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Actuators

Rod Grupen
Department of Computer Science
University of Massachusetts Amherst

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Actuators

…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

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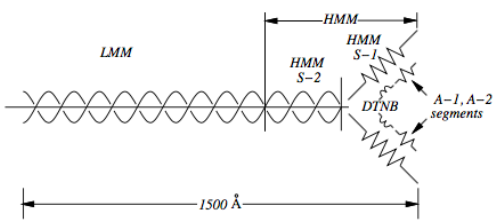
Muscle: Contractile Proteins

myosin



an angstrom is 10^{-10} m

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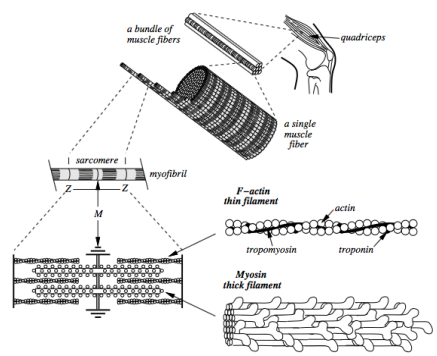
Muscle: the Sliding Filament Model



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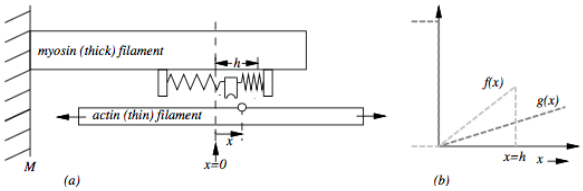
Muscle: Huxley Model



$$\frac{dn(x)}{dt} = [1 - n(x)]\, f(x) - n(x) g(x)$$

n(x): probability of a "crossbridge" forming at displacement *x*

f(x): probability of a new crossbridge

g(x): probability that an existing cross bridge will detach

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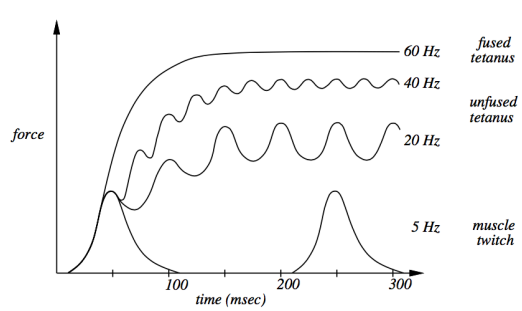
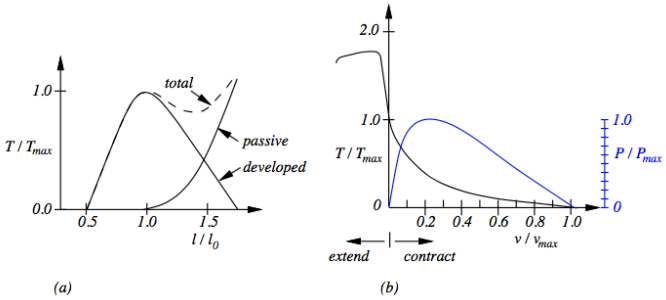
Muscle: Fused Tetanus



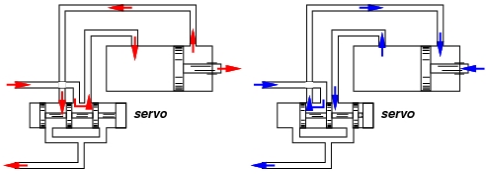
Muscle: Performance



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



Hydraulic

GRLA - Gorilla (SARCOS)

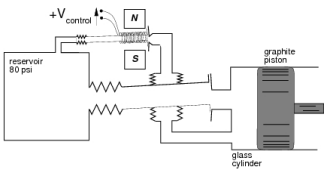
- 1.75 meters from shoulder to wrist
- 3000 psi hydraulic
- exoskeletal master

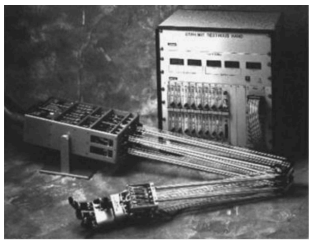
Bio-Hydraulic Actuators

- 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.

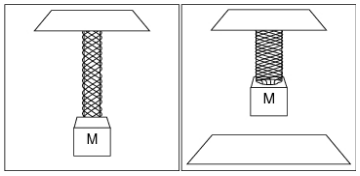
Pneumatic Actuators

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

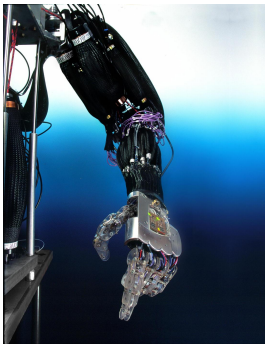




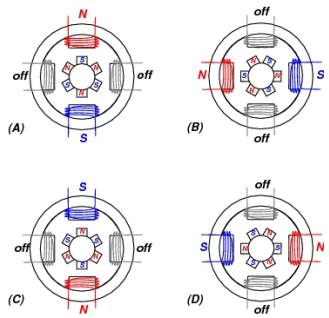
Pneumatic Actuators - McKibben Air Muscles



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

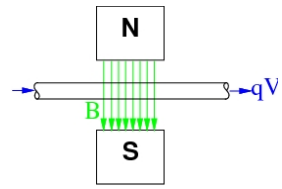


Electric Motors - Stepper



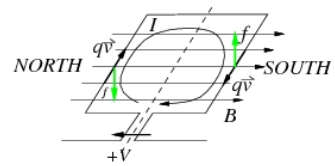
- precise open-loop
- low torque
- resonance
  (50-150 steps/sec)
- cogging

Electric Motors - Permanent Magnet DC



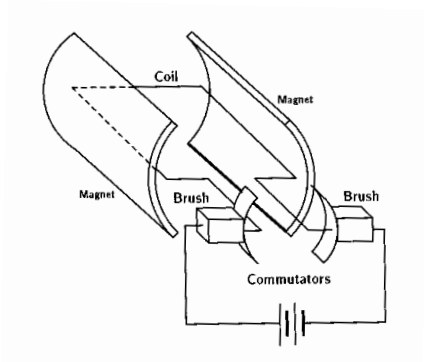
Lorentz force

$$F = qV \times B$$



- back emf
- commutation

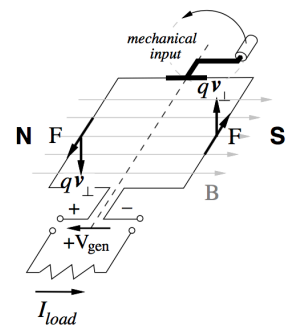
Electric Motors - Commutation



Electric Motors - Generator Effects

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

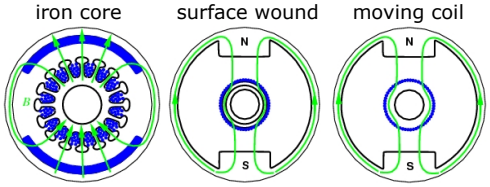
the faster the crank is turned, the more (backwards) electromotive force is generated



Electric Motors - Permanent Magnet DC

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

iron core surface wound moving coil



Hands-On!

- cogging
- the generator effect
- build a DC motor

Electric Motors - Electrodynamics

force: Newton $N = kg \cdot m/sec^2$

torque: the product of a force and a moment arm

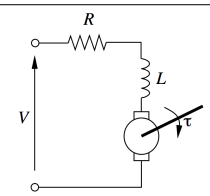
$$N \cdot m = \frac{kg \cdot m^2}{sec^2}$$

power: energy per unit time (Watts)

$$\begin{aligned} P &= VI(\text{electrical}) \\ &= \tau\omega(\text{mechanical}) \end{aligned}$$

$$Watt = \frac{volt \cdot coulomb}{sec} = \frac{Nm}{sec}$$

Electric Motors - Electrodynamics



forward current

$$\sum \tau = J\ddot{\theta} = K_m I = K_m \left[\frac{V}{R} - \frac{K_m \dot{\theta}}{R}\right]$$

back current

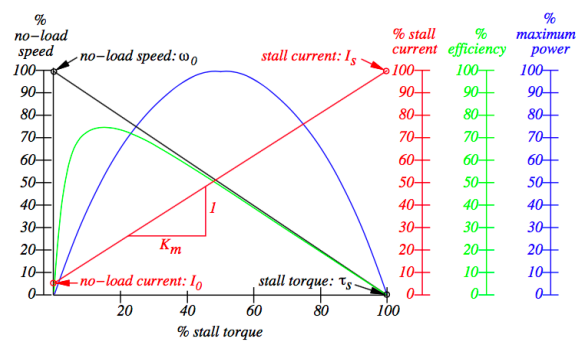
$$\ddot{\theta} + \frac{K^2}{JR}\dot{\theta} + \frac{KV}{JR} = 0$$

manufacturers publish motor parameters: motor torque constant K, rotor inertia J, resistance R, inductance L, overall mass and geometry of the motor package, and integrated motor performance data:

ω_0: no-load velocity τ_s: stall torque

I_0: no-load current I_s: stall current

Electric Motors - Performance



Electric Motors - Performance

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

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

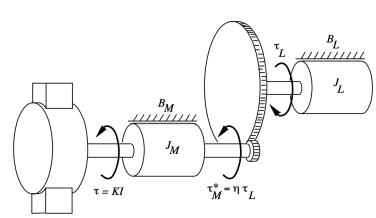
$$\text{Efficiency: } \eta_\tau = \frac{\text{mechanical power out}}{\text{electrical power in}} = \frac{P_{out}}{V_s I}$$

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

Roger's Motor Parameters

PARAMETER	wheel	shoulder	elbow	eye
ω_0 $[rad/sec]$ no-load speed	175.0	30.1	50.3	122.2
I_0 $[A]$ no-load current	0.38	0.26	0.17	0.12
τ_s $[N \cdot m]$ stall torque	475.0	205.3	120.7	2.7
K_m $\left[\frac{N \cdot m}{A}\right]$ $\left[\frac{V \cdot sec}{rad}\right]$ torque constant	0.105	0.623	0.364	0.163

Electric Motors - Gearboxes



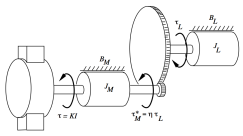
$$\begin{aligned} \tau_{out}\omega_{out} &= \tau_{in}\omega_{in} \\ \tau_{out}(\eta\omega_{in}) &= \tau_{in}\omega_{in} \\ \tau_{out} &= (1/\eta)\tau_{in} \end{aligned}$$

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

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

$$\begin{aligned}\theta_L &= \eta\theta_M,\\ \dot{\theta}_L &= \eta\dot{\theta}_M,\ and\\ \ddot{\theta}_L &= \eta\ddot{\theta}_M\end{aligned}$$



$$\tau = \left[J_M + \eta^2 J_L\right]\ddot{\theta}_M + \left[B_M + \eta^2 B_L\right]\dot{\theta}_M$$

$$\begin{aligned}J_{eff} &= J_M + \eta^2 J_L\\ B_{eff} &= B_M + \eta^2 B_L\end{aligned}$$

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*
- Crystalographic 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/cm^2
- *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 ~ V^2

Artificial Muscles - New Technologies

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