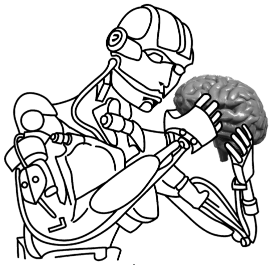
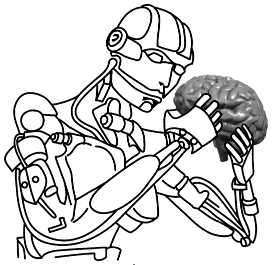


CS545—Contents XIV

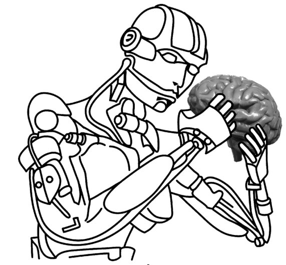
- Interaction Control
  - Compliance
  - Impedance
  - Force control
  - Hybrid control
  - Impedance control
- Sensors and Actuators
- Reading Assignment for Next Class
  - See http://www-clmc.usc.edu/~cs545

Example

Example

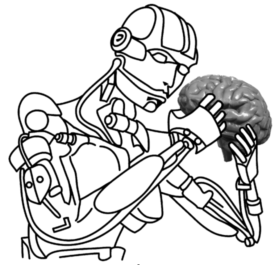


Problems of Interaction Control



- Equations of motion change: Closed loop kinematic chains
- Motion constraints imposed by the environment: Not all movement plans are feasible anymore
- What are the generalized coordinates?
- Planning and execution usually require very high accuracy if only motion control is performed
  - Exact models of the robot are needed
  - Exact models of the environment are needed
- Thus, somehow it is necessary to control the interaction forces

Some Technical Terms



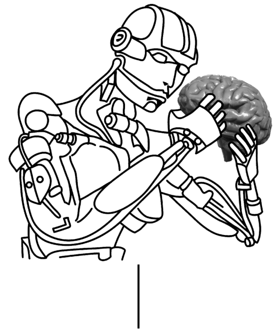
- Stiffness
  - Proportionality constant *k* that relates a static displacement to the force due to this replacement

$$F = k\Delta x$$

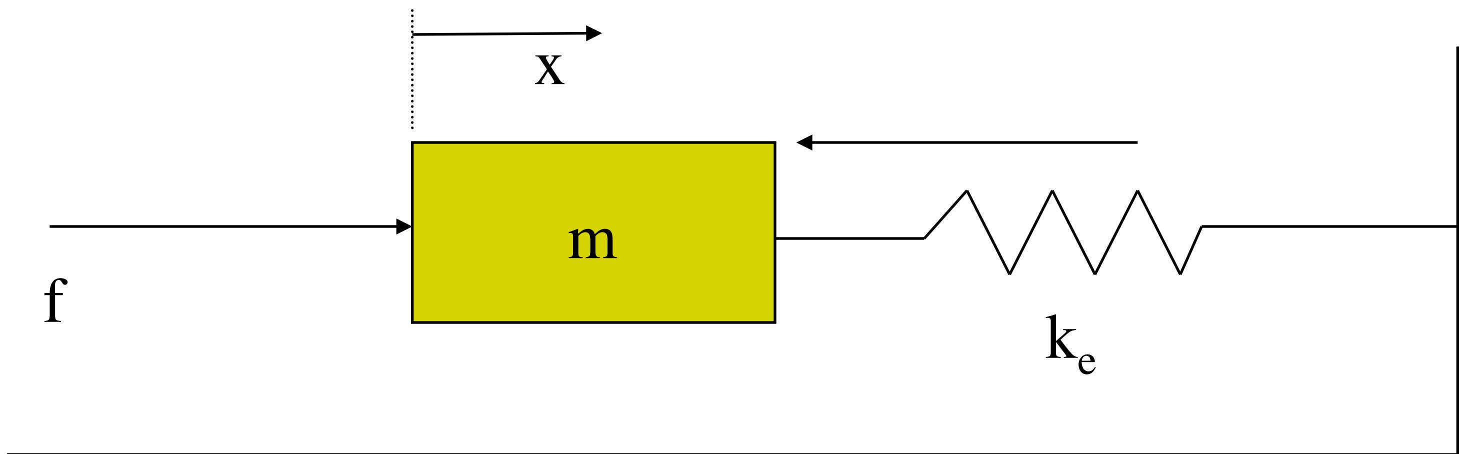
- Compliance
  - Inverse of stiffness
- Active compliance (or stiffness)
  - Controlled compliance in response to an external force, e.g., in order to keep the contact force at a certain limit ("actively giving in")
- Passive compliance (or stiffness)
  - Non-actuated ("internal") tendency of a body to get displaced due to external forces (e.g., mechanical springiness)
- Impedance
  - Dynamic response to an external force due to inertial, friction, and position terms, i.e.,

$$m\ddot{x}_d + b\dot{e} + ke = F \quad \text{where} \quad e = x_d - x$$

Force Control

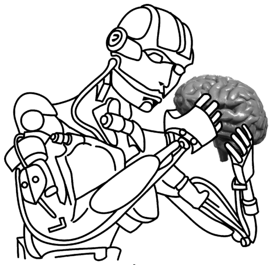


- In the direction of the constraint, it is more appropriate to do force control than position control
- A simple example: A spring-mass system



- What we want to control is the force acting on the environment

Force Control (cont'd)



- Force on the environment:

$$f_e = k_e x$$

- Equations of motion:

$$f = m\ddot{x} + k_e x + f_{dist}$$

- Reformulate in terms of the variable we want to control

$$f = \frac{m}{k_e}\ddot{f}_e + f_e + f_{dist}$$

- Define the error in force

$$e_f = f_d - f_e$$

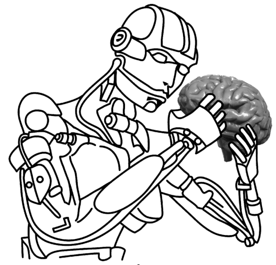
- And generate a control law:

$$f = \frac{m}{k_e}\left(\ddot{f}_d + k_{vf}\dot{e}_f + k_{pf}e_f\right) + f_e + f_{dist}$$

- Insert control law in eqns of motion results in the error dynamics

$$\ddot{e}_f + k_{vf}\dot{e}_f + k_{pf}e_f = 0$$

Force Control (cont'd)



- Problems with the suggested control law:
  - Disturbance force is not known
  - Force sensors are quite noisy, such that the derivatives of sensed forces are hard to obtain
- Dealing with the missing disturbance force:
  - Analyze the control law without the disturbance force:

$$\ddot{e}_f + k_{vf}\dot{e}_f + k_{pf}e_f = \frac{k_e}{m} f_{dist}$$

  - Steady state error:

$$e_f = \frac{k_e}{k_{pf}m} f_{dist}$$

    - If k_e is large, as usually the case in many contact tasks, this error can be quite large

Force Control (cont'd)

- Another control law can improve the steady state error:

$$f = \frac{m}{k_e}\left(\ddot{f}_d + k_{vf}\dot{e}_f + k_{pf}e_f\right) + f_d$$

- Insert into equation of motion:

$$\frac{m}{k_e}\left(\ddot{f}_d + k_{vf}\dot{e}_f + k_{pf}e_f\right) + f_d = \frac{m}{k_e}\ddot{f}_e + f_e + f_{dist}$$

$$\frac{m}{k_e}\left(\ddot{e}_f + k_{vf}\dot{e}_f + k_{pf}e_f\right) + e_f = f_{dist}$$

$$\ddot{e}_f + k_{vf}\dot{e}_f + e_f\left(k_{pf} + \frac{k_e}{m}\right) = \frac{k_e}{m}f_{dist}$$

- Thus, the steady state error becomes:

$$e_f = \frac{\frac{k_e}{m}}{k_{pf} + \frac{k_e}{m}}f_{dist} = \frac{1}{\frac{k_{pf}m}{k_e} + 1}f_{dist}$$

  - For stiff environments, this is quite an improvement

Force Control (cont’d)

- Avoiding force derivatives:
  - As we know: $$f_e = k_e x$$
  - We can make use of: $$\dot{f}_e = k_e \dot{x}$$
    - This assumes that we have good sensors to obtain the velocity of the endeffector
- The final control law thus becomes

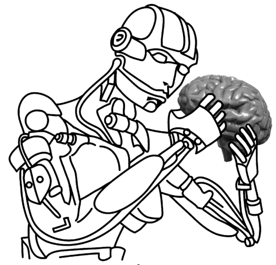
$$f = \frac{m}{k_e}\left(\ddot{f}_d + k_{vf}\left(\dot{f}_d - k_e \dot{x}\right) + k_{pf} e_f\right) + f_d$$

- For static desired contact forces we get:

$$f = m\left(-k_{vf}\dot{x} + \frac{k_{pf}}{k_e} e_f\right) + f_d$$

  - Note that we still need to know k_e

Force Control In A Complete Robot



- For force control, an operational space controller needs to be employed that includes inverse dynamics compensation:
  - The general rigid body dynamics equation is:

$$\mathbf{B}(\mathbf{q})\ddot{\mathbf{q}}+\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{G}(\mathbf{q})=\mathbf{u}$$

  - Try an inverse dynamics control law

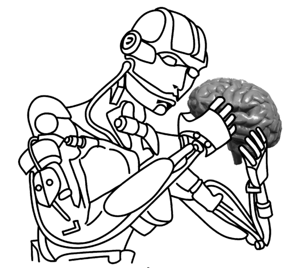
$$\mathbf{u}=\mathbf{B}(\mathbf{q})\mathbf{y}+\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}+\mathbf{G}(\mathbf{q})+J^T(\mathbf{q})f$$

    - But what is **y**? There is no desired acceleration term!
- Solutions to this problem:
  - Set **y** to zero
    - This should not matter too much since the interaction motion is usually rather slow or almost static
  - Employ more complex operational control schemes (S&S, Ch.7.4)

Hybrid Control

- The endeffector is usually not constraint in all direction
  - Solution:
    - In task space, use force control in the direction of the constraints
    - Use position control in the unconstrained direction
    - Note: need to transform task controller signals into operational space
  - Example:
    - Wiping clean a window

Impedance Control



- Goal: Control the dynamic response of the endeffector according to a pre-specified second order dynamics system

$$m\ddot{x}_d + b\dot{e} + ke = F \quad \text{where} \quad e = x_d - x$$

  - This mean we want to make the robot behave as if it were a different dynamical system
- A possible control law is:

$$\mathbf{u} = \mathbf{B}(\mathbf{q})\mathbf{y} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) - \mathbf{B}^{-1}(\mathbf{q})J^{T}(\mathbf{q})f_e$$

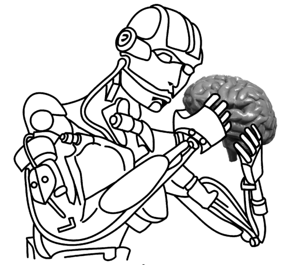
  - Where

$$\mathbf{y} = J^{-1}(\mathbf{q})\mathbf{M}_d^{-1}\left(\mathbf{M}_d\ddot{\mathbf{x}}_d + \mathbf{K}_D\dot{\mathbf{e}} + \mathbf{K}_P\mathbf{e} - \mathbf{M}_d\dot{J}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}\right)$$

  - Which results in the desired error dynamics:

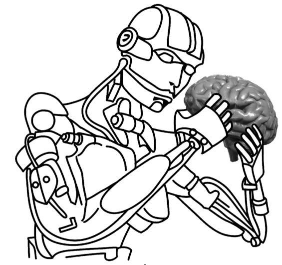
$$\mathbf{M}_d\ddot{\mathbf{e}} + \mathbf{K}_D\dot{\mathbf{e}} + \mathbf{K}_P\mathbf{e} = \mathbf{M}_d J^{-T}(\mathbf{q})\mathbf{B}(\mathbf{q})J^{-1}(\mathbf{q})f_e$$

Sensors and Actuators



- Elements of an robotic system
  - Power supply
  - Power amplifier
  - Servomotor
  - Transmission
  - sensors
- Servomotors:
  - Pneumatic
  - Hydraulic
  - Electric motors
- Transmission
  - Gears
  - Pullies and belts or chains
  - No (direct drive)

Sensors



- Sensor types
  - Tactile sensors
  - Proximity sensors
  - Range sensors
  - Vision systems
  - Position sensors (linear and rotary)
  - Velocity sensors (linear and rotary)
  - Acceleration sensors (linear and rotary)
  - Force sensors (linear and torque)
- Analog and Digital sensors exist