ECE 1675/2570: Robotic Control (Spring 2022)

Module I: Robotics and Controls Primer

Lectures 3 and 4: Robot Control Architectures; Time Responses of Dynamical Systems; PID Control

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Outline

- Homework 2 (due Feb. 9)
- Robot control architectures
  - Deliberative control
  - Reactive control
  - "Hybrid" control
  - Behavior-based control
- Time responses of dynamical systems
  - First-order systems
  - Second-order systems
  - Time response specifications of design
  - Frequency responses
- PID control

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Robot control architectures

- Why does a robot need a control architecture?
  - How would you put multiple feedback controllers together?
  - What if you need more than feedback control?
  - How would you decide what is needed, which part of the control system to use in a given situation and for how long, and what priority to assign to it?

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Might have multiple subtasks

Robot control architectures

- Why does a robot need a control architecture?
- What is control architecture?
  - A robot *control architecture* provides guiding principles and constraints for organizing a robot's control system (its brain)
  - Robot control can take place in hardware and in software, but the more complex the controller, the more likely it is to be implemented in software

Robot control architectures

- Why does a robot need a control architecture?
- What is control architecture?
  - A robot *control architecture* provides guiding principles and constraints for organizing a robot's control system (its brain)
  - Robot control can take place in hardware and in software, but the more complex the controller, the more likely it is to be implemented in software
  - Robot controllers can be implemented in various languages: *C/C++*, *Python*, *C#*, *Matlab*, *Java*, *Assembly*, *Hardware Description Languages* (HDLs), *LISP*, *industrial robot languages*, *BASIC*, *Pascal*, etc.

Note: There is *no "best" language*; as robotics grows and matures, there are more and more specialized programming languages and tools.

Robot control architectures

- Why does a robot need a control architecture?
- What is control architecture?
- Types of control architectures
  - Deliberative control
  - Reactive control
  - "Hybrid" control
  - Behavior-based control

Deliberative control

- Definition
  - *Deliberation* refers to thinking hard ("thoughtfulness in decision and action")
    - Deliberative control grew out of early AI (e.g. Shakey)
    - Deliberative control looks into the future, and it works on a *long time-scale*

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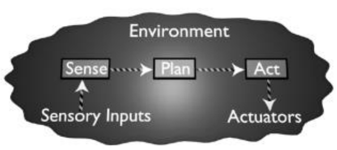
Deliberative control

- Definition
  - *Deliberation* refers to thinking hard
  - Deliberative control involves three steps: SPA
    - *Sensing (S)*
    - *Planning (P)*, the process of determining possible outcomes of actions and searching for the best sequence of actions to achieve a goal
    - *Acting (A)*



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Deliberative control

- Definition
- Drawbacks
  - *Time-scale:* it can be very slow (due to large state space)
  - *Space:* it can be very memory-intensive (state space representation requires significant storage)
  - *Information:* sometimes information is outdated
  - *Execution:* executing a plan can be difficult

Note: Since the 1980s, purely deliberative architectures are no longer used for the majority of physical robots

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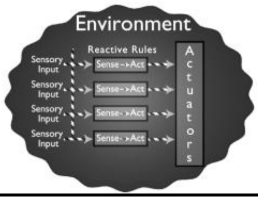
Reactive control

- Definition
  - *Reactive control* is control that tightly couples sensing and acting
    - It does not plan ahead (does not use any internal representations of the environment)
    - It is very fast
    - It is the most common control method in robotics



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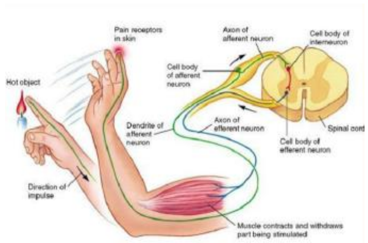
Reactive control

- Definition
  - *Reactive control* is control that tightly couples sensing and acting
  - Reactive control is similar to neural reflexes

spinal cord



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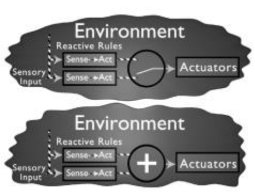
Reactive control

- Definition
- Action selection
  - *Action selection* is the process of deciding among multiple possible actions or behaviors
  - Two basic types
    - *Arbitration:* select one candidate
    - *Fusion:* combine multiple candidate actions into a single action



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Reactive control

- Definition
- Action selection
  - *Action selection* is the process of deciding among multiple possible actions or behaviors
  - Two basic types
  - *Multitasking:* reactive systems must be able to support parallelism, the ability to monitor and execute multiple rules at once

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Reactive control

- Definition
- Action selection
- Subsumption architecture (SA)
  - SA is the best known architecture for reactive control (introduced by Prof. Rodney Brooks at MIT in 1985)

Herbert the robot

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Reactive control

- Definition
- Action selection
- Subsumption architecture (SA)
  - SA is the best known architecture for reactive control
  - The *basic idea* is to build systems incrementally, from the simple parts to the more complex, using the already existing components as much as possible in the newly added stuff
    - This is called *bottom-up* design
    - This idea mimics our models of *evolutionary biology*

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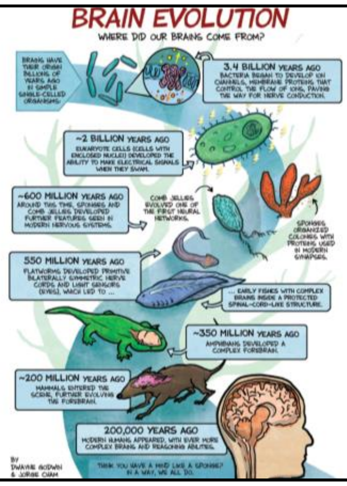

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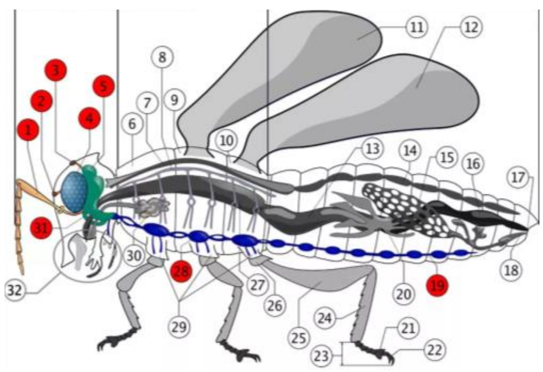

Nervous system of an insect

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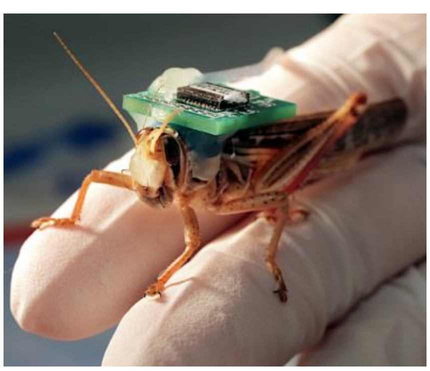

Study of insect brains to enhance robot control

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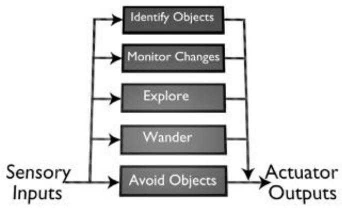
Reactive control

- Definition
- Action selection
- Subsumption architecture (SA)
  - SA is the best known architecture for reactive control
  - The basic idea
  - SA is modular, with a hierarchy among the modules, which are suggestively called layers



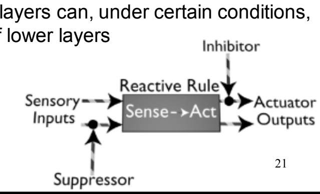
Reactive control

- Definition
- Action selection
- Subsumption architecture (SA)
  - SA is the best known architecture for reactive control
  - The basic idea
  - SA is modular, with a hierarchy among the modules, which are suggestively called layers
    - Each layer performs some task (e.g. avoiding objects)
    - Each layer is largely independent of other layers (allowing each to be designed and debugged separately)

Reactive control

- Definition
- Action selection
- Subsumption architecture (SA)
  - SA is the best known architecture for reactive control
  - The basic idea
  - SA is modular, with a hierarchy among the modules, which are suggestively called layers
    - Each layer performs some task
    - Each layer is largely independent of other layers
    - *Subsumption:* higher layers can, under certain conditions, "subsume" aspects of lower layers

The subsumption can occur by either suppressing the inputs or inhibiting the outputs



Reactive control

- Definition
- Action selection
- Subsumption architecture (SA)
  - SA is the best known architecture for reactive control
  - The basic idea
  - SA is modular, with a hierarchy among the modules, which are suggestively called layers
    - Each layer performs some task
    - Each layer is largely independent of other layers
    - *Subsumption*
    - "*The world is its own best model*," so no internal model is used
    - No sequencing of tasks between layers is used; they are all running in parallel all the time

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Reactive control

- Definition
- Action selection
- Subsumption architecture (SA)
- Drawbacks of reactive control
  - No (or minimal) state
  - No internal representations of the world
  - No memory
  - No (or minimal) learning

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"Hybrid" control

- Definition
  - *"Hybrid" control* involves the combination of reactive and deliberative control within a single robot control system (it roughly means to think and act independently and concurrently)
  - This concept is different from the concept of hybrid control used in controls literature

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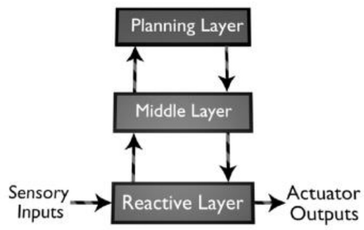
“Hybrid” control

- Definition
- Three-layer architecture
  - Three layers: a *reactive layer*, a *planning layer*, and a *middle layer* linking the two

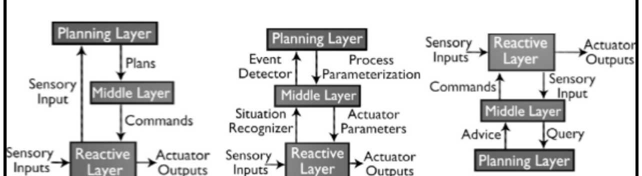


“Hybrid” control

- Definition
- Three-layer architecture
  - Three layers: a *reactive layer*, a *planning layer*, and a *middle layer* linking the two
  - The “magic middle”
    - compensates for the limitations of the other two
    - reconciles their disparate time-scales
    - reconciles their different representations
    - reconciles contradictory commands

“Hybrid” control

- Definition
- Three-layer architecture
  - Three layers: a *reactive layer*, a *planning layer*, and a *middle layer* linking the two
  - The “magic middle”
  - Various ways of managing layer interaction



"Hybrid" control

- Definition
- Three-layer architecture
- Drawbacks of "hybrid" control
  - The middle layer is difficult to design and build
  - The middle layer is specialized to a specific problem/robot
  - Sometimes the reactive and deliberative layers work to the detriment of each other

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Behavior-based control

- Definition
  - *Behavior-based control* involves the use of "behaviors" as modules for control
  - About *behaviors*
    - Behaviors achieve and/or maintain particular goals
    - Behaviors are time-extended, not instantaneous
    - Behaviors can take inputs from sensors and also from other behaviors, and can send outputs to effectors and to other behaviors—we can create network of behaviors
    - Behaviors are more complex than actions

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Behavior-based control

- Definition
- Connections with the other control architectures
  - Behavior-based control is closer to reactive control than to hybrid control, and farthest from deliberative control
  - Behavior based systems have reactive components, just as hybrid systems do, but they do not have traditional deliberative components

Note: Reactive control is too inflexible (incapable of representation or learning); deliberative control is too slow and cumbersome; and hybrid systems require complex interaction among components

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Behavior-based control

- Definition
- Connections with the other control architectures
- Principles of design
  - Behaviors are typically executed in parallel
  - Networks of behaviors are used to store state and construct world models/representations
  - Behaviors operate on compatible time-scales

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Behavior-based control

- Definition
- Connections with the other control architectures
- Principles of good design
- Key properties
  - The ability to react in real-time
  - The ability to use representations to generate (not only reactive) behavior
  - The ability to use a uniform structure and representation throughout the system (with no intermediate layers)

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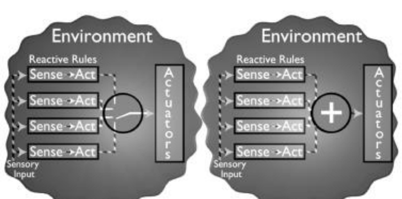
Behavior-based control

- Definition
- Connections with the other control architectures
- Principles of good design
- Key properties
- Behavior coordination (or action selection)



Fixed Heirarchy
Dynamic Heirarchy
Decision Theory
Probability

Potential Fields
Fuzzy Logic
Dynamical Systems
Motor Schemas

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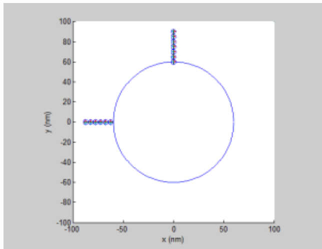
Behavior-based control

- Definition
- Connections with the other control architectures
- Principles of good design
- Key properties
- Behavior coordination
- Emergent behavior
  - Definition: *Emergent behavior* is structured (patterned, meaningful) behavior that is apparent from the observer's viewpoint, but not from the controller's /robot's view point



Behavior-based control

- Definition
- Connections with the other control architectures
- Principles of good design
- Key properties
- Behavior coordination
- Emergent behavior
  - Definition
  - Architectures and emergence
    - *Reactive* and *behavior-based* systems employ parallel rules and behaviors, respectively, which interact with each other and the environment, thus providing the perfect foundation for exploiting emergent behavior by design
    - *Deliberative* systems are sequential (with no parallel interactions between the components) and thus would require environment structure to have any behavior emerge over time
    - *Hybrid* systems follow the deliberative model in attempting to produce a coherent, uniform output of the system, minimizing interactions and thus minimizing emergence

Time responses of first-order systems

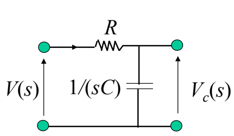
- First-order systems

$$G(s) = \frac{C(s)}{R(s)} = \frac{b_0}{s+a_0} = \frac{K}{\tau s+1}$$

dc gain

Time constant

- Examples:

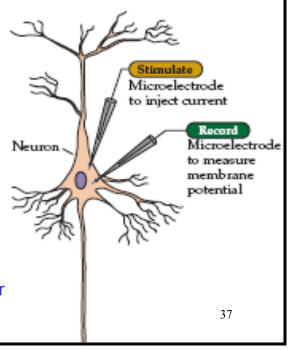


$$G(s) = \frac{V_C(s)}{V(s)} = \frac{1/(Cs)}{R+1/(Cs)} = \frac{1}{RCs+1}$$

Question: What does this circuit often used for?

Time responses of first-order systems

- First-order systems
  - Examples
    - Cruise control model
    - Leaky water tank model
    - Eye movement control model



Neuron as leaky-integrator

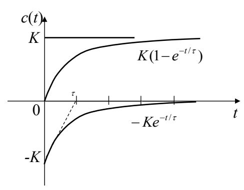
Time responses of first-order systems

- First-order systems $G(s) = \frac{C(s)}{R(s)} = \frac{K}{\tau s + 1}$
- Step response

$$R(s) = 1/s,$$

$$C(s) = \frac{1}{s}\frac{K/\tau}{s+1/\tau} = \frac{K}{s} - \frac{K}{s+1/\tau},$$

$$c(t) = K(1-e^{-t/\tau}), \quad t > 0$$



The limit of $c(t)$ as t goes to infinity is called the final value, or steady-state value of the response.

The parameter τ is called time constant; we may consider an exponential term to be zero after four time constants.

Time responses of first-order systems

- First-order systems $G(s) = \frac{C(s)}{R(s)} = \frac{K}{\tau s + 1}$
- Step response

$$R(s) = 1/s,$$

$$C(s) = \frac{1}{s}\frac{K/\tau}{s+1/\tau} = \frac{K}{s} - \frac{K}{s+1/\tau},$$

$$c(t) = K - Ke^{-t/\tau}, \quad t > 0$$

Forced response or steady-state response

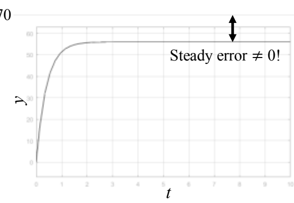
Natural response or transient response

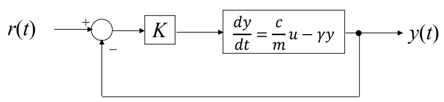
Time responses of first-order systems

- First-order systems
- Step response

$$c(t) = K(1 - e^{-t/\tau}), \quad t > 0$$

  - Example: using P control in cruise control





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Time responses of first-order systems

- First-order systems
- Step response

$$G(s) = \frac{C(s)}{R(s)} = \frac{K}{\tau s + 1}$$

- System dc gain
  - The system dc gain is the steady-state gain to a constant input for the case the output has a final value, and it is equal to the system transfer function evaluated at $s = 0$ (why?)

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Time responses of second-order systems

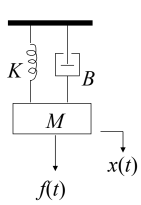
- Second-order systems

Natural frequency

$$G(s) = \frac{C(s)}{R(s)} = \frac{b_0}{s^2 + a_1 s + a_0} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

Damping ratio

  - Examples:



$$M\frac{d^2x}{dt^2} = f(t) - B\frac{dx}{dt} - Kx$$

$$G(s) = \frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Bs + K}$$

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Time responses of second-order systems

- Second-order systems
  - Examples:

An example from Dr. Ruiping Xia's research project (I am a collaborator)

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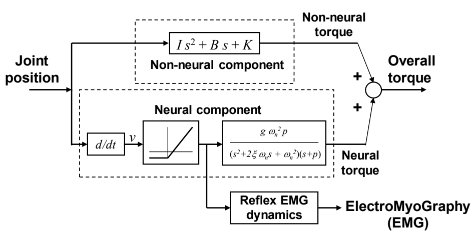
Time responses of second-order systems

- Second-order systems
  - Examples:



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Time responses of second-order systems

- Second-order systems $G(s) = \dfrac{\omega_n^{\ 2}}{s^2 + 2\varsigma\omega_n s + \omega_n^{\ 2}}$
- Step response
  - Case 1: $\zeta < 1$ (underdamped), including $\zeta = 0$ (undamped)

$$\boxed{c(t) = 1 - \frac{1}{\beta} e^{-\varsigma\omega_n t} \sin(\beta\omega_n t + \theta),}$$ where $\beta = \sqrt{1-\varsigma^2}$ and $\theta = \tan^{-1}(\beta/\varsigma)$

  - Case 2: $\zeta > 1$ (overdamped)

$$\boxed{c(t) = 1 + k_1 e^{-t/\tau_1} + k_2 e^{-t/\tau_2},}$$ where $\tau_{1,2} = 1/\left(\varsigma\omega_n \pm \omega_n\sqrt{\varsigma^2 - 1}\right)$

  - Case 3: $\zeta = 1$ (critically damped)

$$\boxed{c(t) = 1 + k_1 e^{-t/\tau} + k_2 t e^{-t/\tau},}$$ where $\tau = 1/\omega_n$

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Time responses of second-order systems

- Second-order systems $G(s)=\dfrac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$
- Step response

Case 1: $\zeta<1$ (underdamped)

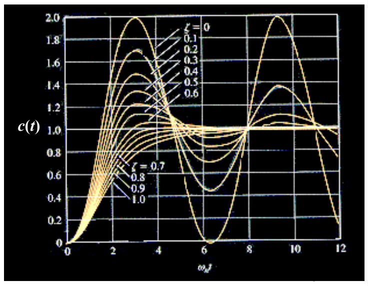
$$c(t)=1-\frac{1}{\beta}e^{-\zeta\omega_n t}\sin(\beta\omega_n t+\theta),$$

Case 2: $\zeta>1$ (overdamped)

$$c(t)=1+k_1e^{-t/\tau_1}+k_2e^{-t/\tau_2},$$

Case 3: $\zeta=1$ (critically damped)

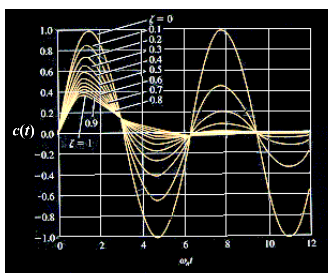
$$c(t)=1+k_1e^{-t/\tau}+k_2te^{-t/\tau},$$



Time responses of second-order systems

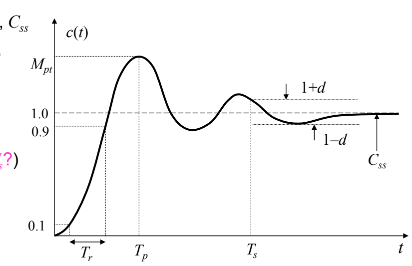
- Second-order systems $G(s)=\dfrac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$
- Step response
  - Case 1
  - Case 2
  - Case 3
  - Initial condition and impulse response

The initial condition excitation of higher-order systems cannot be modeled as simply as that of the first-order system; however, the impulse response of any system does give an indication of the nature of the initial-condition response, and thus the transient response



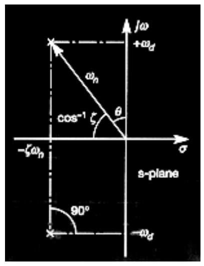
Time response specifications in design

- Some parameters
  - Rise time, T_r
  - Peak value of the step response, M_{pt} ; time to reach it, T_p (how to calculate T_p?)
  - Steady state value, C_{ss}
  - Percent overshoot, $\dfrac{M_{pt}-C_{ss}}{C_{ss}}\times 100$
  - Settling time, T_s (how to calculate T_s?)



Time response specifications in design

- Some parameters
- Time response and pole locations
  - The settling time is inversely related to the real part of the poles (the speed of response is increased by moving the poles to the left in the s-plane)
    $$\boxed{T_s = k\tau = \frac{k}{\varsigma\omega_n}}$$
  - Decreasing the angle $\cos^{-1}\zeta$ (increasing ζ) reduces the percent overshoot



Time response specifications in design

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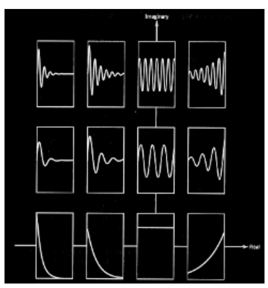

This picture shows how changing pole locations in the *s*-plane affects responses

Frequency response of systems

- Frequency response: steady-state response of systems to sinusoidal inputs

$$r(t) = A\cos\omega_1 t, \quad R(s) = \frac{As}{s^2+\omega_1^2},$$

$$\lim_{t\to\infty} c_g(t) = 0$$

$$C(s) = G(s)R(s) = \frac{k_1}{s-j\omega_1} + \frac{k_2}{s+j\omega_1} + C_g(s)$$

$$k_1 = \frac{1}{2}AG(j\omega_1),\ k_2 = \frac{1}{2}AG(-j\omega_1),\quad \boxed{G(j\omega_1) = |G(j\omega_1)|e^{j\phi(\omega_1)}}$$

$$c_{ss}(t) = k_1 e^{j\omega_1 t} + k_2 e^{-j\omega_1 t} = A|G(j\omega_1)|\frac{e^{j(\omega_1 t+\phi(\omega_1))} + e^{-j(\omega_1 t+\phi(\omega_1))}}{2}$$

$$= A|G(j\omega_1)|\cos(\omega_1 t + \phi(\omega_1))$$

Frequency response of systems

- Frequency response: steady-state response of systems to sinusoidal inputs

$$r(t) = A\cos\omega_1 t, \quad G(j\omega_1) = |G(j\omega_1)|e^{j\phi(\omega_1)}$$

$$\boxed{c_{ss}(t) = A\left|G(j\omega_1)\right|\cos(\omega_1 t + \phi(\omega_1))}$$

  – The steady-state gain of a system for a sinusoidal input is the magnitude of the transfer function evaluation at $s = j\omega_1$, and the phase shift of the output sinusoid relative to the input sinusoid is the angle of $G(j\omega_1)$

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Frequency response of systems

- Frequency response: steady-state response of systems to sinusoidal inputs
  – The steady-state gain of a system for a sinusoidal input is the *magnitude* of the transfer function evaluation at $s = j\omega_1$, and the *phase shift* of the output sinusoid relative to the input sinusoid is the angle of $G(j\omega_1)$
  – $G(j\omega)$ is defined as the frequency response function

$$G(j\omega) = |G(j\omega)|e^{j\phi(\omega)}$$

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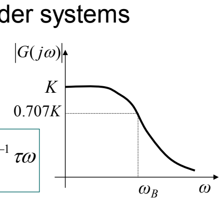
Frequency response of systems

- Frequency response: steady-state response of systems to sinusoidal inputs
- Frequency response of first-order systems

$$G(s) = \frac{K}{\tau s + 1}$$

$$\boxed{|G(j\omega)| = \frac{K}{\left(1+\tau^2\omega^2\right)^{1/2}}, \quad \phi(\omega) = -\tan^{-1}\tau\omega}$$



  – System bandwidth, ω_B: The frequency at which the gain is equal to $1/\text{sqrt}(2)$ (approximately 0.707) times the gain at very low frequencies

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Frequency response of systems

- Frequency response: steady-state response of systems to sinusoidal inputs
- Frequency response of first-order systems
- Frequency response of second-order systems

$$G(s)=\frac{\omega_n^{\ 2}}{s^2+2\varsigma\omega_n s+\omega_n^{\ 2}}=\frac{1}{(s/\omega_n)^2+2\varsigma(s/\omega_n)+1}$$

$$G(j\omega)=\frac{1}{[1-(\omega/\omega_n)^2]+j2\varsigma(\omega/\omega_n)}$$

$$\boxed{|G(j\omega)|=\frac{1}{\left[\left(1-(\omega/\omega_n)^2\right)^2+\left(2\varsigma(\omega/\omega_n)\right)^2\right]^{\frac{1}{2}}}}$$

Question: What will happen if $\zeta=0$ and $\omega=\omega_n$?

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Frequency response of systems

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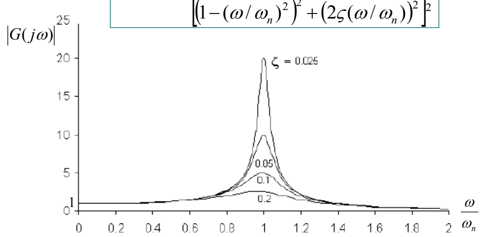

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PID control

- Proportional control
  - In proportional control, steady-state error tends to depend inversely upon proportional gain
  - Proportional control has a tendency to make a system faster
  - Proportional control does not change the order of the system

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PID control

- Proportional control
- Integral control
  - In integral control, steady-state error should be zero (prerequisite: the closed loop system has to be stable)
  - Integral control has a tendency to make a system slower and may even sacrifice stability
  - Integral control changes the order of the system

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PID control

- Proportional control
- Integral control
- Derivative control
  - Derivative control tends to increase the stability of the system
  - Derivative control tends to reduce the overshoot and improve the transient response
  - Derivative control changes the order of the system

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PID control

- Proportional control
- Integral control
- Derivative control

Closed-loop response	Rise time	Overshoot	Settling time	Steady-state error
K_P	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	Small change	Decrease	Decrease	Small change

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PID control

- Proportional control
- Integral control
- Derivative control
- Another view on PID control
  - The proportional term gives the controller output a component that is a function of the present state of the system
  - The integrator output is determined by the past state of the system
  - The differentiator is a function of the slope of its input and thus can be considered to be a predictor of the future state of the system
  - The PID controller can viewed as giving control that is a function of the past, the present, and the predicted future

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