

Haptics for Medical Robotics

Actuators

Lecture 2

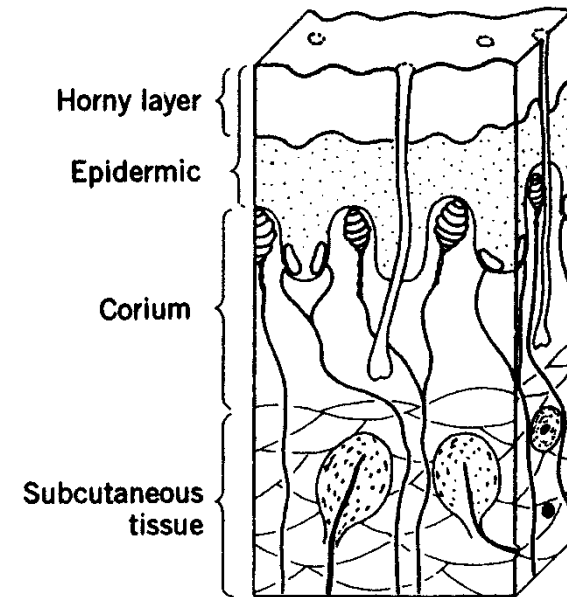
Outline for Today

- Review of Haptic Sensing and Control
- Actuators
- Discuss Homework# 1
- Paper presentations

Unless otherwise mentioned, all figures in this presentation are from the course textbook by Burdea.

Skin

- ❑ Heaviest organ in the human body
- ❑ Fingers have the highest density of specialized receptors that corresponds to a large sensory cortex surface
- ❑ Sensorial mapping is dynamic
- ❑ Glabrous skin has five major receptor types: free receptors (nerve endings), Meissner corpuscles, Merkel's disks, Pacinian corpuscles, and Ruffini corpuscles



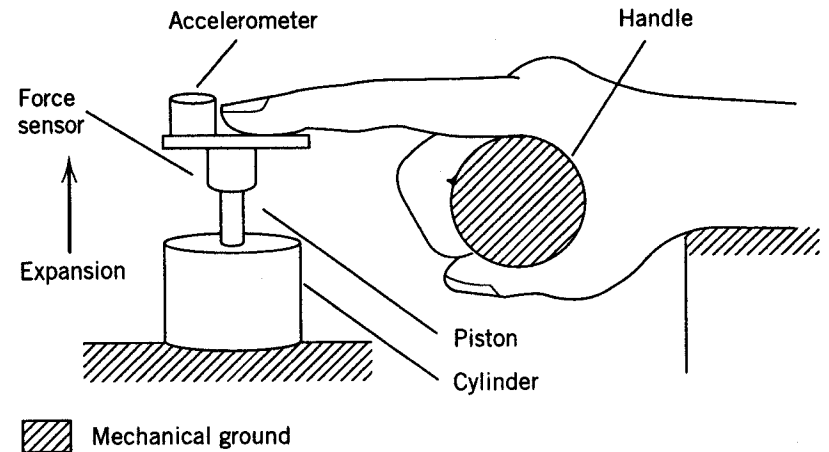
From Seow, Physiology of touch, grip, and gait, 1988 John Wiley & Sons, Inc.

Summary of skin mechanoreceptors

Receptor Type	Rate of Adaptation	Stimulus frequency, Hz	Receptive Field	Function
Merkel Disks	SA-I	0.3-3	Small, well defined	Pressure, vibratory response
Ruffini Corpuscles	SA-II	15-400	Large, indistinct	Pressure, skin shear
Meissner corpuscles	RA-I	3-40	Small, well defined	Velocity, edges
Pacinian corpuscles	RA-II	100-300 (typically >250)	Large, indistinct	Acceleration, vibration

Finger Mechanical Impedance

- Impedance is the relationship between the applied force and the corresponding displacement
- Human-arm/hand impedance is the key to stable human-machine interfaces



Finger mechanical impedance evaluation (Hajian and Howe, 1994)

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = f(t)$$

Sensing and Control bandwidth

- ❑ Sensing bandwidth – Frequency with which tactile and kinesthetic stimuli are sensed
- ❑ Control bandwidth – Rapidity with which humans can respond
- ❑ Sensing bandwidth is much larger than the control bandwidth
- ❑ Output loop or the control bandwidth has a typical force response of 5-10 Hz bandwidth while the kinesthetic / proprioceptive sensing bandwidth is about 20-30 Hz and tactile sensing bandwidth is 0-400Hz. Surface feature recognition requires a much higher bandwidth of about 5000-10000Hz

Sensing and Control bandwidth

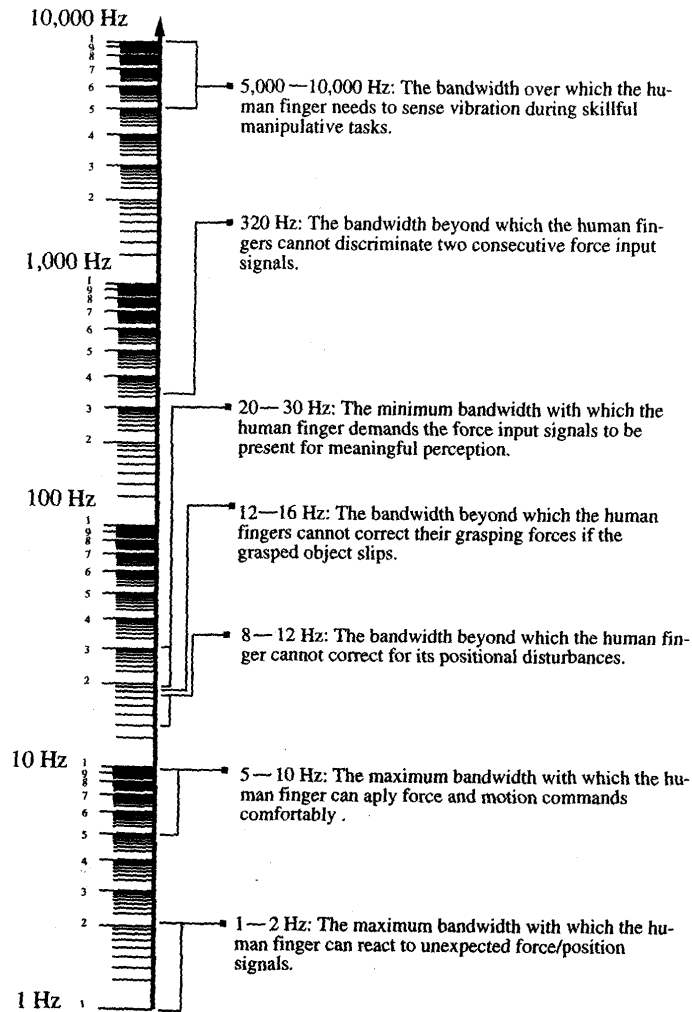


Figure 2.14 Human finger sensing and control bandwidth. Adapted from Shimoga [1992].
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Tactile/Force interface requirements

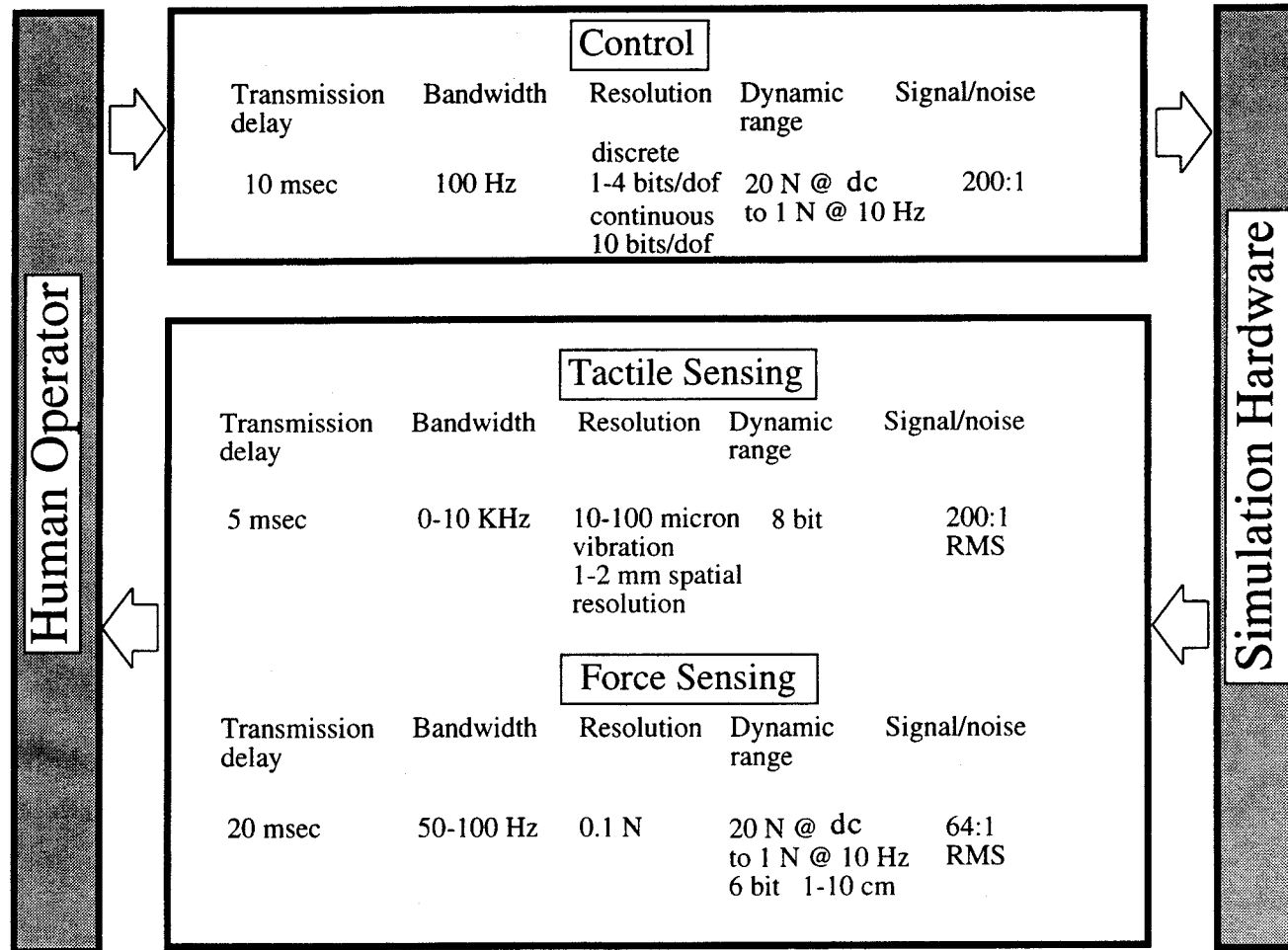


Figure 2.15 Tactile/force feedback interface requirements. Adapted from Ellis [1995]. Reprinted by permission of IDG Communications Verlag AG.

Actuators

- ❑ Actuators feed back force or tactile information
- ❑ Active and Passive actuators
- ❑ Actuators made up of electrical motors, hydraulics, pneumatics, magnetostrictive, piezoelectric, polymeric gels, etc.
- ❑ Key parameters in actuators is the maximum force output, sustained force or torque, power consumption, and bandwidth
- ❑ Power vs. weight is an important characterization (maximum power for minimal weight)
- ❑ PHANToM produces realistic simulation with only 8.5N (20% of max. exerted hand force)



Actuators

- ❑ Interface should be **transparent**? What does that mean?
- ❑ Should force be exerted on the user's hands when there is no interaction with the environment (virtual or real)?
- ❑ This requires the actuators to be **backdrivable**
- ❑ **Backdrivability** requires minimal static friction and low actuator inertia
- ❑ **Dynamic range** – Maximum output force divided by its friction

Electrical Actuators

- Direct current (DC) motors –
 - Brushed motors (field windings and armature windings; need for brushes for commutation)
 - Brushless motors (PM in armature)
- Classification of brushed DC motors according to the field windings

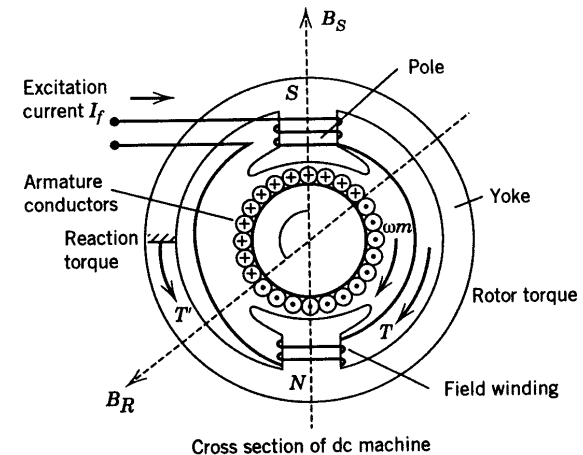


Figure 3.1 Cross section of a brushed dc motor. Reprinted from Rizzoni, *Principles and Applications of Electrical Engineering*, 1993, by permission of Richard D. Irwin.

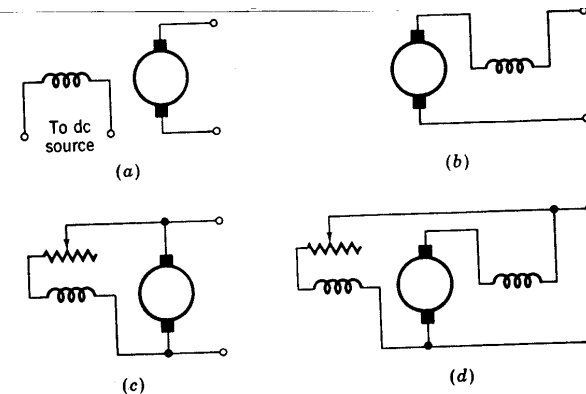


Figure 3.2 Field-circuit connections of dc motors: (a) separate excitation, (b) series, (c) shunt, (d) compound. Reprinted with permission from Fitzgerald et al., 1983, *Electric Machinery*, The McGraw-Hill Companies.

Brushed DC motors

Magnetic flux $f(t) = k_f i_f(t)$

Motor torque $t_m = k_m f(t) i_a(t) = k_m k_f i_f(t) i_a(t)$

$t_m = k_s i^2(t)$ (series DC motor)

- Series motors have very high starting torque and are useful in low-speed, high-torque applications (haptic interfaces)
- Output is not equal to the input due to inertial and viscous damping torques

$$t_{load} = t_m - J_m \frac{dw_m}{dt} - b_m w_m$$

Brushed DC motors

- DC motors with miniature PM's (no field current) are useful in haptic interfaces due to their light-weight and compactness
- Simpler torque to current relationship
- Stall torque can be increased by increasing the supply voltage (without overheating the motor; excessive heat can demagnetize the stator)
- Torque constant depends on temperature
- Torque vs. velocity characteristic of MicroMo model 1331-012S

$$t_{mPM} = k_{sPM} i_a(t)$$

$$t_{mPM} = \frac{V_s}{R_a} k_{sPM} - \frac{\omega_m}{R_a} k_{sPM} k_{aPM}$$

$$t_{mPM-stall} = \frac{V_s}{R_a} k_{sPM}$$

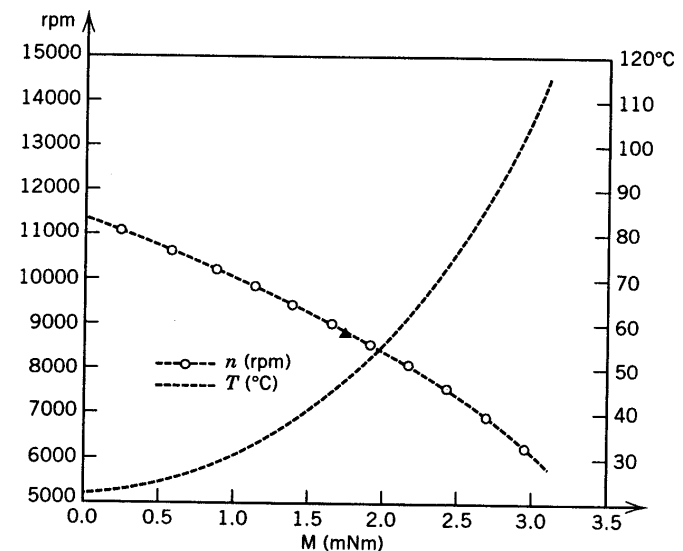


Figure 3.3 Torque and velocity characteristic of the MicroMo Model 1331-012S PM dc motor. Courtesy of MicroMo Electronics Inc.

Brushless DC motors

- ❑ Consist of coils in the stator and a rare earth (samarium cobalt) permanent magnet in the rotor
- ❑ Lower motor inertia and improved dynamic response
- ❑ Smaller motor size than the corresponding brushed motors
- ❑ Disadvantage is the requirement of an additional position sensor and a complex controller for producing a rotating magnetic field

	Brush Motor	Brushless motor
Advantages	Lower cost; Simpler electronics; Smaller controller	Smaller motor; Improved dynamics; Better heat dissipation
Disadvantages	EMG interference; Brush wear (shorter life); Smaller maximum speed; Poorer dynamic response	Electronic commutation required; Position sensor required; Higher cost

Magnetic Particle Brakes (Passive)

- ❑ Magnetic particle brakes are passive actuators since they take force input from the user and dissipate the power generated by the user
- ❑ Stronger the current, more magnetic particles are attached to the disk and the chamber walls resulting in increased resistance to the rotation of the brake shaft.
- ❑ Resistive torque:

$$t_b = k_b i_b$$

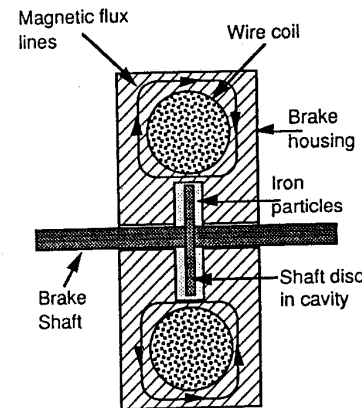


Figure 3.6 Cross section of a magnetic particle brake. Reprinted by permission of the ASME from Russo and Tadros [1992].

Magnetic Particle Brake

- Can be used to simulate dissipate devices but not energy-storing elements. Brake power is always positive: $P_{in} = \mathbf{t}_b \mathbf{w}_b > 0$
- Simplest element to simulate using the MPB is a damper (but not a spring, since the spring stores energy while an MPB cannot store energy)
- Best use of MPB is to simulate a hard wall since electrical motors simulate it with a very stiff spring model which can result in contact instabilities
- Major problem with MPB is hysteresis, i.e., the magnetic particles maintain alignment when the power is removed from the brake coil

Shape memory metals (SMM)

- ❑ SMM such as TiNi are alloys that exhibit mechanical-memory effect. Structural transition from the martensitic phase to the austenitic phase characterized by higher crystalline symmetry
- ❑ This is achieved when the alloy is heated past its austenitic start temperature and ends upon reaching the austenitic finish temperature.
- ❑ High tensile forces produced. When current interrupted, alloy cools and returns to martensitic phase. Cooling takes significantly longer than heating
- ❑ Have large deformation but produce smaller forces. Have a large power to weight ratio (typically 200W/Kg)
- ❑ Ideal for haptic interfaces (compact, light, and high power-to-weight ratio)

SMM as tactile simulators

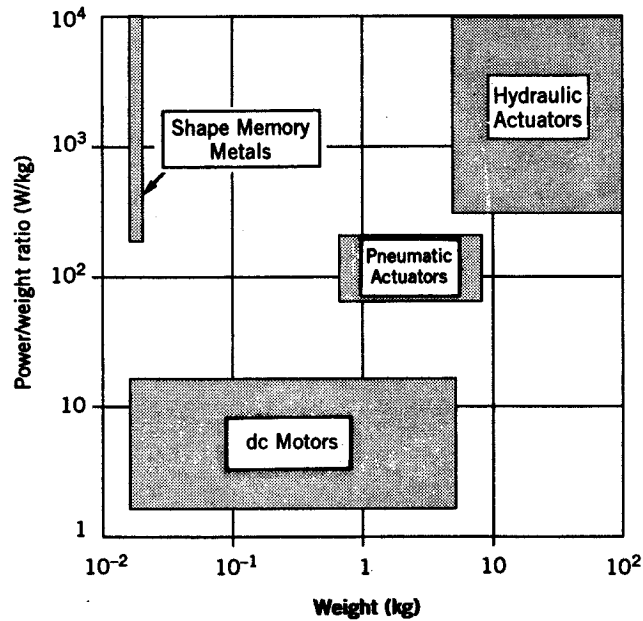


Figure 3.8 Shape memory metal (SMM) power density vs. other actuators. Adapted from Hirose et al. [1989] and Hollerbach et al. [1992]. Reprinted by permission of the MIT Press.

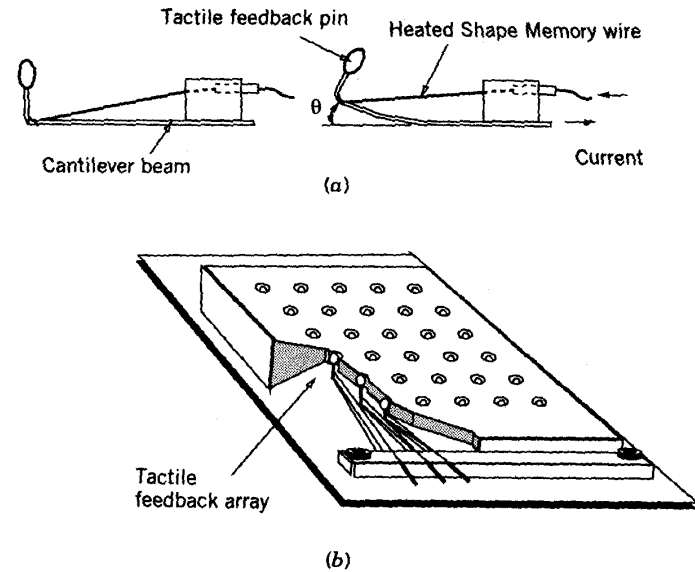


Figure 3.9 Shape memory metal (SMM) tactile stimulator. (a) Single actuator. (b) Actuator array. Adapted from Johnson [1992]. © Éditions Hermès. Reprinted by permission.

Novel Actuators

- ❑ Metal hydrades, Piezoelectric actuators, Magnetostrictive actuators, and polymeric gels
- ❑ **Metal hydrades** have the ability to release large amounts of hydrogen when heated and when the alloy is cooled (below 300C) hydrogen is re-absorbed.
- ❑ Shimizu et.al used two Peltier heat pumps to test this actuation technique. Pressure of the released gas was controlled as a function of the voltage supplied to the Peltier pumps
- ❑ Overall weight is 300g and force output is 20Kgf – Large force-to-weight ratio due to large diameter bellow and hydrogen gas pressure

Piezoelectric Actuators

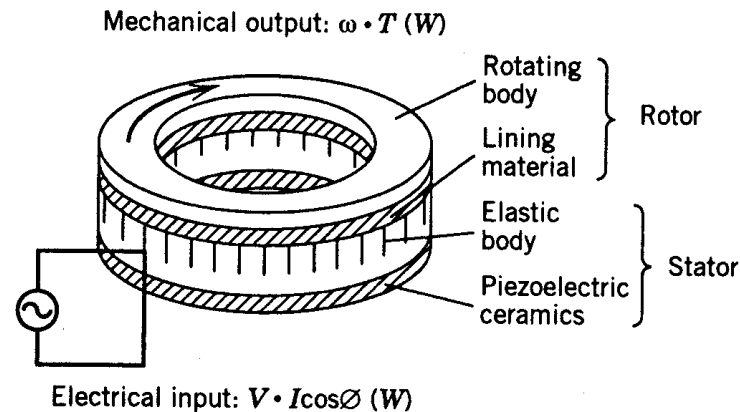


Figure 11.2 The construction of a rotary piezoelectric actuator. From PCIM Staff [1987]. Reprinted by permission of Intertec International Inc.

- ❑ Piezoelectric motor – disk shaped stator pressed against a laminated disk rotor.
- ❑ Stator is constructed of small elastic piezoelectric elements that oscillate in a state of resonance. High frequency oscillations produce a micro-slipping motion at the contact surface with the rotor.

Piezoelectric actuator

- Overall PEM's have a 10-fold higher torque compared to conventional motors of the same volume, little inertia, good controllability, and are compact.
- Power to mass ratio of around 225W/kg and torque to mass ratio of 70N-m/Kg

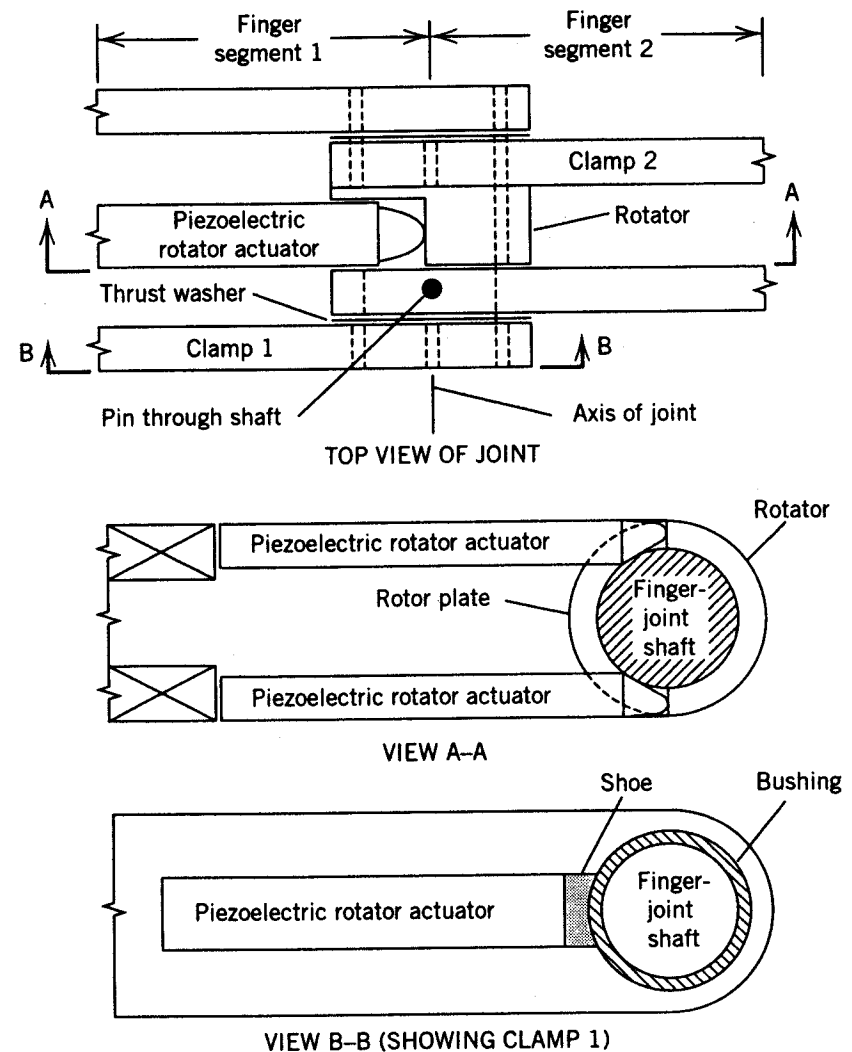


Figure 11.3 The construction of a piezoelectric direct-drive actuator for robotic fingers. Reprinted by permission from NASA [1994].

Magnetostrictive actuator

- Magnetostrictive ones expand or shrink when placed in a high magnetic field. Eg., Terfenol-D

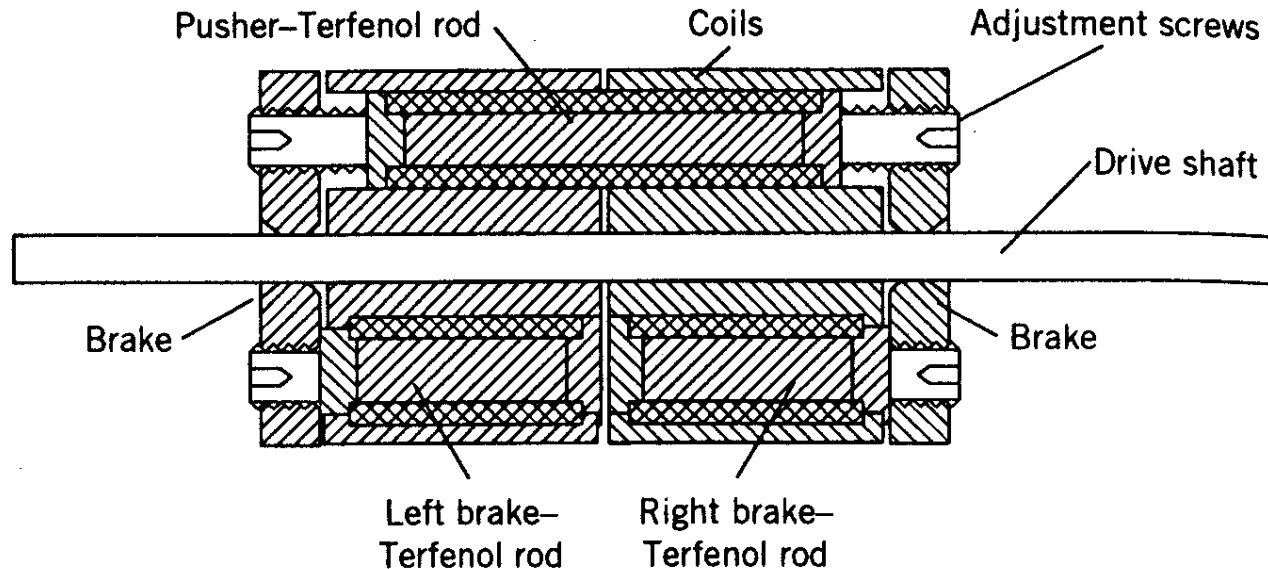


Figure 11.4 The construction of a magnetostrictive linear actuator. Reprinted by permission from Brimhall and Hasser [1994]. © SPIE.

Polymeric Gels

- ❑ Quick volume change as a function of pH of the surrounding liquid. Convert Chemical to Mechanical Energy by shrinking up to 1000 times their original volume
- ❑ Large output forces and long life cycle. Force proportional to the number for fibers
- ❑ Disadvantage is unidirectional output, low control bandwidth ($<2\text{Hz}$), and complex piping system

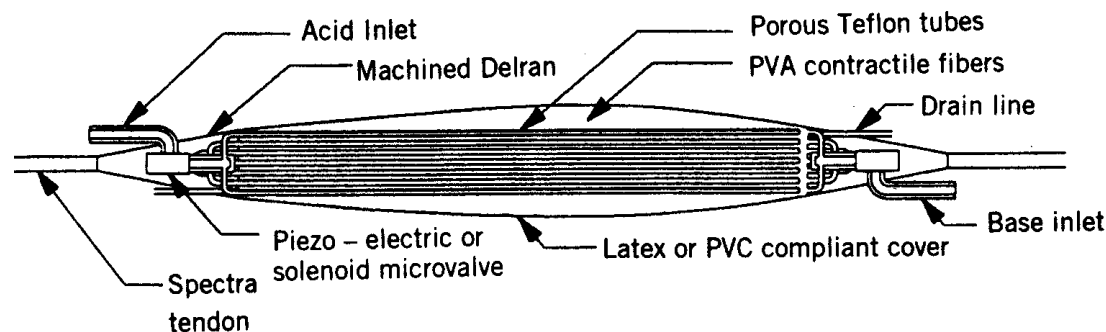


Figure 11.6 Artificial muscle made of Polyvinyl alcohol fiber bundles. Reprinted by permission from Brock [1991].

Novel actuators

TABLE 11.1 Review of Novel Actuator Technology

Actuator Type	Power/mass (Power/volume)	Stall torque Stall force	Max. speed	Mass
Metal hydrades		196 N	1 cm/sec	300 g
Piezoelectric finger motor	225 W/kg	0.5 N-m	12.6 rad/sec	6-8 g
Magneto-strictive motor		10 N	14 cm/sec	16 g
Polymeric gels	6 W/kg			

Next Lecture

- ❑ Sensors
- ❑ Homework# 2 due
- ❑ Discuss Homework# 2
- ❑ Homework#3 handed out
- ❑ Paper readings
- ❑ Questions?