Actuators

Rod Grupen
Department of Computer Science
University of Massachusetts Amherst

...physical devices that transform electrical, chemical, or thermal energy into mechanical energy...

- muscle
- electric
  - stepper
  - permanent magnet DC
- hydraulic
- pneumatic
- artificial muscles
  - shape memory alloys
  - polymers
  - biological
  - bucky tubes

Muscle: Contractile Proteins

myosin

an angstrom is $10^{-10}$ m

Muscle: the Sliding Filament Model

Muscle: Huxley Model

Muscle: Fused Tetanus
**Muscle: Performance**

The performance of muscle tissue and the arrangement and attachment of muscles to the skeleton contribute to stability, smooth movement, and safety passively (at the molecular level). Motor control exploits these tacit properties.

**Hydraulic**

- 1000-3000 psi
- open-loop control
- 5KHz bandwidth
- great power-to-weight
- messy/high maintenance

**GRLA - Gorilla (SARCOS)**

- 1.75 meters from shoulder to wrist
- 3000 psi hydraulic
- exoskeletal master

**Bio-Hydraulic Actuators**

- spiders cannot extend their legs by activating muscles alone; they generally have less developed extensor musculature
- blood acts as hydraulic fluid; BP is very high compared to other insects and animals
- special valves and muscles compress their forebodies and act as hydraulic actuators for their legs.

**Pneumatic Actuators**

- **pneuma** 300 BC - animal spirits
- 60-100 psi
- jet-pipe servo valves
- passively backdrivable
- delicate

**Pneumatic Actuators - McKibben Air Muscles**

- stroke about 40% of free length
- 0-60 psi
- power-to-weight up to 100:1
- backdrivable
- easily packaged
- relatively slow
Electric Motors - Stepper

- precise open-loop
- low torque
- resonance (50-150 steps/sec)
- cogging

Electric Motors - Permanent Magnet DC

Lorentz force

\[ F = qV \times B \]

- back emf
- commutation

Electric Motors - Commutation

Faraday’s Law -
electromotive force that pushes electrons around a closed circuit is proportional to the time rate of change of the magnetic flux (# field lines) surrounded by the loop

the faster the crank is turned, the more (backwards) electromotive force is generated

Electric Motors - Generator Effects

- cheap reliable
- cogging
- big torques
- good power-to-weight
- continuous operation
- high speeds

Hands-On!

- cogging
- the generator effect
- build a DC motor
Manufacturers publish motor parameters: motor torque constant $K_m$, rotor inertia $J$, resistance $R$, inductance $L$, overall mass and geometry of the motor package, and integrated motor performance data:

- $\omega_0$: no-load velocity
- $\tau_s$: stall torque
- $I_0$: no-load current
- $I_s$: stall current

Power: the product of torque and speed ($\tau \omega$) for loads $[0, \tau_s]$

$$P_{\text{out}} = \tau_{\text{load}} \omega_{\text{load}} = \tau_{\text{load}} \left[ \omega_0 - \frac{\Delta \omega}{\Delta \tau} \tau_{\text{load}} \right] = -\frac{\Delta \omega}{\Delta \tau} \tau_{\text{load}}^2 + (\omega_0)\tau_{\text{load}}$$

Efficiency: $\eta = \frac{\text{mechanical power output}}{\text{electrical power input}} = \frac{P_{\text{out}}}{V I_s}$

$$\eta = -\frac{(\Delta \omega/\Delta \tau)^2 \tau_{\text{load}}^2 + (\omega_0)\tau_{\text{load}}}{V (I_0 + \tau_{\text{load}}/K_m)}$$

If $\eta = 0.01$, the output shaft carries one hundred times the torque at one hundredth the velocity of the input shaft.
Electric Motors – Inertial Loads

\[
\tau = \left[ J_M \ddot{\theta}_M + B_M \dot{\theta}_M \right] + \eta \left[ J_L \ddot{\theta}_L + B_L \dot{\theta}_L \right]
\]

\[
\theta_L = \eta \theta_M, \quad \dot{\theta}_L = \eta \dot{\theta}_M, \quad \text{and} \quad \ddot{\theta}_L = \eta \ddot{\theta}_M
\]

\[
\tau = [J_M + \eta^2 J_L] \ddot{\theta}_M + [B_M + \eta^2 B_L] \dot{\theta}_M \quad J_{eff} = J_M + \eta^2 J_L \\
B_{eff} = B_M + \eta^2 B_L
\]

The inertia of the motor/load can be dominated by the inertia of the motor.

Artificial Muscles

**Mechanical properties:** elastic modulus, tensile strength, stress-strain, fatigue life, thermal and electrical conductivity

**Thermodynamic issues:** efficiency, power and force density, power limits

**Packaging:** power supply/delivery, device construction, manufacturing, control, integration

Artificial Muscles - Shape Memory Alloys

- Nickel Titanium - Nitinol
- Crystallographic phase transformation from Martesite to Austenite
- Contract (when heated) 5-7% of length - 100 times greater effect than thermal expansion
- Relatively high forces
- About 1 Hz

Artificial Muscles - New Technologies

- **Chemical polymers - gels** (Jello, vitreous humor)
  - 1000 fold volume change ~ temp, pH, electric fields
  - force up to 100 N/cm²
  - 25 um fibers -> 1 Hz, 1 cm fiber -> 1 cycle/2.5 days

- **Electroactive polymers**
  - store electrons in large molecules
  - change length of chemical bonds - batteries/capacitors
  - deform ~ V²

- **Biological Muscle Proteins**
  - actin and myosin
  - 0.001 mm/sec in a petri dish

- **Fullerenes and Nanotubes**
  - graphitic carbon
  - high elastic modulus -> large displacements, large forces
  - macro-, micro-, and nano-scale
  - extremely robust
  - potentially superior to biological muscle