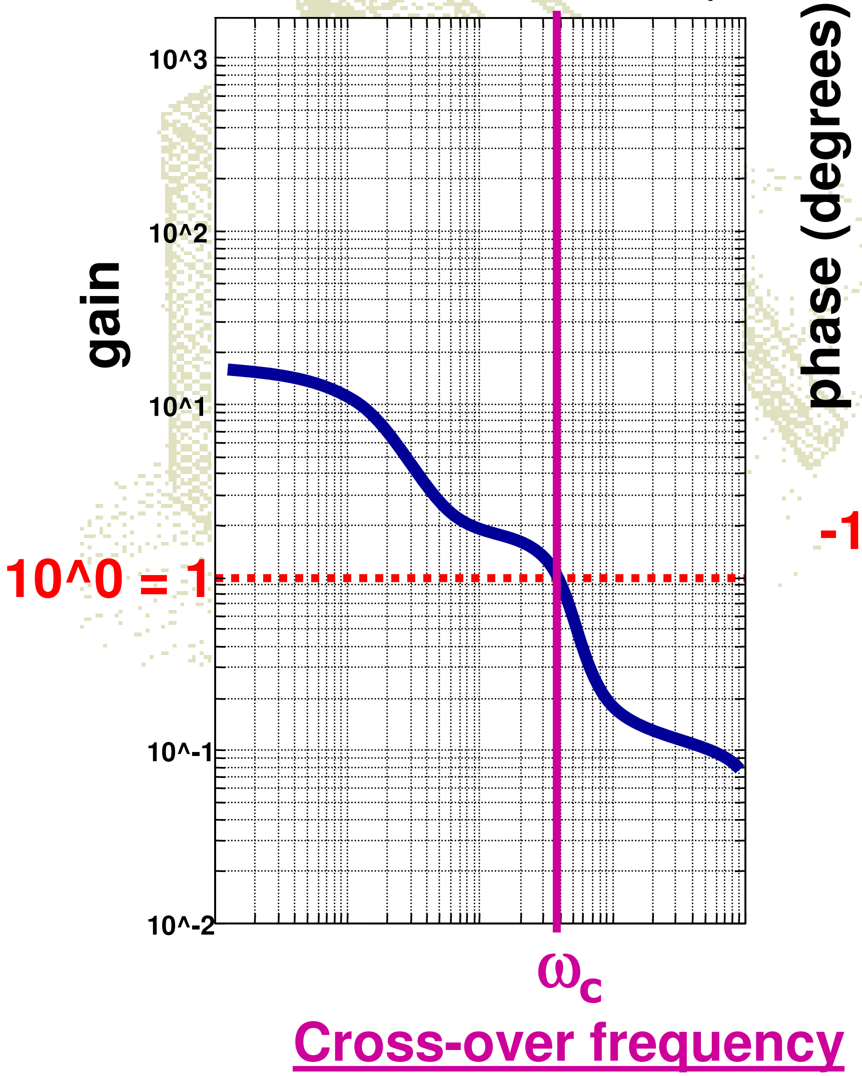
Phase-margin & gain-margin



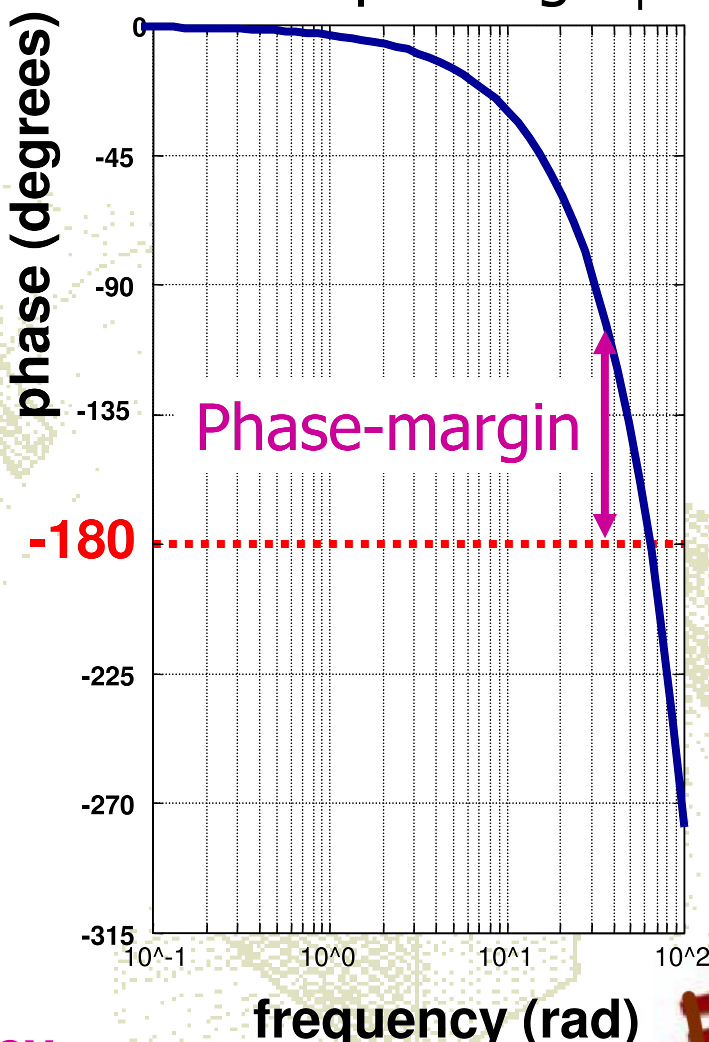
Nyquist
plot
H_r

Phase-margin

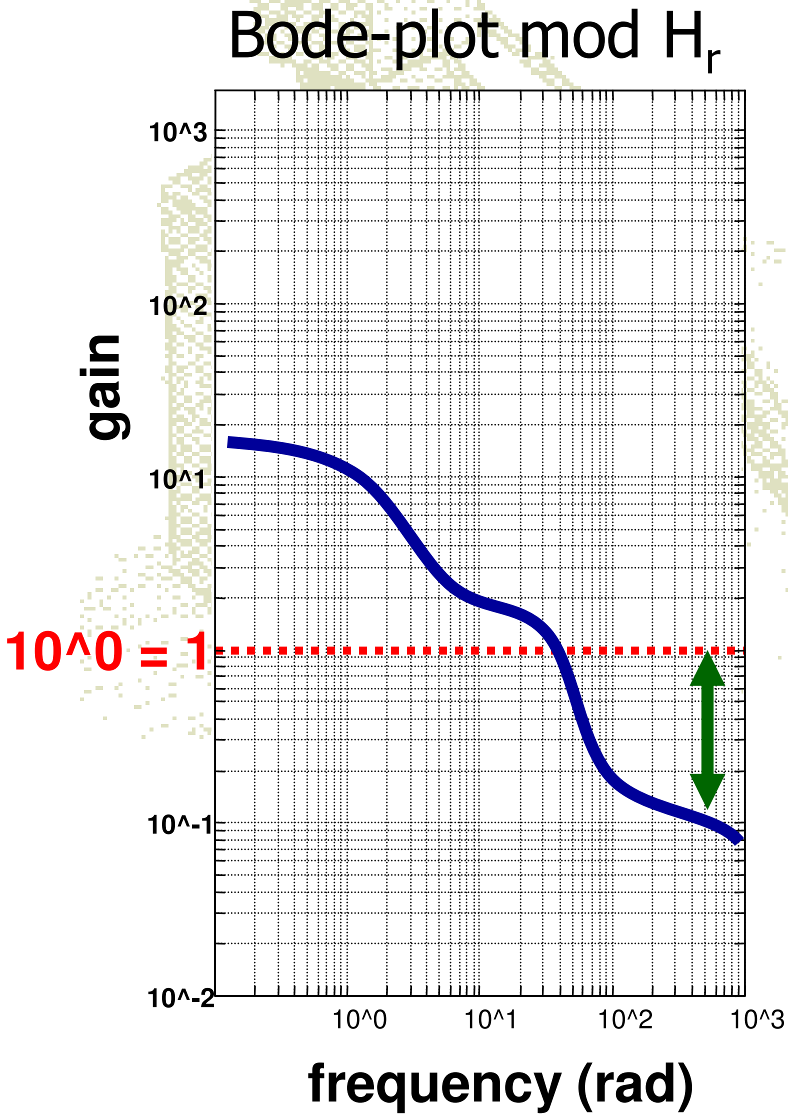
Bode-plot mod H_r

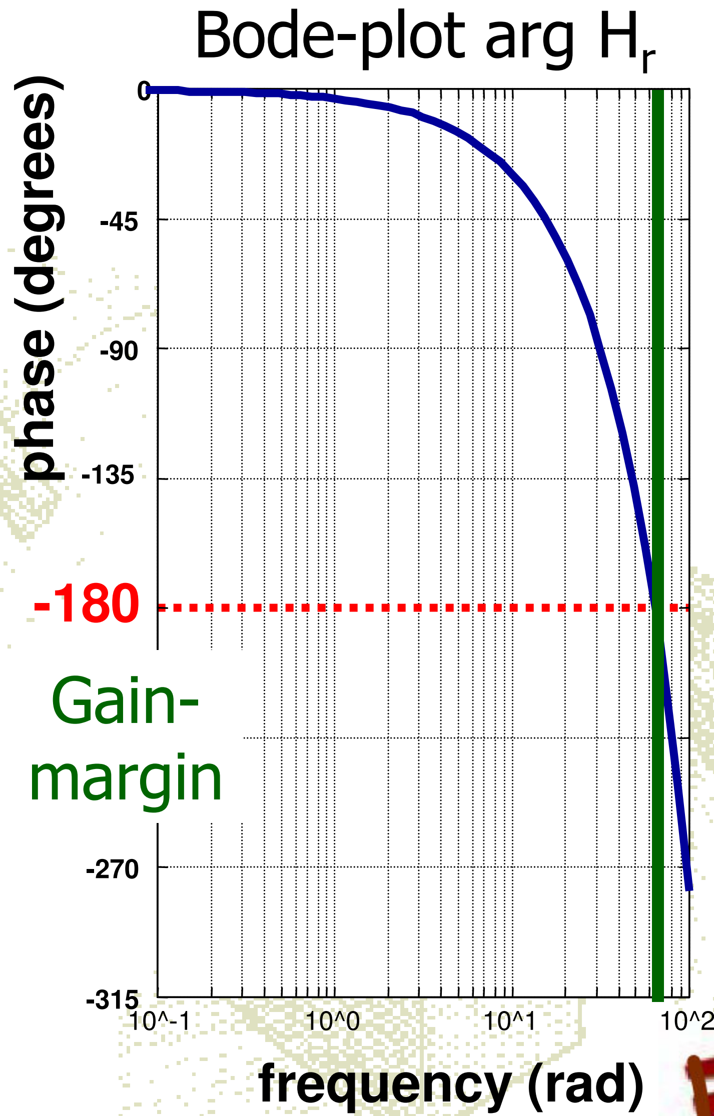


Bode-plot arg H_r



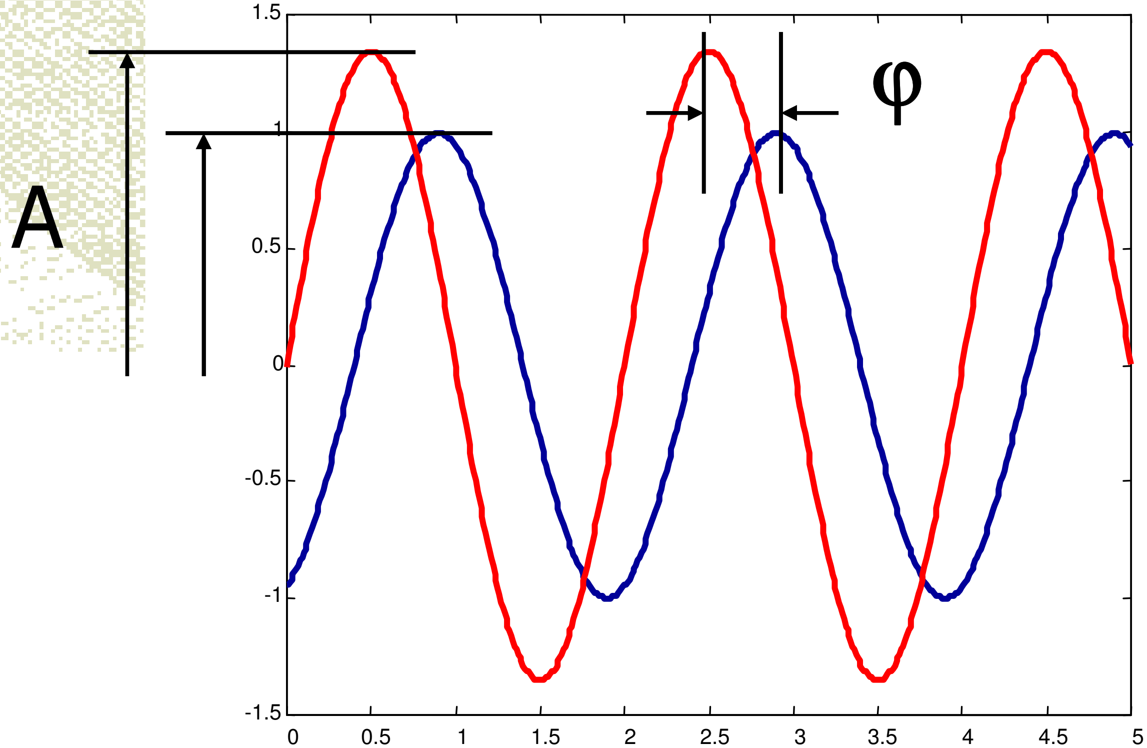
Gain-margin


Bode-plot mod H_r
gain
10^3
10^2
10^1
10^0 = 1
10^-1
10^-2
10^0
10^1
10^2
10^3
frequency (rad)

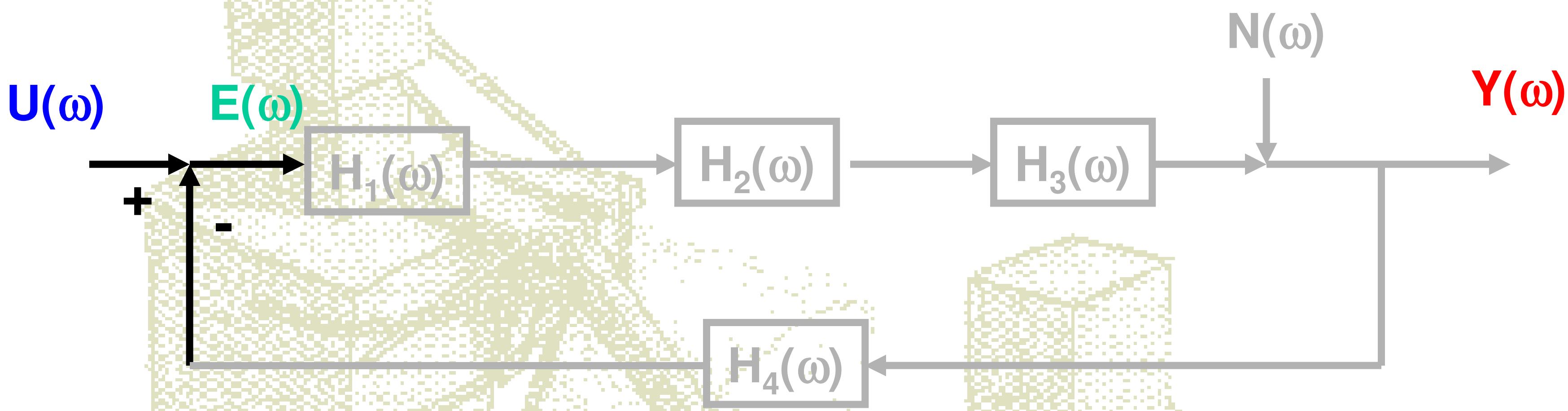

Bode-plot arg H_r
phase (degrees)
0
-45
-90
-135
-180
-270
-315
10^-1
10^0
10^1
10^2
frequency (rad)
Gain-
margin

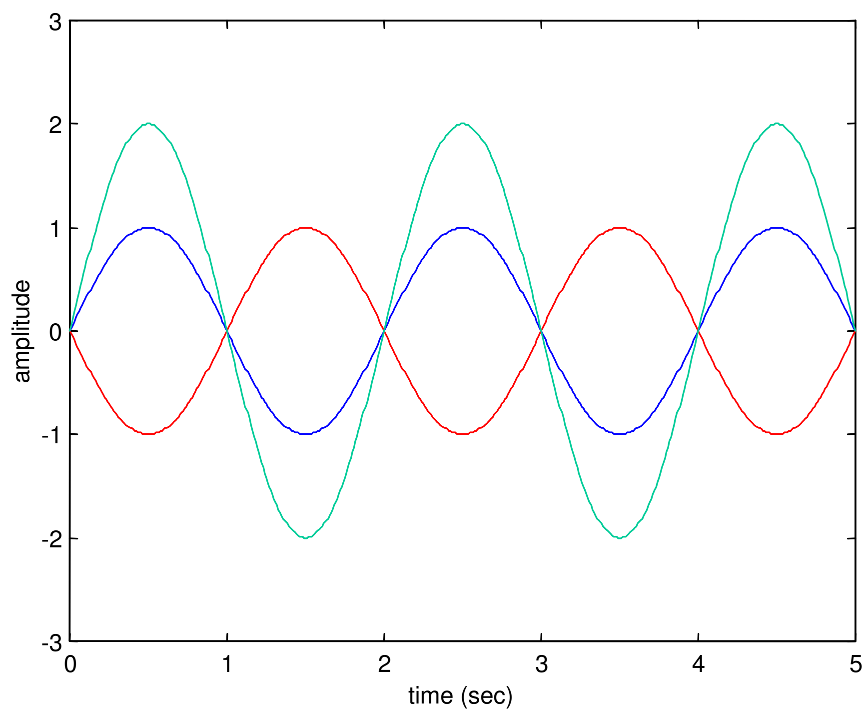
Input- & output signals

- Input: $u(t) = \sin(\omega t)$
- Output: $y(t) = A \sin(\omega t + \varphi)$
- Gain A en phase φ



Stability of a control loop

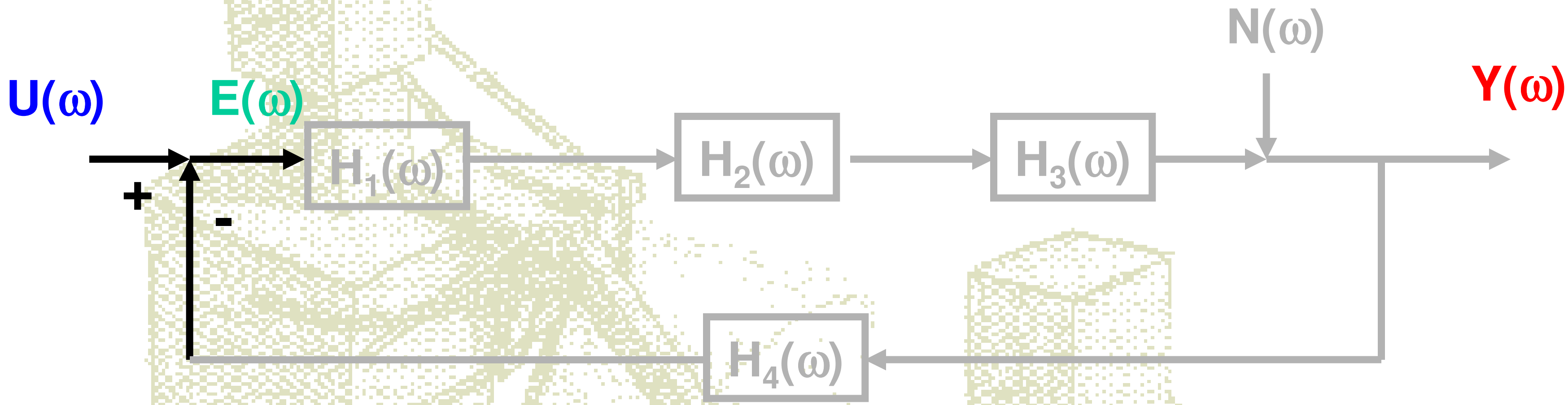


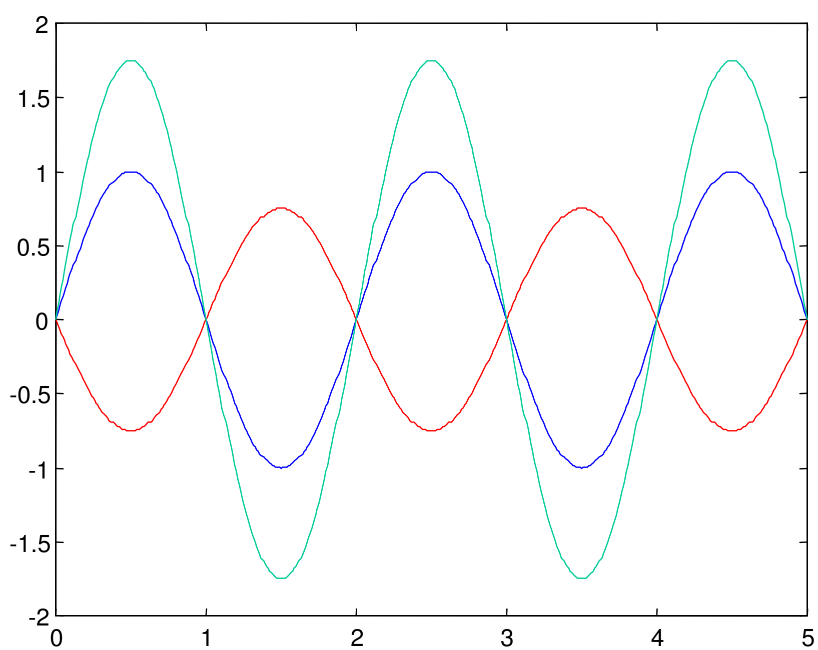


Phase-lag H_r = -180°

- Gain H_r < 1
  ⇒ stable
- Gain H_r = 1
  ⇒ on verge of instability
- Gain H_r > 1
  ⇒ unstable

Stability of a control loop

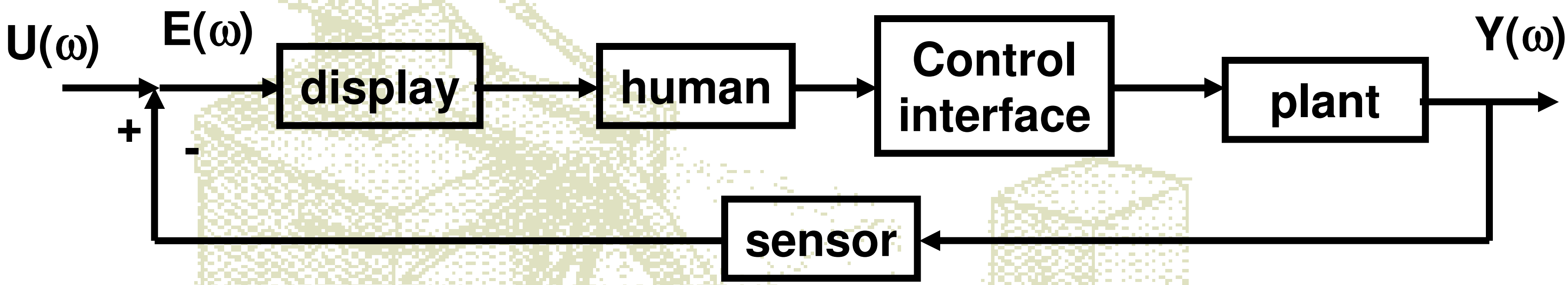


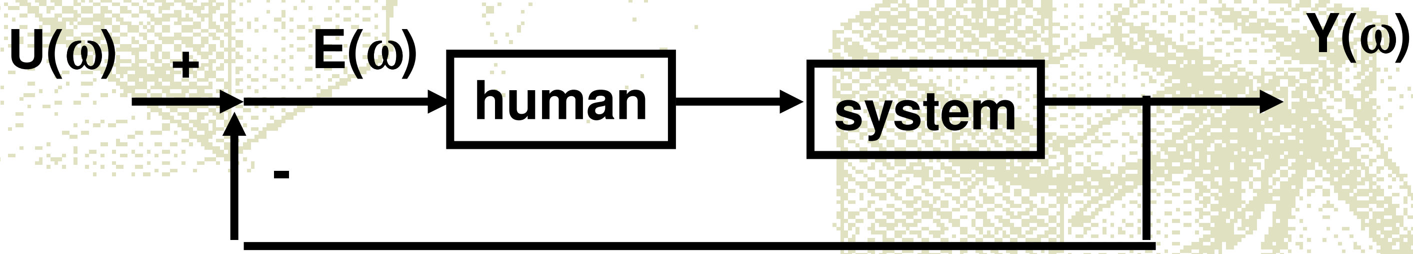


Phase shift = -180 degrees
gain = 0.75

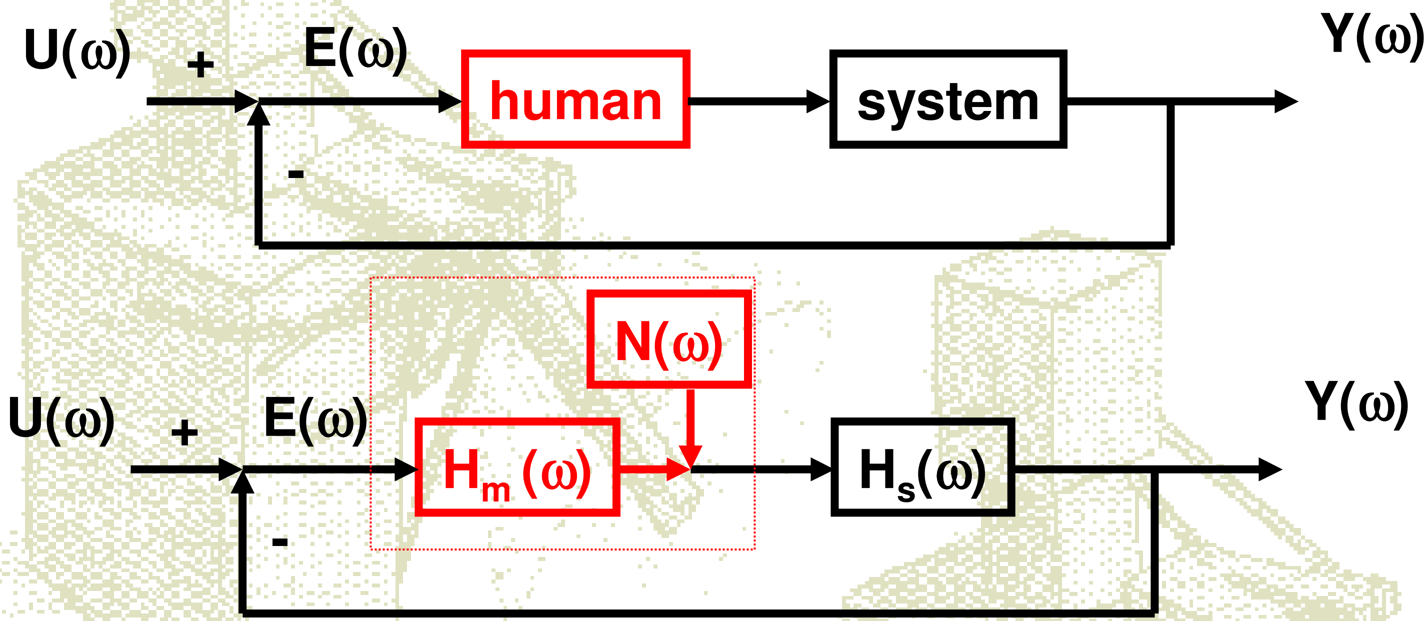
Positive gain margin

Model human controller





Model human controller 1

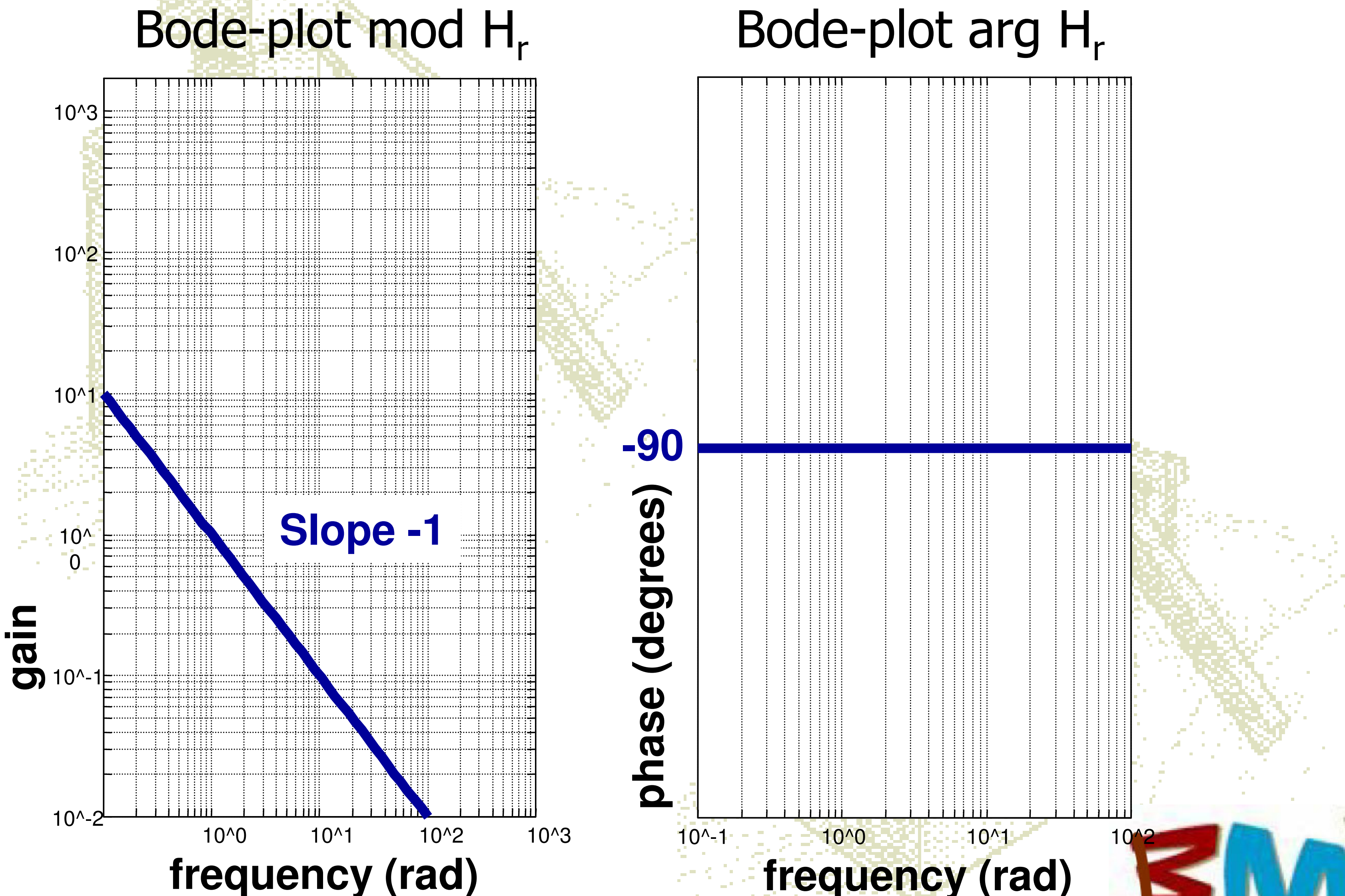


McRuer:

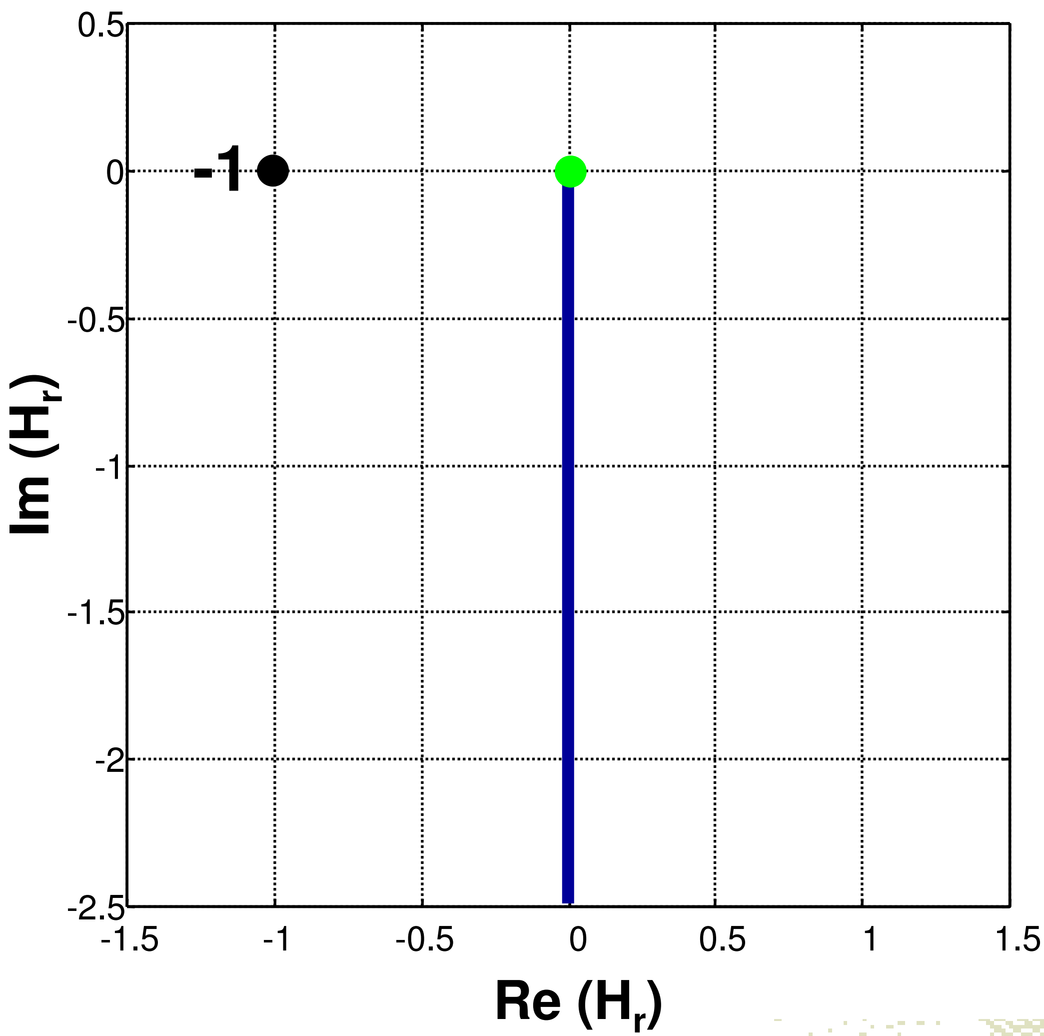
- Human shows different behaviour when controlling different systems
- Human tries to simulate servo-behaviour:

$$H_r(\omega) = H_m(\omega).H_s(\omega) = 1/j\omega$$

Optimal servo behaviour: $H_r(\omega) = 1/j\omega$



Optimal servo behaviour: $H_r(\omega) = 1/j\omega$

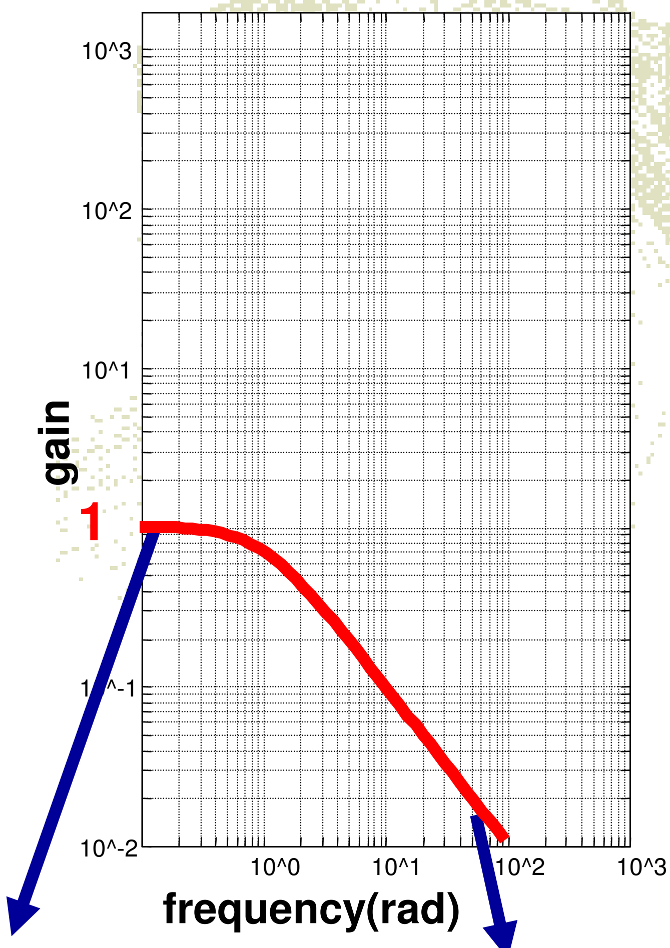


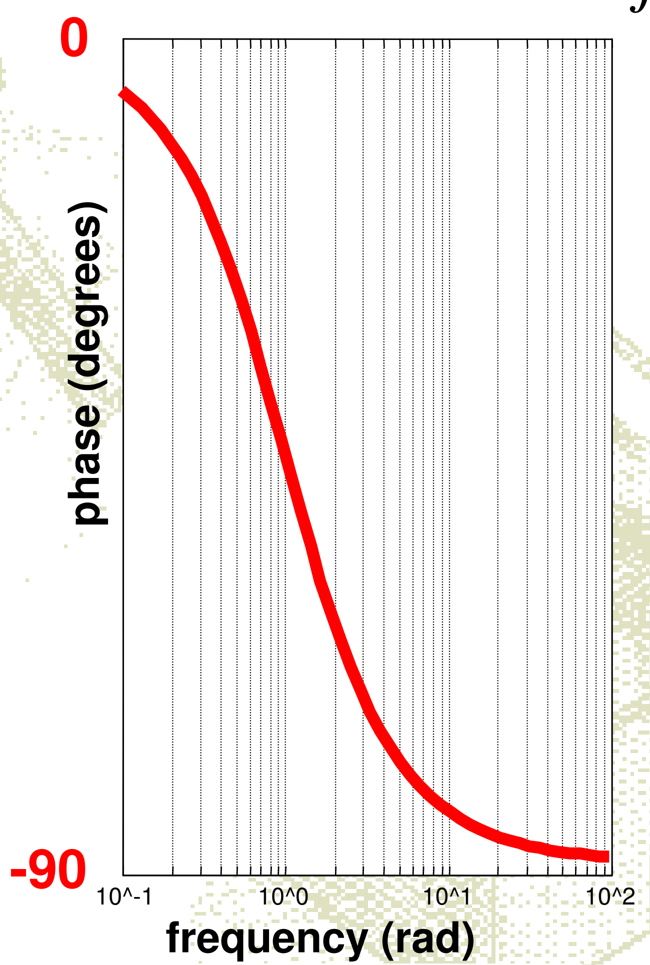
Nyquist plot H_r

Always stable

Transfer input-output

$$H_{uy}(\omega) = \frac{Y(\omega)}{U(\omega)} = \frac{\frac{1}{j\omega}}{1+\frac{1}{j\omega}} = \frac{1}{j\omega + 1}$$



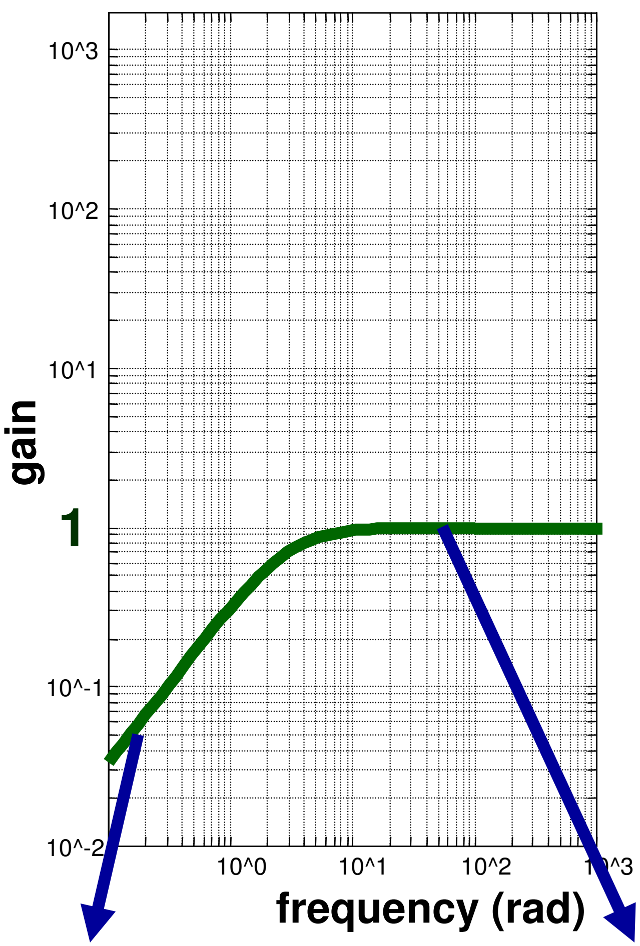


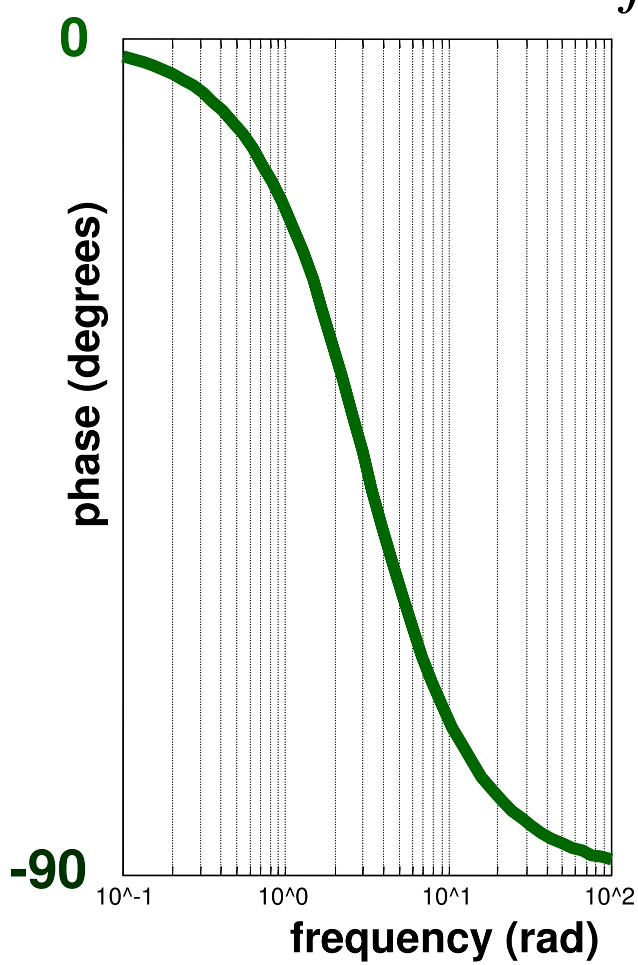
Low frequencies: tra **High frequencies: transfer almost 0**

Input is followed acc **Input is followed badly**

Transfer input-error

$$H_{ue}(\omega) = \frac{E(\omega)}{U(\omega)} = \frac{1}{1+\frac{1}{j\omega}} = \frac{j\omega}{j\omega+1}$$

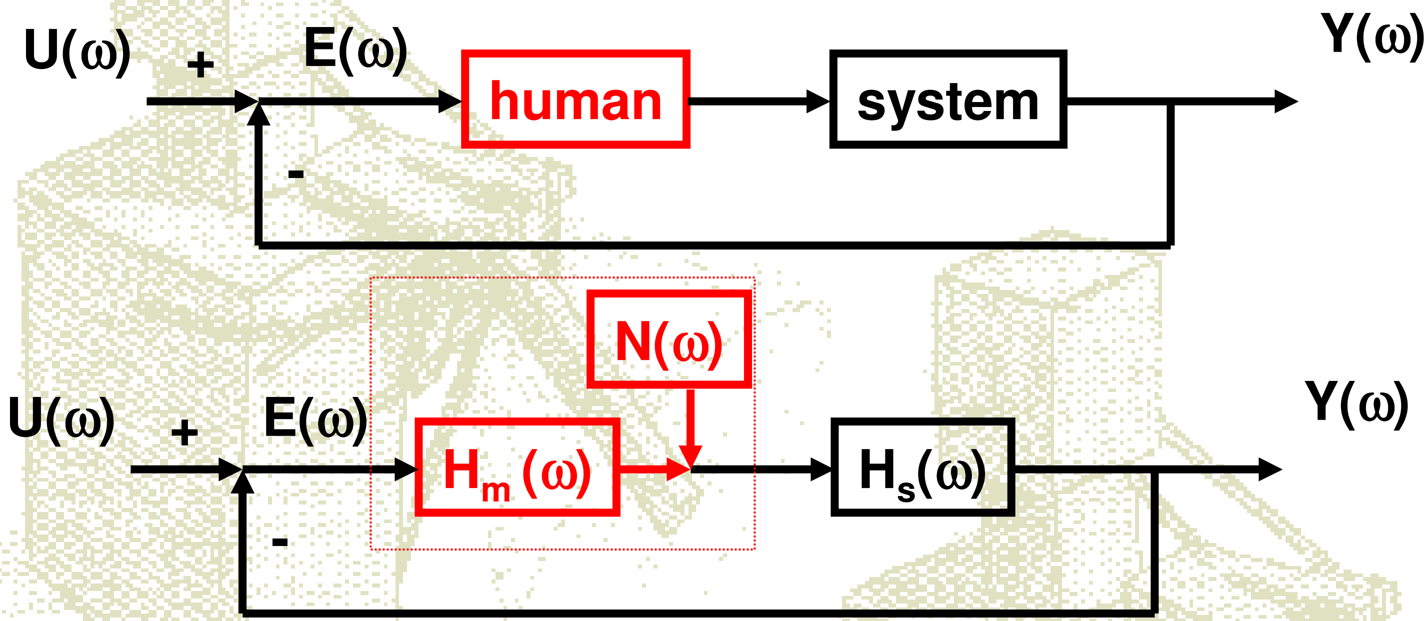




Low frequencies: error
Input is followed accur

High frequencies: error = input
Input is followed badly

Model human controller 2



McRuer:

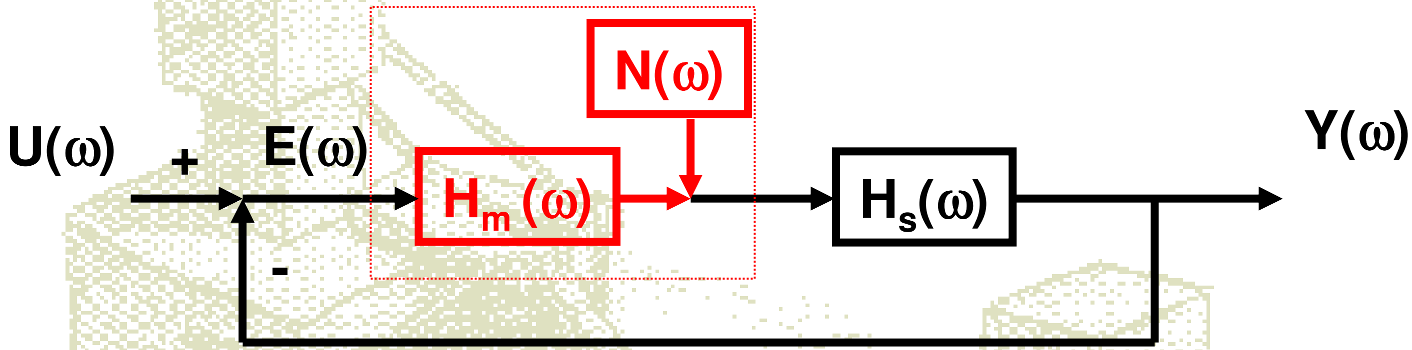
- Human tries to approximate optimal servo-behaviour: $H_r(\omega) = H_m(\omega).H_s(\omega) \approx 1/j\omega$

But is not perfect!

Limitations & adaptability human controller

- Limitations:
  - Human needs processing time
  - Inertia neuromuscular system arm with control organ
  - Human has limited accuracy
  - Human can estimate speed reasonably but cannot estimate acceleration
- Adaptability:
  - Human can adapt well to system dynamics
  - Human tries to develop optimal control strategy (effort versus result)

Cross-over model



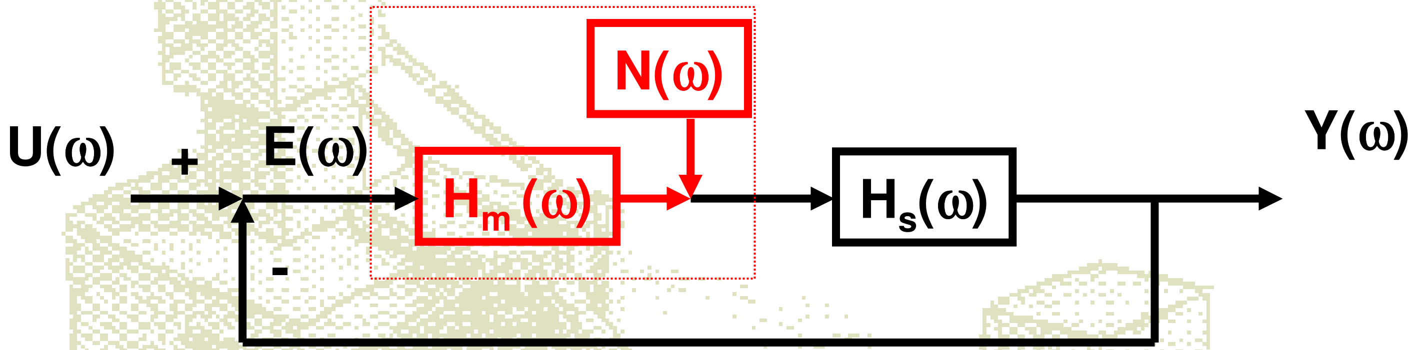
$$H_m(\omega) = K_m \frac{1 + j\omega\tau_1}{1 + j\omega\tau_2} \cdot \frac{1}{1 + j\omega\tau_3} . e^{-j\omega\tau_v}$$

adaptability　　limitations

For low frequencies (ω < 3 rad/s ≈ 0.5 Hz):

$$H_m(\omega) = K_m \frac{1 + j\omega\tau_1}{1 + j\omega\tau_2} . e^{-j\omega\tau_e}$$

Cross-over model

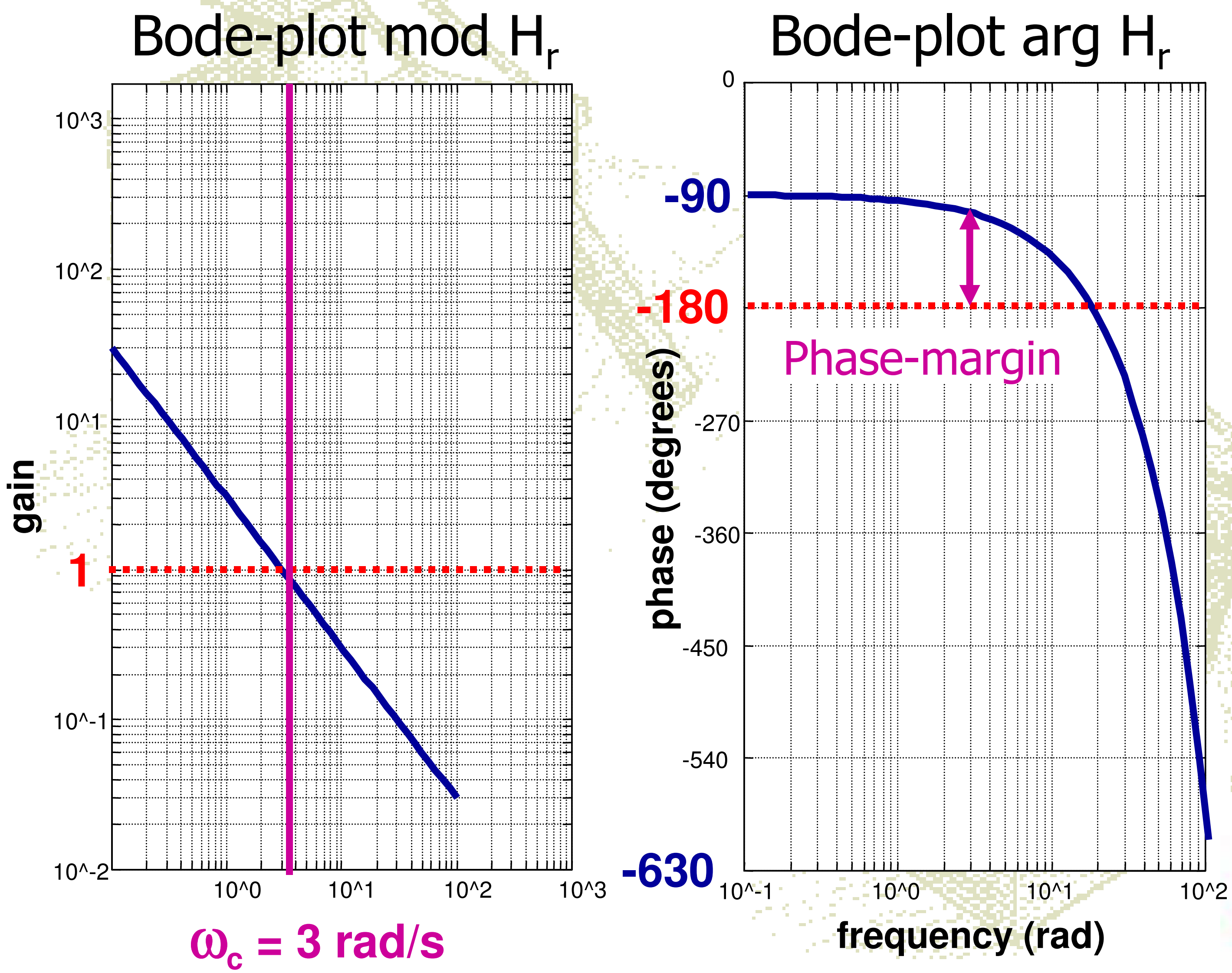


For frequencies around $\omega = \omega_c$ human tries to:

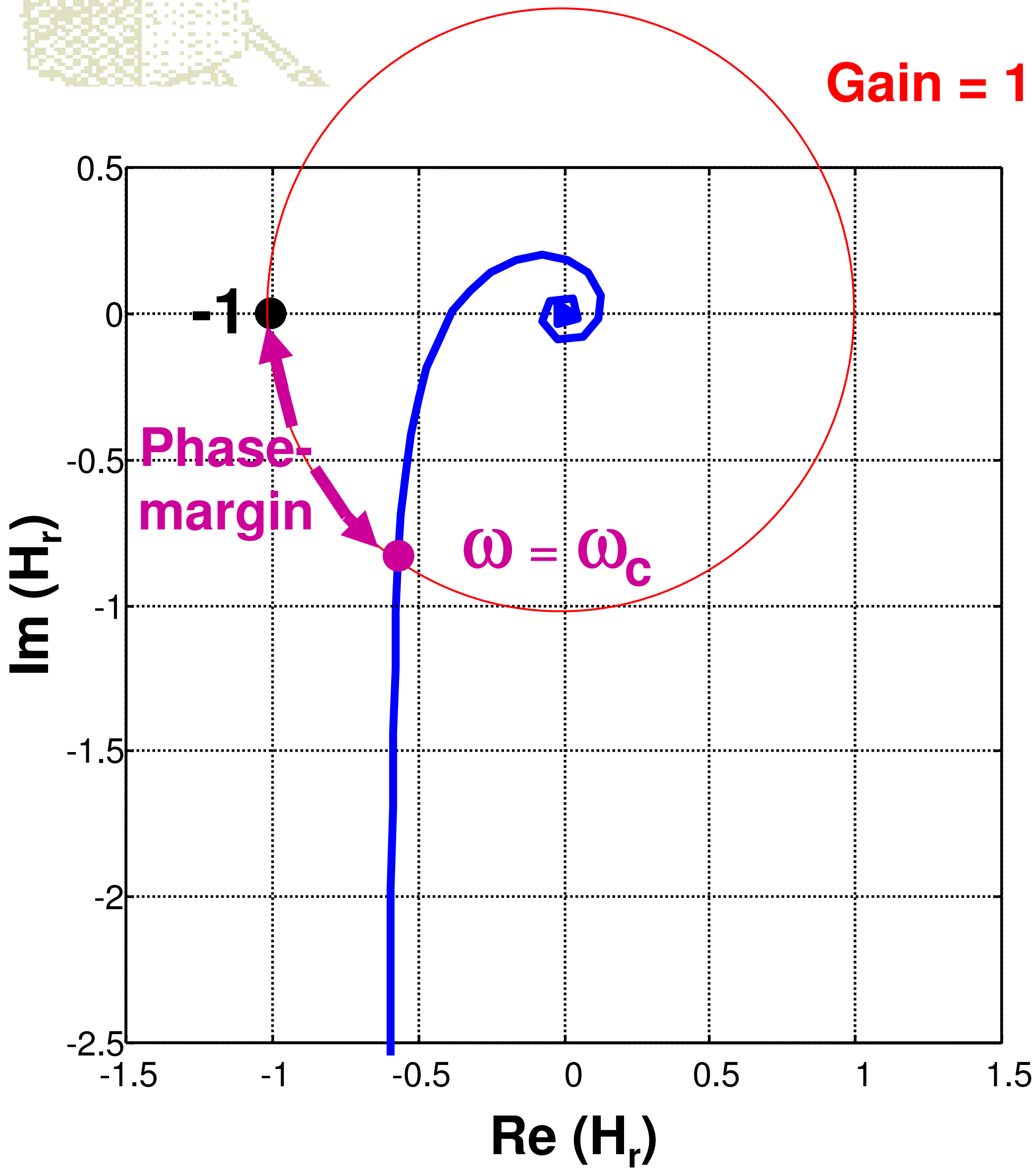
$$H_m(\omega).H_s(\omega) = \frac{\omega_c}{j\omega} e^{-j\omega\tau_e}$$

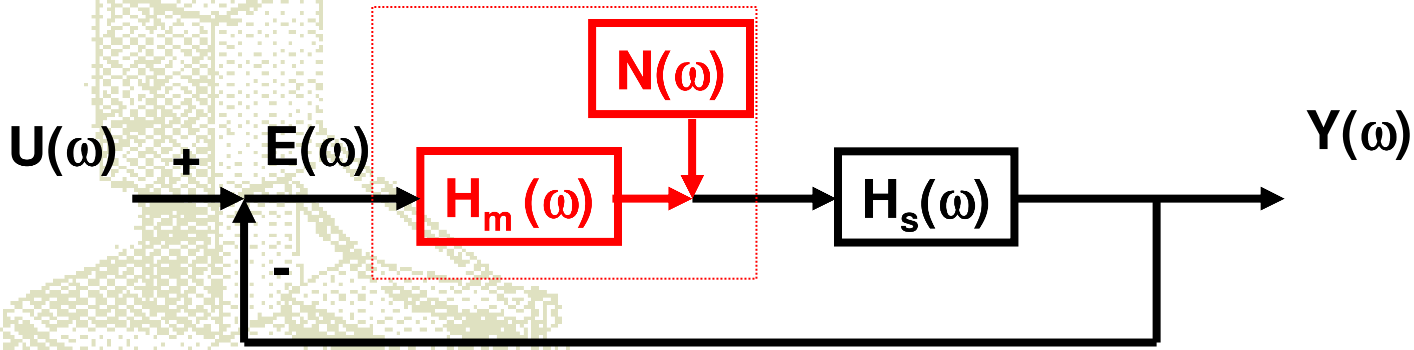
- Loop gain is then equal to 1
- Loop gain function approximates integrator
- ω_c roughly between 2 & 6 rad/s (≈ 0.3 & 1 Hz)
- τ_e equal to 200 till 300 ms

$$H_r(\omega) = H_m(\omega).H_s(\omega) = \omega_c \,/\, j(\omega) \;.\; e^{-j\omega\tau_e}$$



$$H_r(\omega) = H_m(\omega) . H_s(\omega) = \omega_c / j(\omega) . e^{-j\omega\tau_e}$$





Human tries to:

$$H_m(\omega).H_s(\omega) = \frac{\omega_c}{j\omega} e^{-j\omega\tau_e}$$

Human is able to:

$$H_m(\omega) = K_m \frac{1 + j\omega\tau_1}{1 + j\omega\tau_2} . e^{-j\omega\tau_e}$$

Examples of adaptation

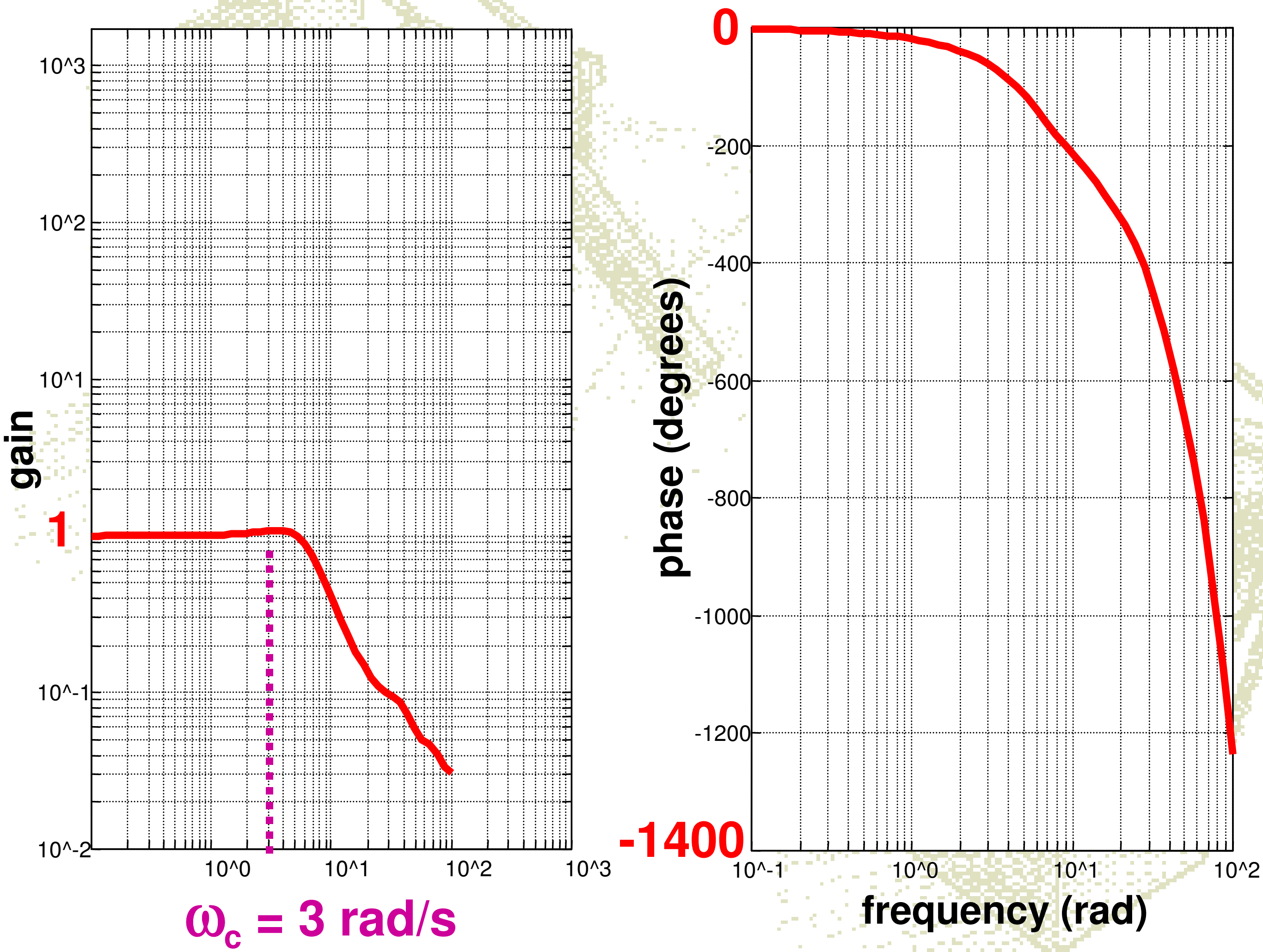
$$H_m(\omega).H_s(\omega) = \frac{\omega_c}{j\omega}.e^{-j\omega\tau} \rightarrow H_m(\omega) = \frac{\omega_c}{j\omega}.\frac{1}{H_s(\omega)}.e^{-j\omega\tau}$$

$$H_m(\omega) = K_m.\frac{1+j\omega\tau_1}{1+j\omega\tau_2}.e^{-j\omega\tau_e}$$

- $H_s(\omega) = K_s \rightarrow K_m.\frac{1+j\omega\tau_1}{1+j\omega\tau_2} = \frac{\omega_c}{j\omega}.\frac{1}{K_s} \rightarrow \tau_2 >> 1,\ \tau_1 = 0,\ \mathrm{K_m} = \frac{\omega_c.\tau_2}{K_s}$
- $H_s(\omega) = \frac{K_s}{j\omega} \rightarrow K_m.\frac{1+j\omega\tau_1}{1+j\omega\tau_2} = \frac{\omega_c}{j\omega}.\frac{j\omega}{K_s} \rightarrow \tau_2 = 0,\ \tau_1 = 0,\ \mathrm{K_m} = \frac{\omega_c}{K_s}$
- $H_s(\omega) = \frac{K_s}{(j\omega)^2} \rightarrow K_m.\frac{1+j\omega\tau_1}{1+j\omega\tau_2} = \frac{\omega_c}{j\omega}.\frac{(j\omega)^2}{K_s} \rightarrow \tau_2 = 0,\ \tau_1 >> 1,\ \mathrm{K_m} = \frac{\omega_c}{K_s.\tau_1}$
- $H_s(\omega) = \frac{K_s}{(j\omega)^3} \rightarrow K_m.\frac{1+j\omega\tau_1}{1+j\omega\tau_2} = \frac{\omega_c}{j\omega}.\frac{(j\omega)^3}{K_s} \rightarrow$ not controllable

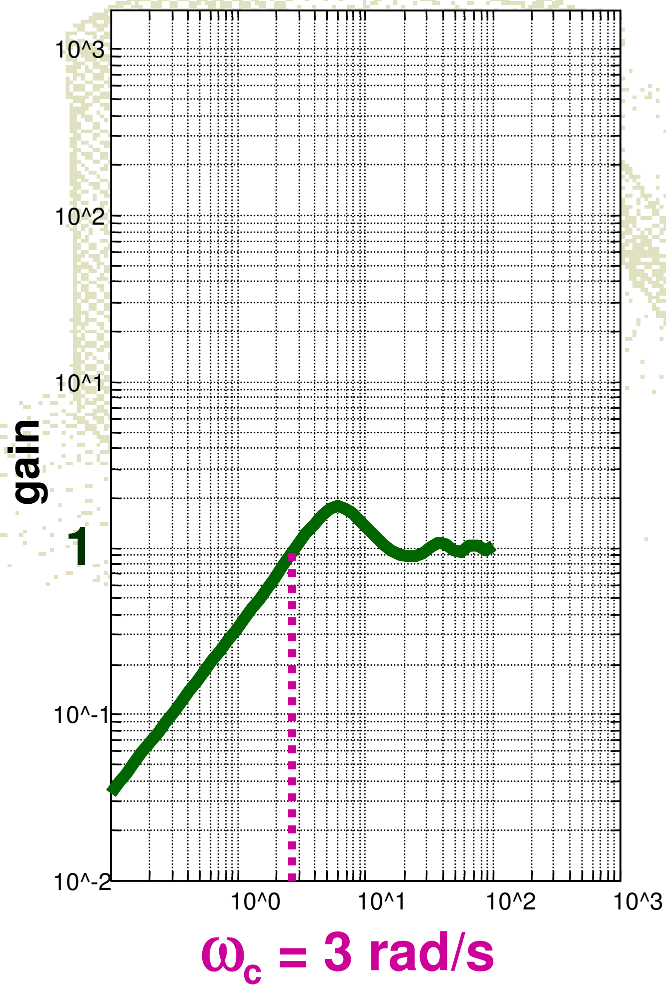
Transfer input-output

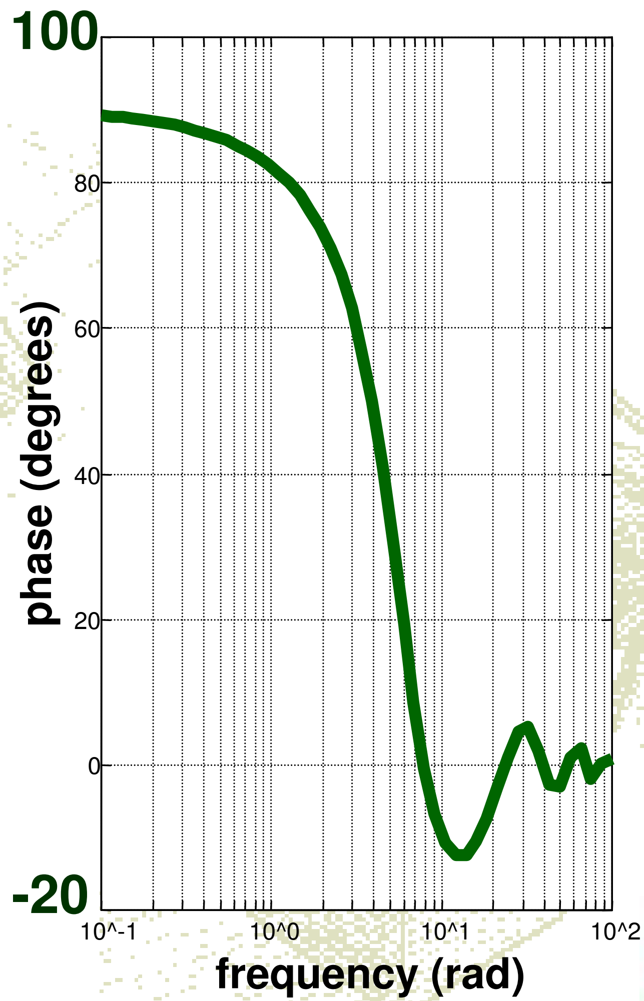
$$H_{uy}(\omega) = \frac{Y(\omega)}{U(\omega)} = \frac{\frac{\omega_c}{j\omega}\, e^{-j\omega\tau_e}}{1 + \frac{\omega_c}{j\omega}\, e^{-j\omega\tau_e}} = \frac{\omega_c\, e^{-j\omega\tau_e}}{j\omega + \omega_c\, e^{-j\omega\tau_e}}$$



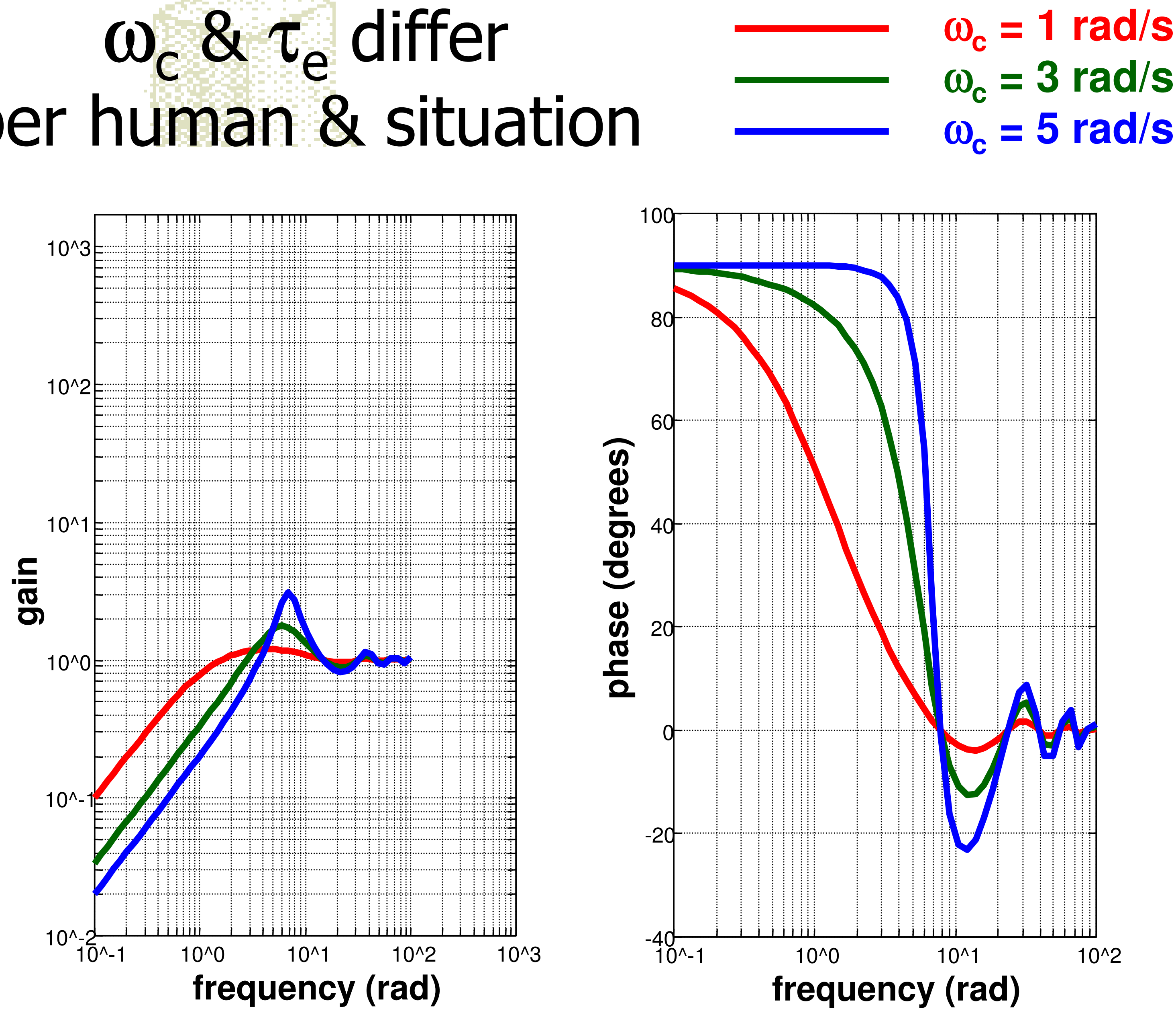
Transfer input-error

$$H_{ue}(\omega) = \frac{E(\omega)}{U(\omega)} = \frac{1}{1 + \frac{\omega_c}{j\omega}\, e^{-j\omega\tau_e}} = \frac{j\omega}{j\omega + \omega_c\, e^{-j\omega\tau_e}}$$

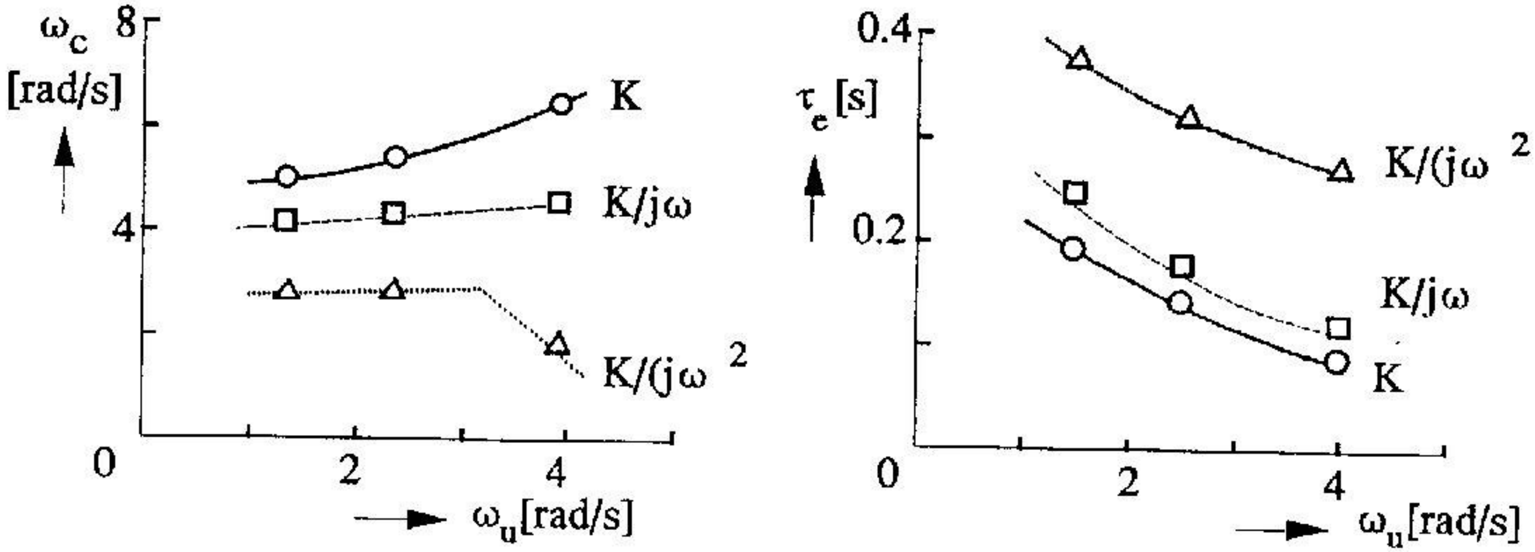




ω_c & τ_e differ per human & situation



Effect bandwidth input & order system on ω_c & τ_e



Higher bandwidth
$\Rightarrow$ More effort $\Rightarrow$ higher ω_c and lower τ_e

Higher order system
$\Rightarrow$ More difficult $\Rightarrow$ lower ω_c and higher τ_e

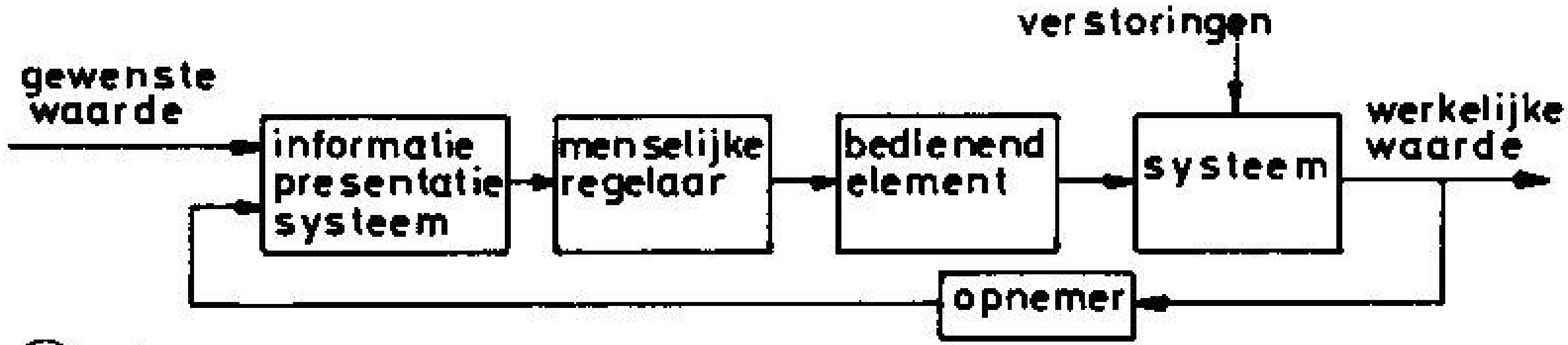
Demonstration

Conclusions

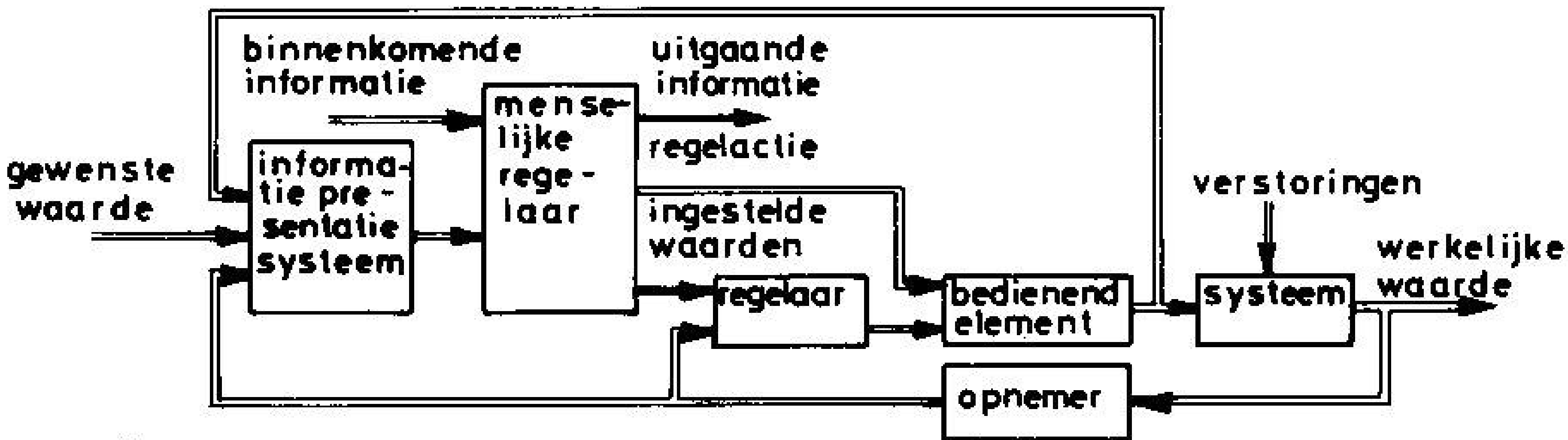
- Humans can adapt to the system to be controlled:
  - K_m, τ_1 and τ_2: Adaptation parameters
  - ω_c: Determines bandwidth of controlled system
- Still some limitations apply:
  - Only zero, first order and second order systems can be controlled!!
  - Human controller properties known for systems with visual and vestibulary feedback, not for tactile feedback, etc.
- Design of biomechatronic systems:
  - Be aware that humans must be able to control the system

Supervisory control situations

- System with automated control loops
  - FES system with artificial sensors, controller and stimulator
  - Above-knee prosthesis with automatic knee locking
- Humans should be in control of <u>whole</u> system
  - Monitoring:
    - Feedback of result
    - Feedback of performance controller
  - Actions:
    - Setpoint generation for controller
    - Overruling of controller

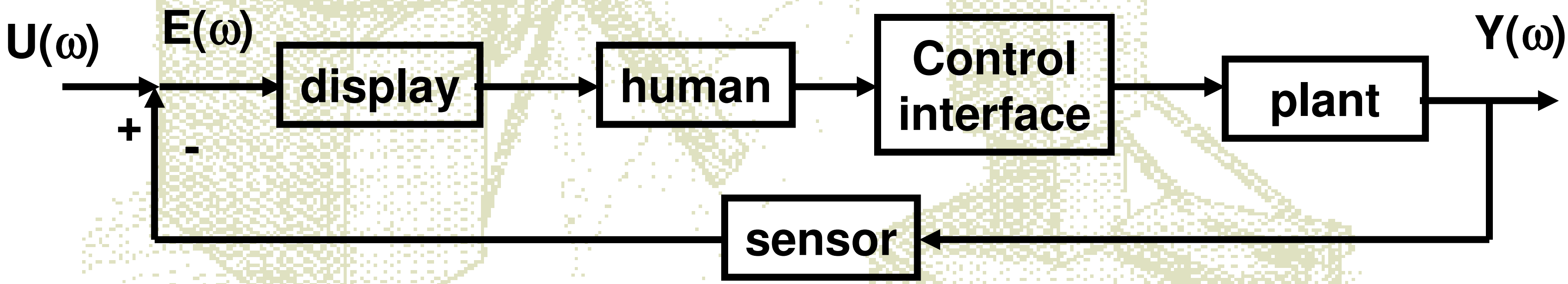


(a) handregeling

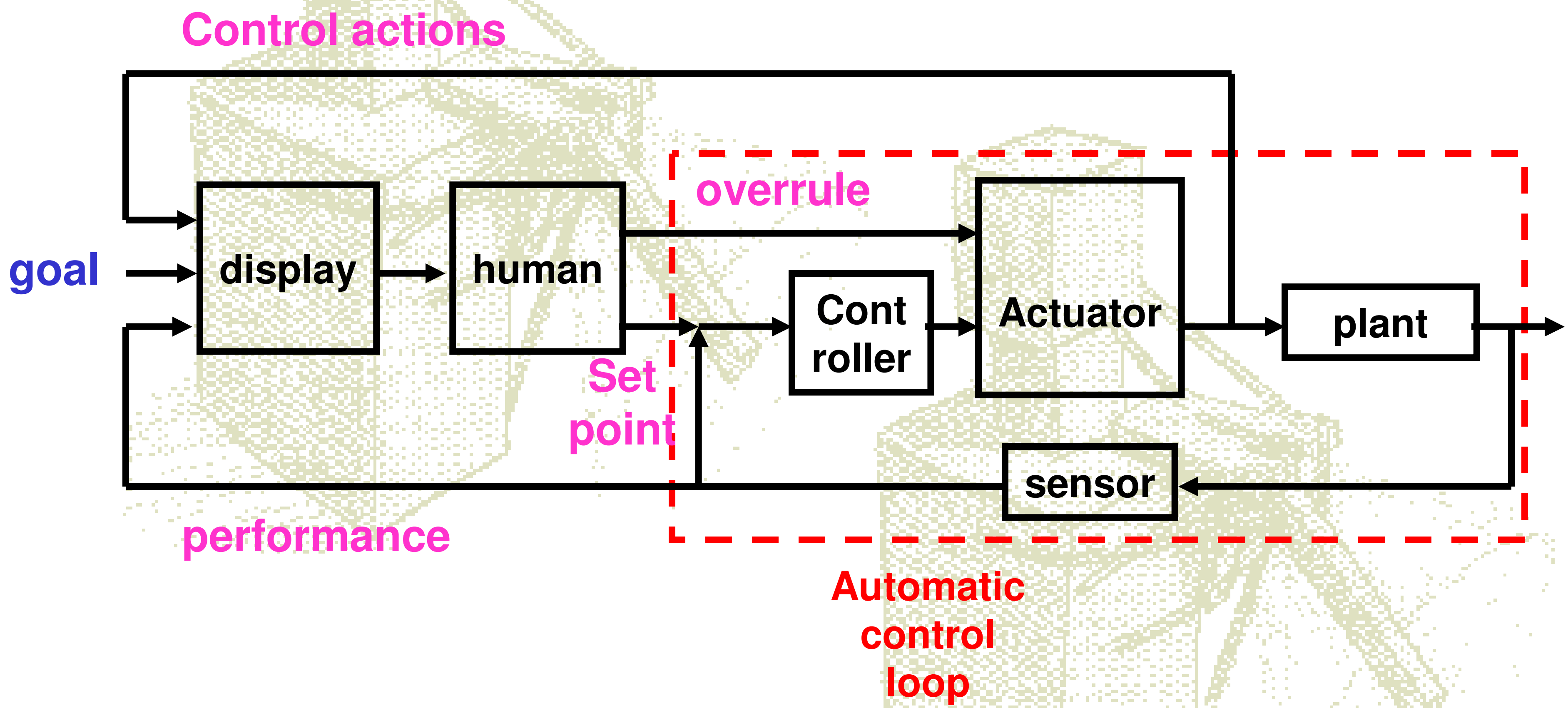


(b) supervisieregeling

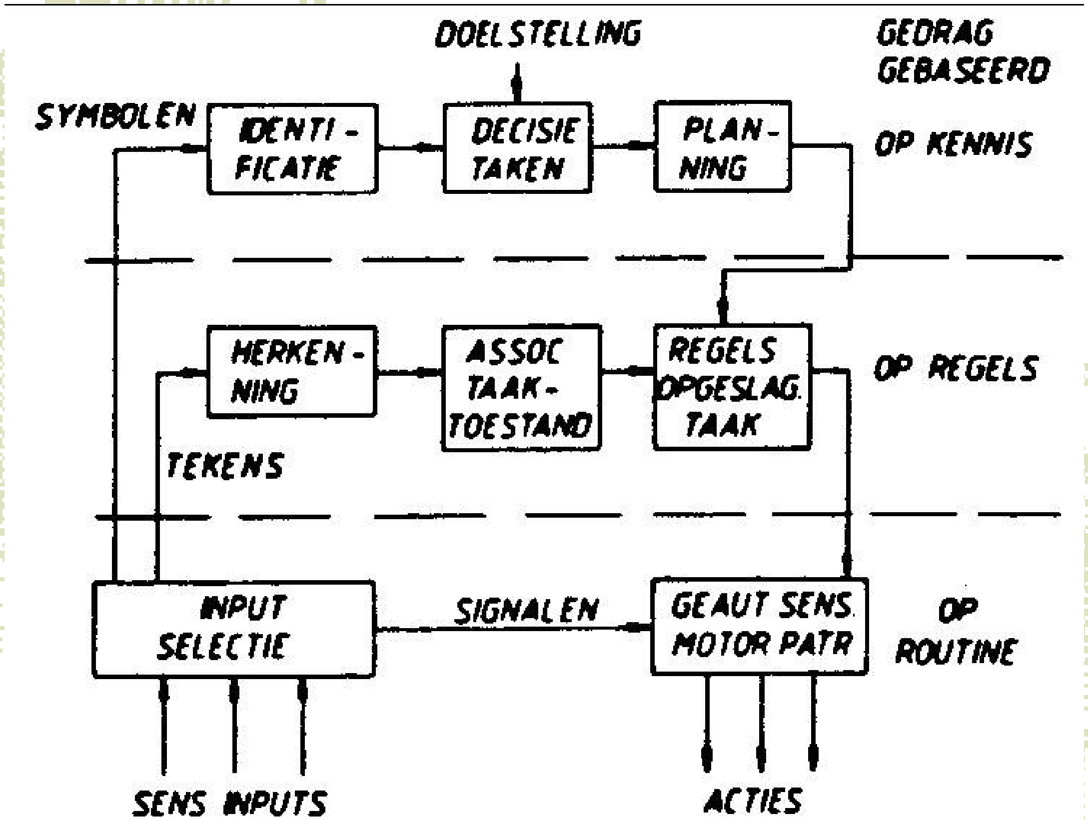
Manual control



Supervisory control



Model Rasmussen



Knowledge-based

Rule-based

Skill-based

Model Rasmussen

- Knowledge-based behaviour:
  - Difficult tasks
  - performance based on reasoning
  - Requires much attention: High mental loading
  - Examples: control room, FES walking?
- Rule-based behaviour:
  - Tasks with intermediate difficulty
  - Performance based on applying standard rules
  - Examples: Control of helping robots
- Skill-based behaviour:
  - Easy tasks, incorporated in normal behaviour
  - Performance based on well-trained skills
  - Requires little mental effort
  - Examples: Body-powered prosthesis, Bladder control, Cochlear implants

Model Rasmussen

- <u>Decrease mental load</u>: From knowledge-based behaviour to skill-based behaviour
- Humans generate <u>internal</u> model of system
- ‘<u>Ecological’</u> interface displays system output resembling internal model
- ‘Ecological’ interfaces allow for an <u>intuitive</u> control