Sensors and Actuators

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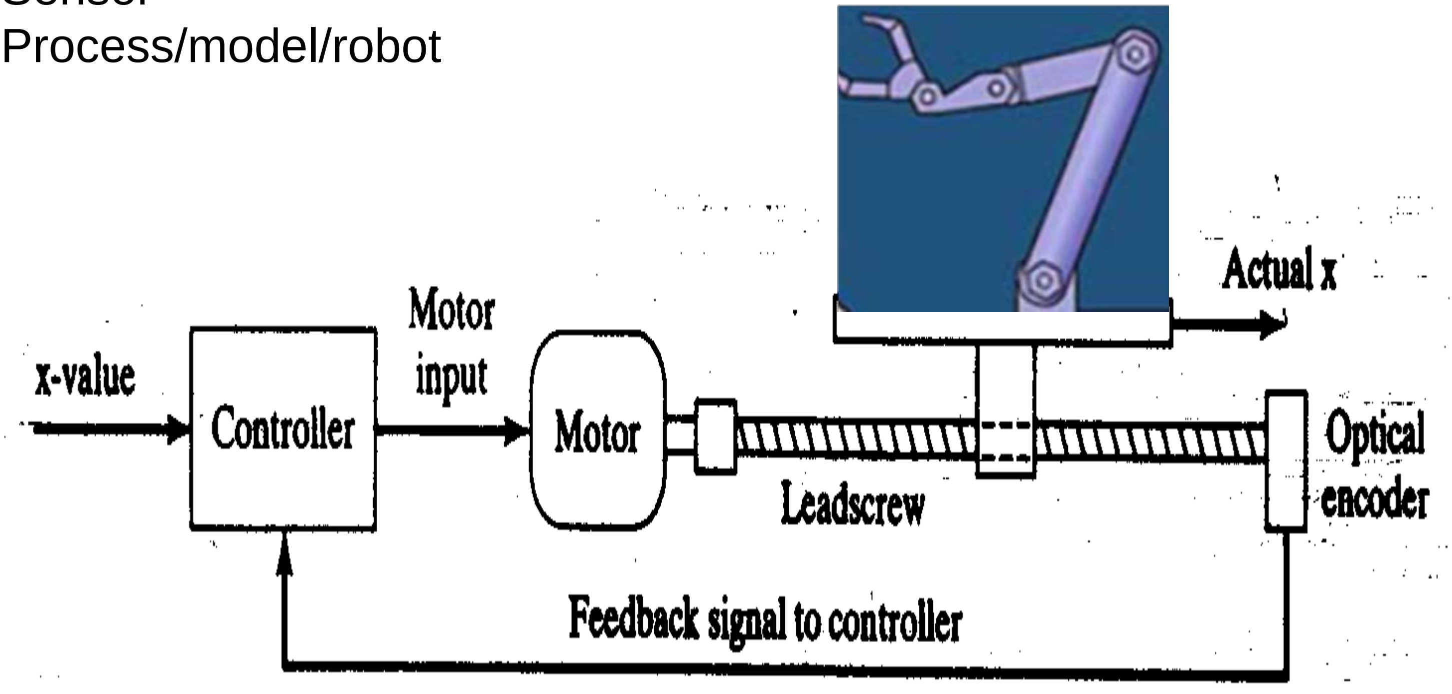
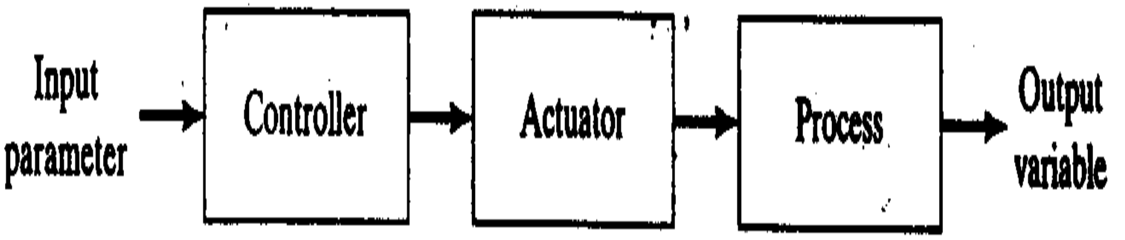
Sub-systems in robot control

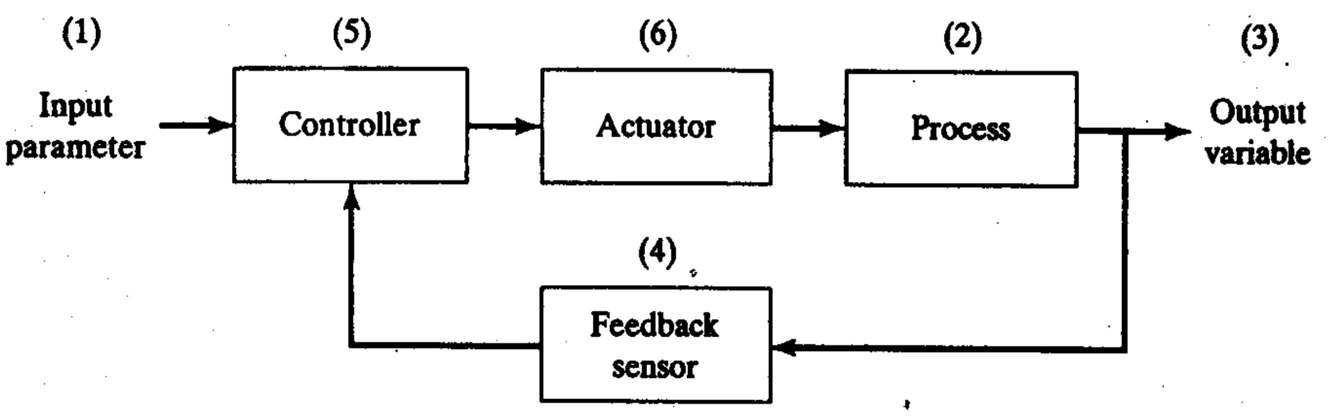
- Controller
- Actuator
- Sensor
- Process/model/robot



SIZE EFFECT ?

Open loop and closed loop





Basic elements

- Sensors
- Actuators
- Controllers
- System model

General Classification of Sensors

- **Internal sensors:** required for basic working of the system (e.g. position, velocity,).

- **External sensors:** interaction with the environment (vision, force, …).

Sensors used for closed loop position control: Internal sensors

- Position
- Velocity
- Acceleration

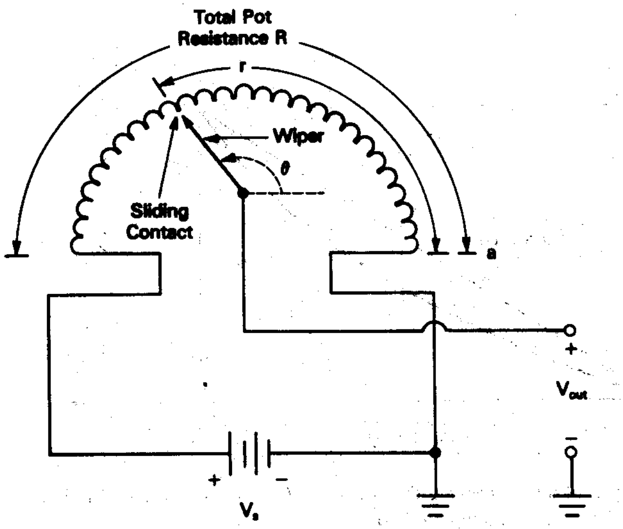
e.g. potentiometers, encoders, LVDT, Tachometers, Accelerometers

Sensors for interaction with the environment: External sensors

- **Touch**
- **Force**
- **Pressure**
- **Slip**
- **Proximity**
- **Vision**

e.g. on/off switches, ultrasonic, force sensor, hall effect, inductive sensor, piezo sensor

Position Sensor : Potentiometer



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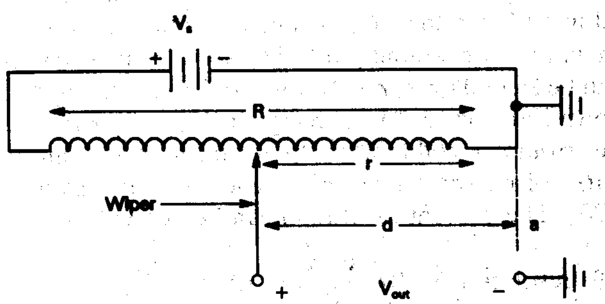
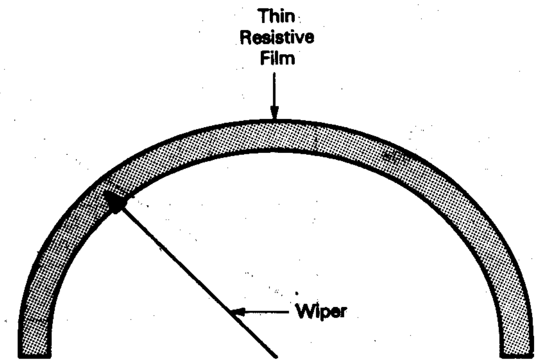
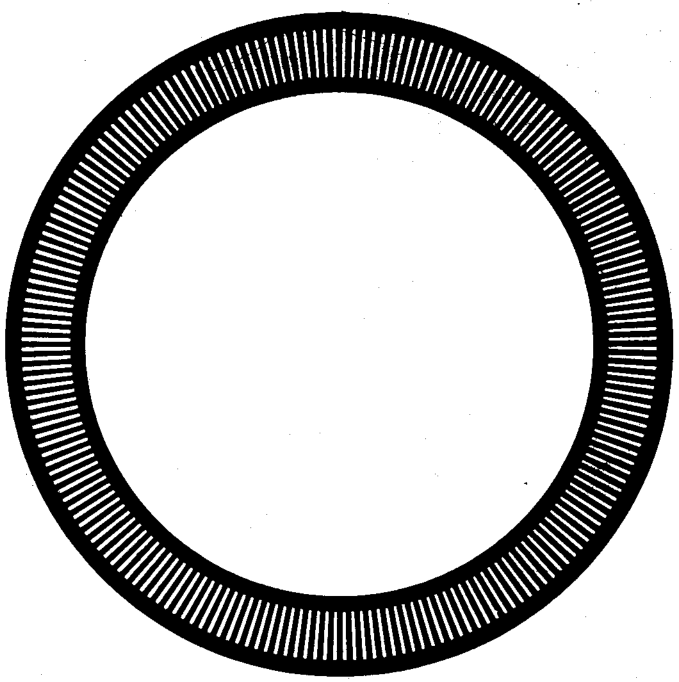
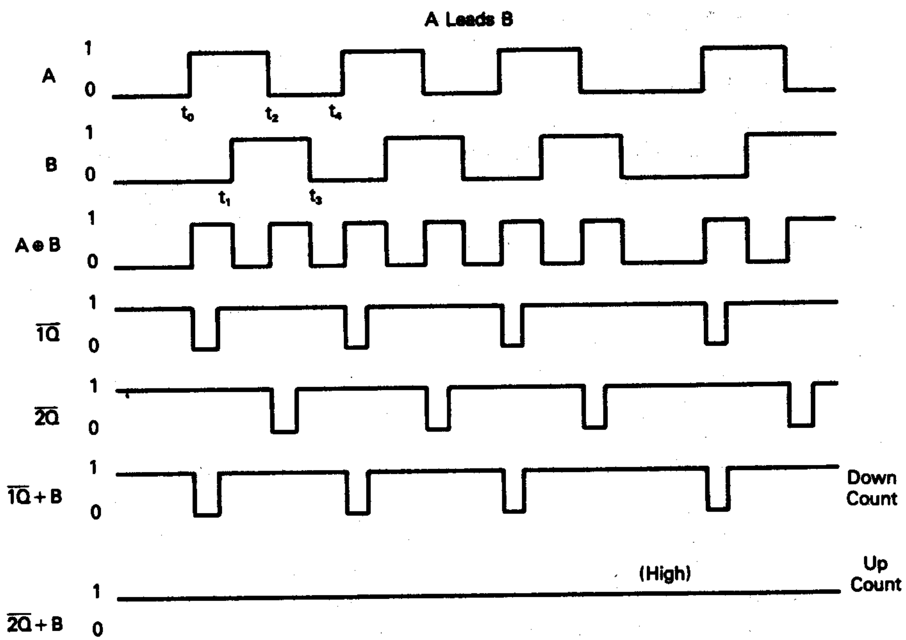


(b)



Position sensor: Incremental Encoder

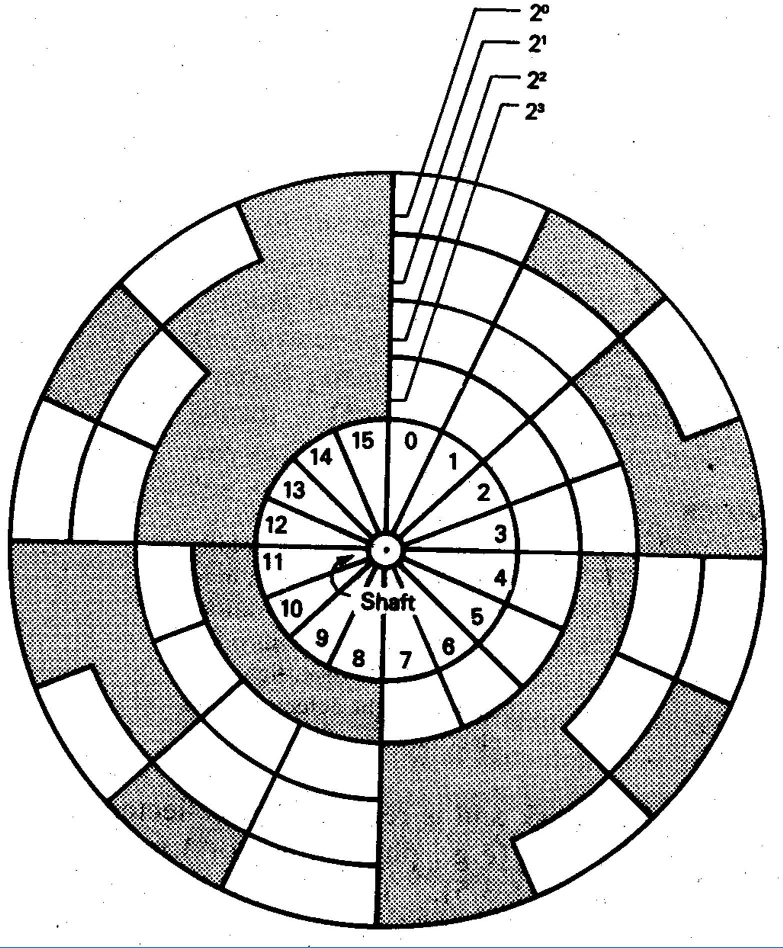




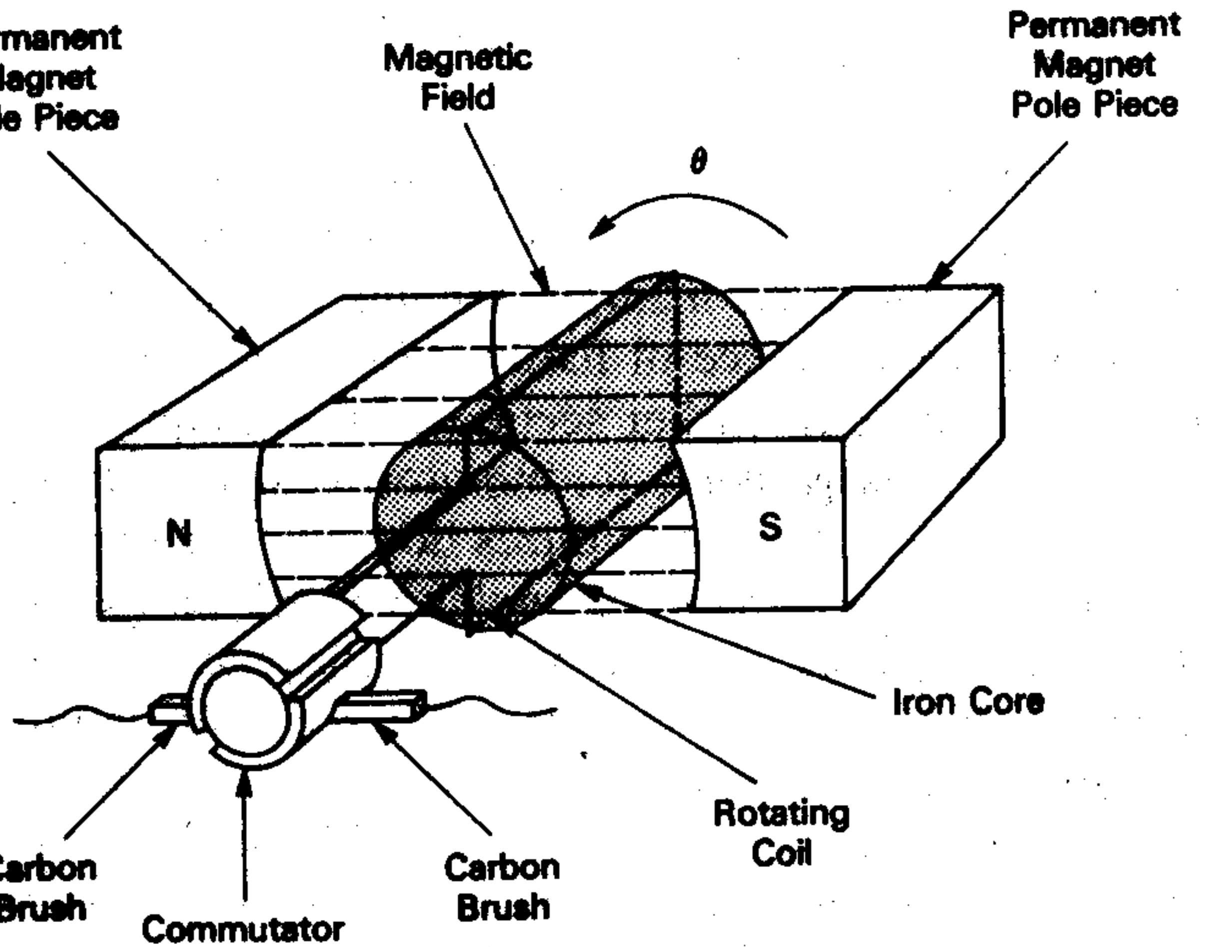
Using XOR gate

Position sensor : Absolute encoder

Grey code



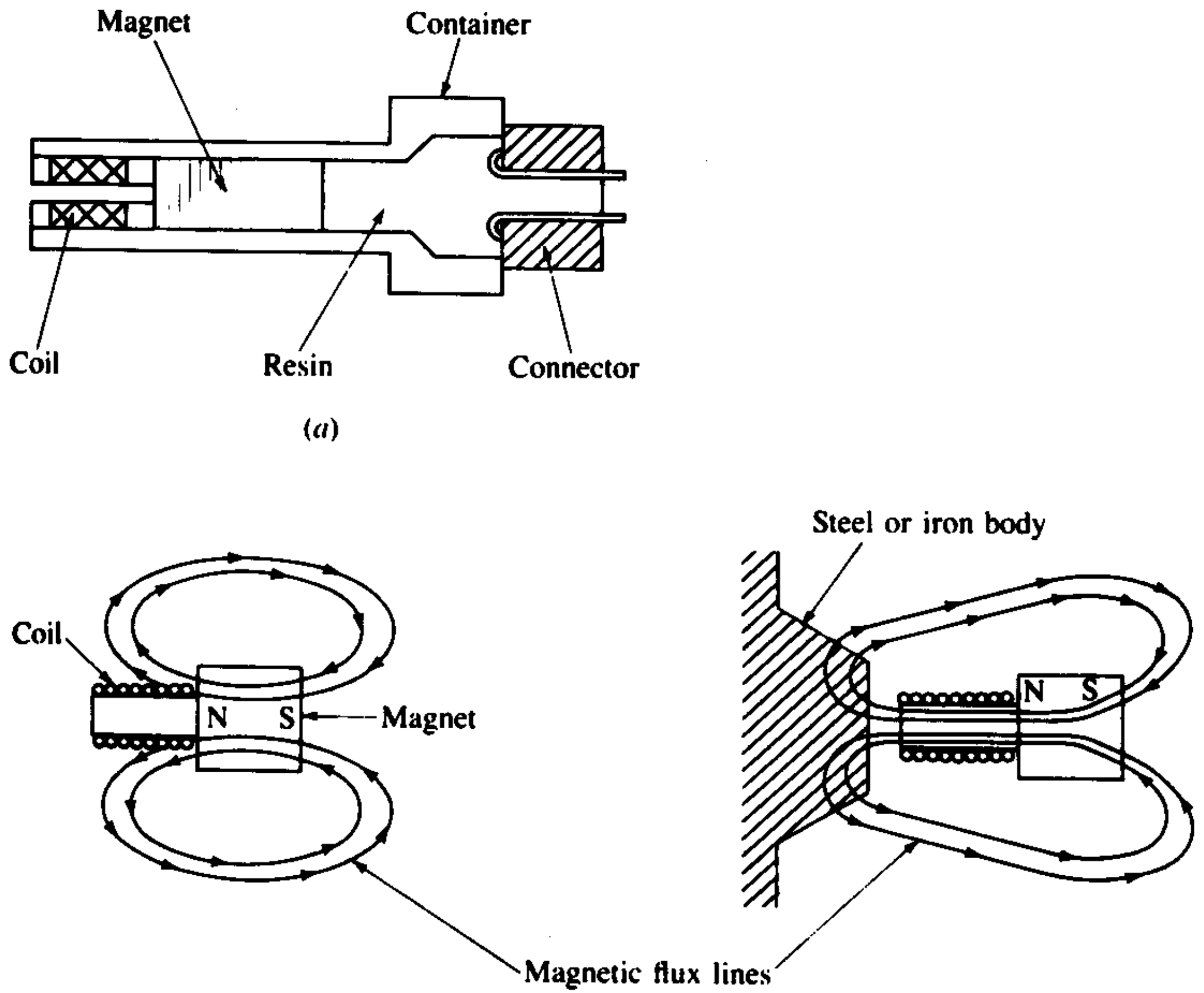
Velocity and acceleration sensors



Touch sensors

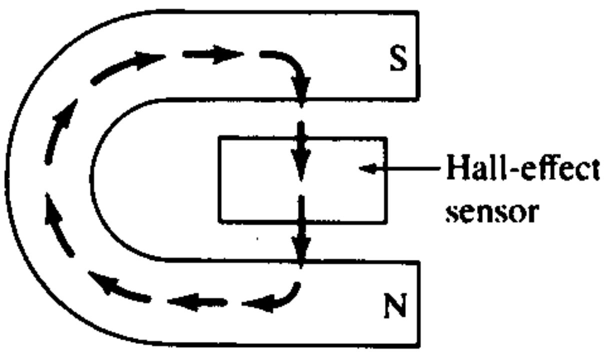
- On /Off switches
- Emitter / receiver pairs.
- Thermal / pressure sensors

Proximity sensor : Inductive sensor



(b) (c)

Proximity sensor: Hall effect sensor



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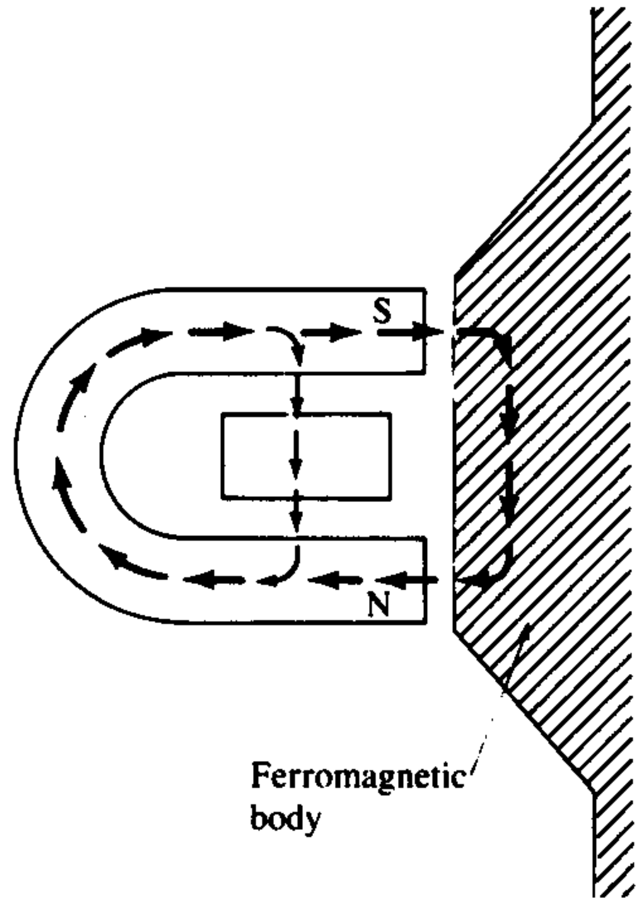
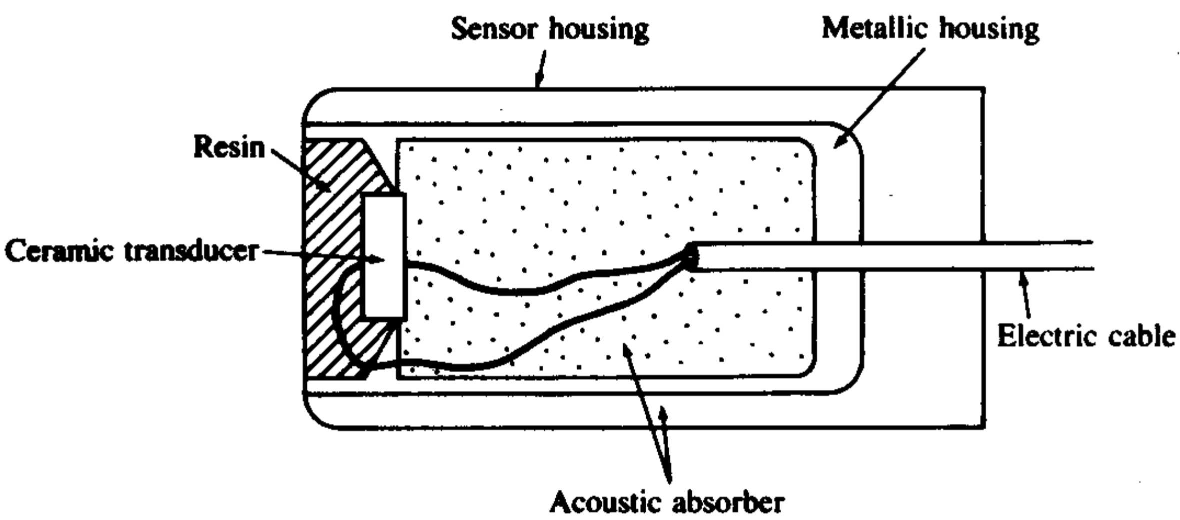
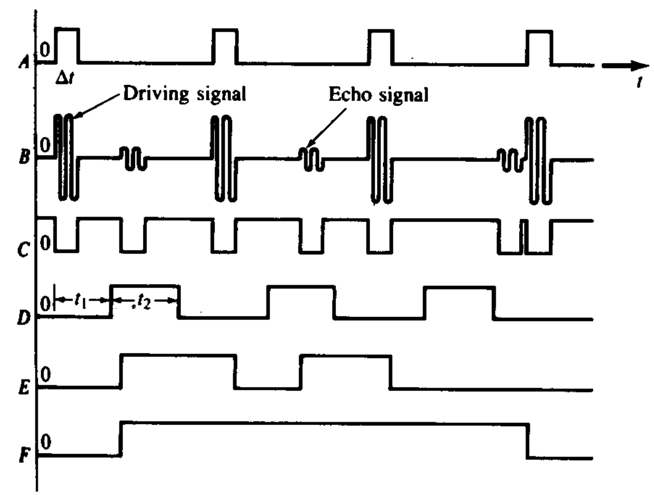


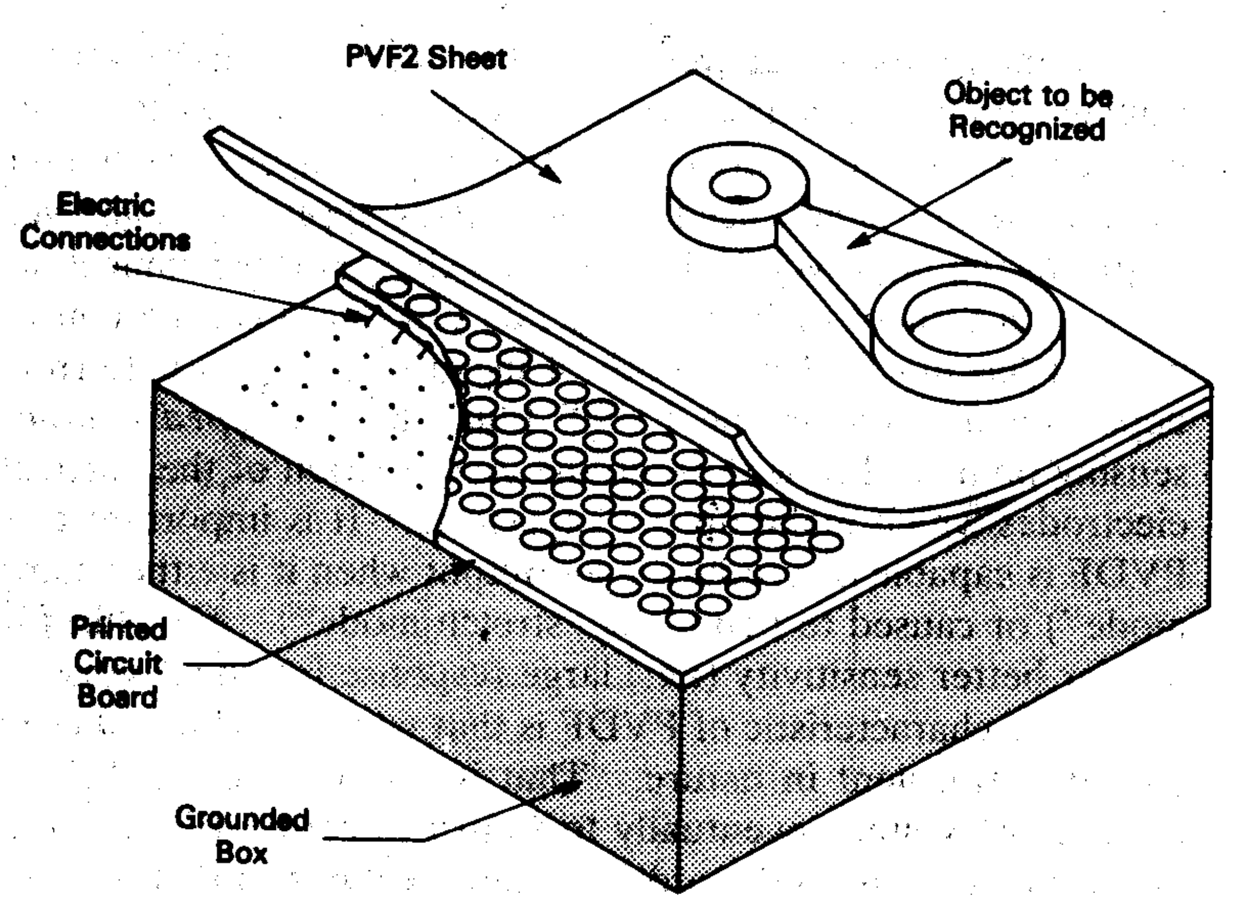
(b)

Range sensor : Ultrasonic sensor

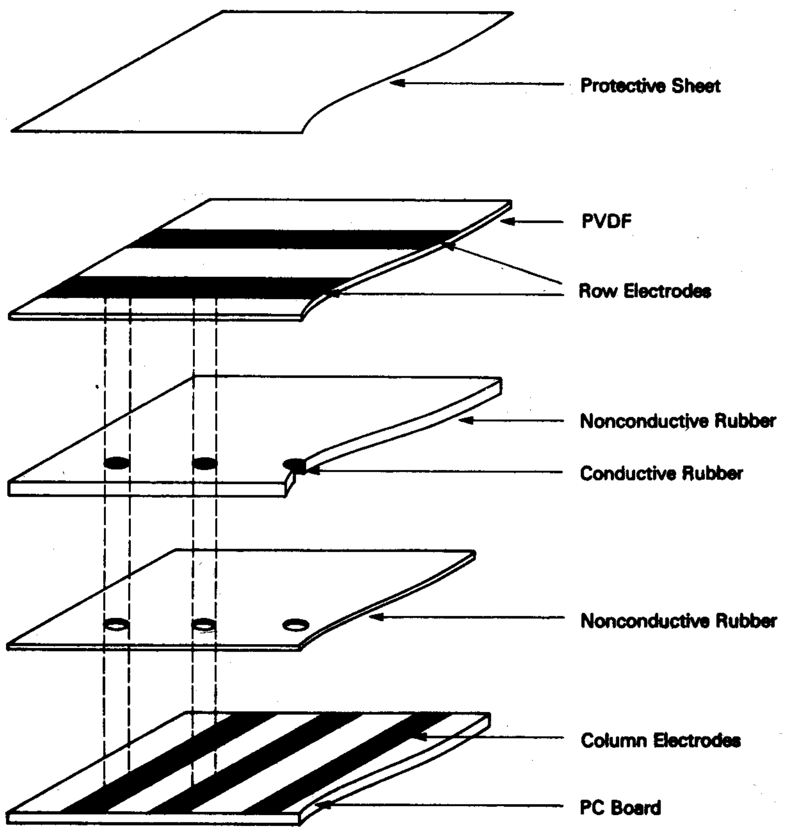


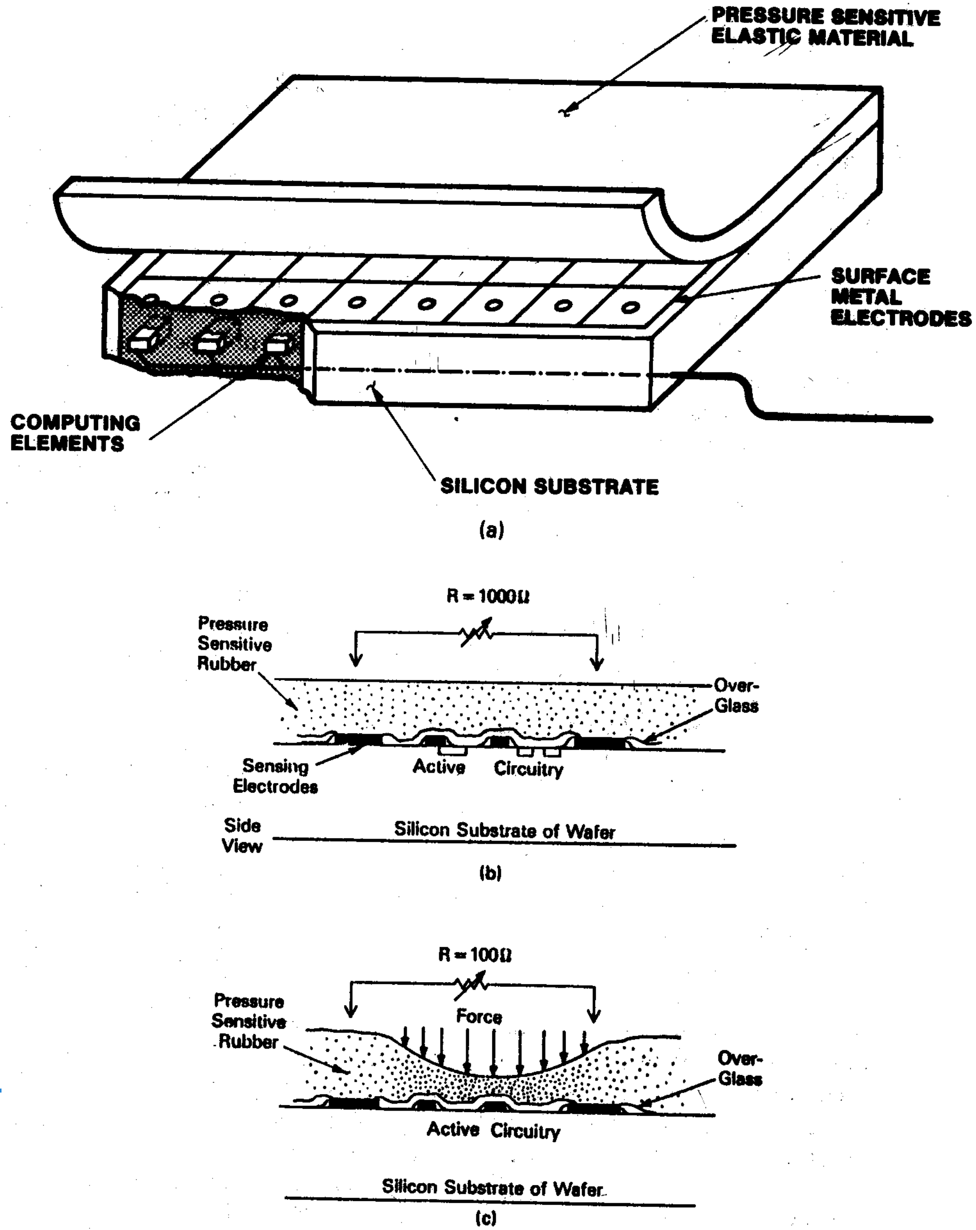


Touch sensor

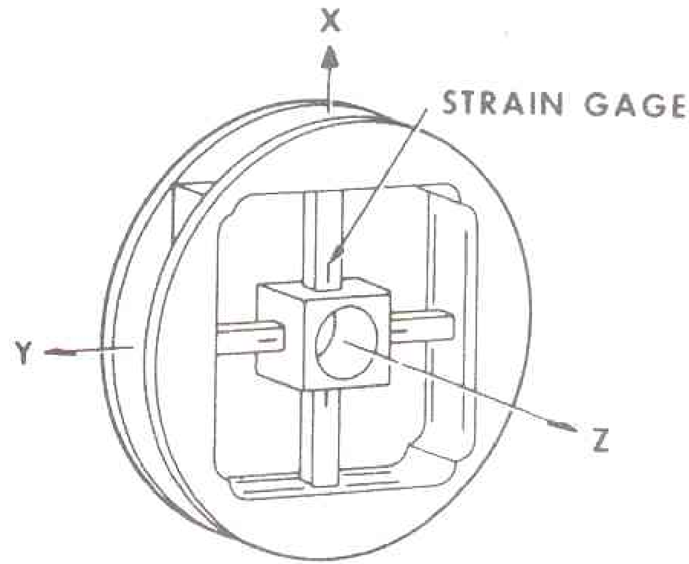


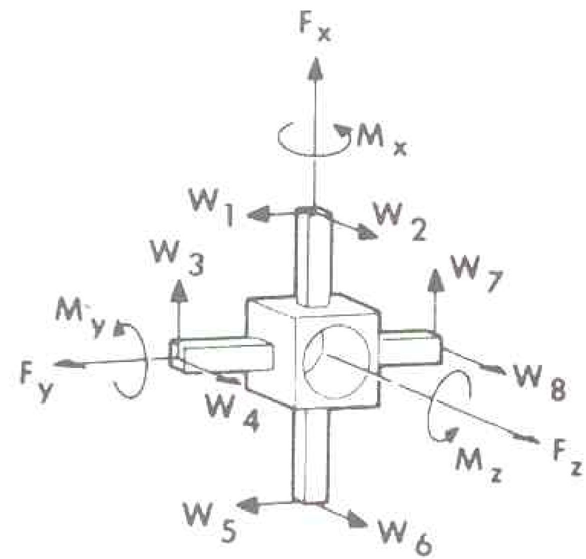
Pressure sensor





Force sensors





TRANSFORMATION MATRIX UNDER IDEAL CONDITIONS

FORCES AND TORQUES REFERENCED TO X-Y-Z SENSOR COORDINATES

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & k_{13} & 0 & 0 & 0 & k_{17} & 0 \\ k_{21} & 0 & 0 & 0 & k_{25} & 0 & 0 & 0 \\ 0 & k_{32} & 0 & k_{34} & 0 & k_{36} & 0 & k_{38} \\ 0 & 0 & 0 & k_{44} & 0 & 0 & 0 & k_{48} \\ 0 & k_{52} & 0 & 0 & 0 & k_{56} & 0 & 0 \\ k_{61} & 0 & k_{63} & 0 & k_{65} & 0 & k_{67} & 0 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ W_4 \\ W_5 \\ W_6 \\ W_7 \\ W_8 \end{bmatrix}$$

FORCES SENSED AT SPOKE ELEMENTS

Actuators

- *Electrical* : stepper motors, DC servo motors

- *Pneumatic* : air pressure

- *Hydraulic* : fluid pressure (oil pressure).

- *Advanced actuators* : ultrasonic motors, artificial muscles, molecular motors.

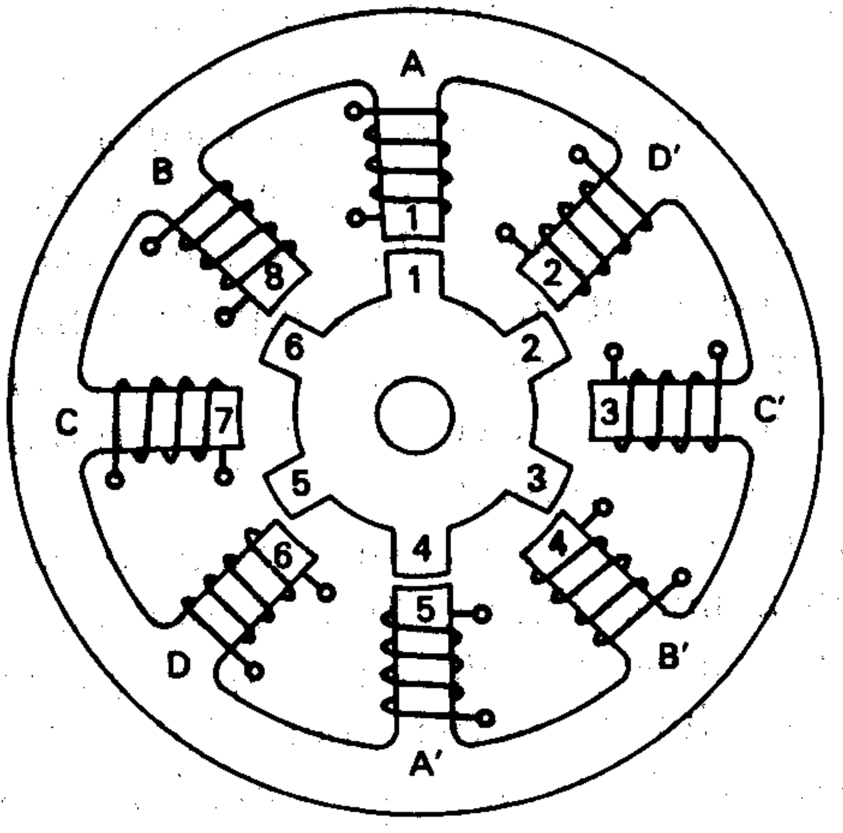
Mapping

Actuator Space

Joint Space

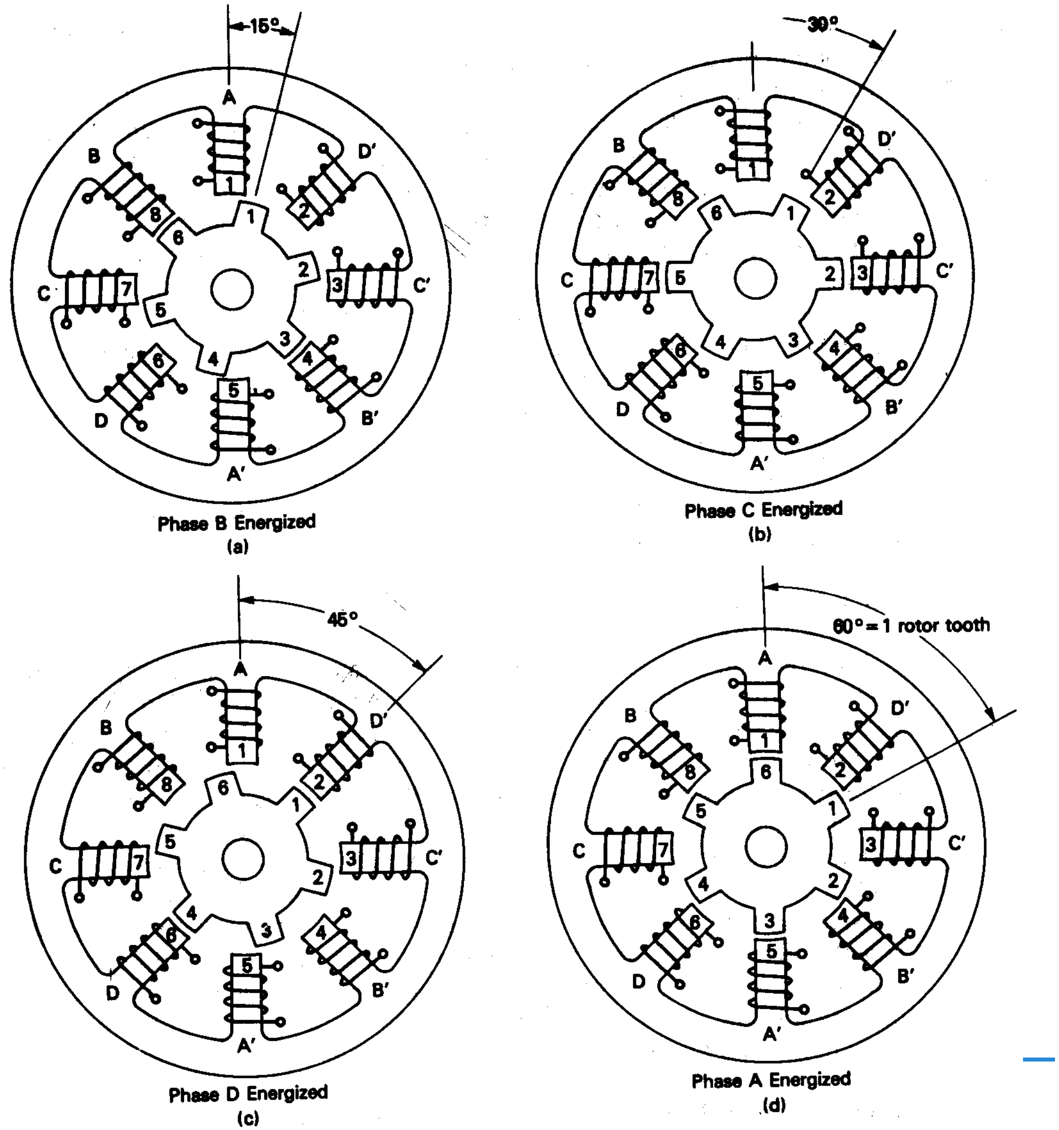
End effector Space

Stepper motors : Variable reluctance, permanent magnet

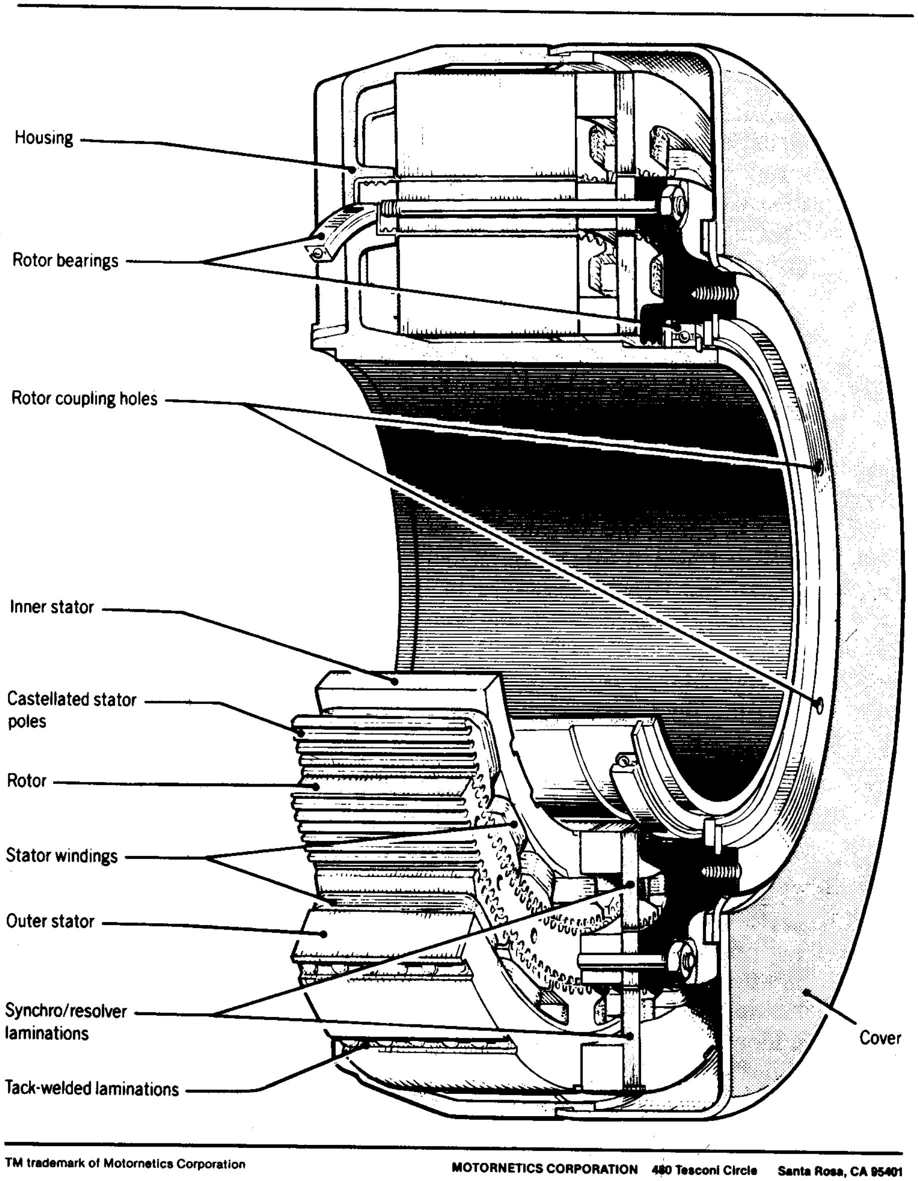


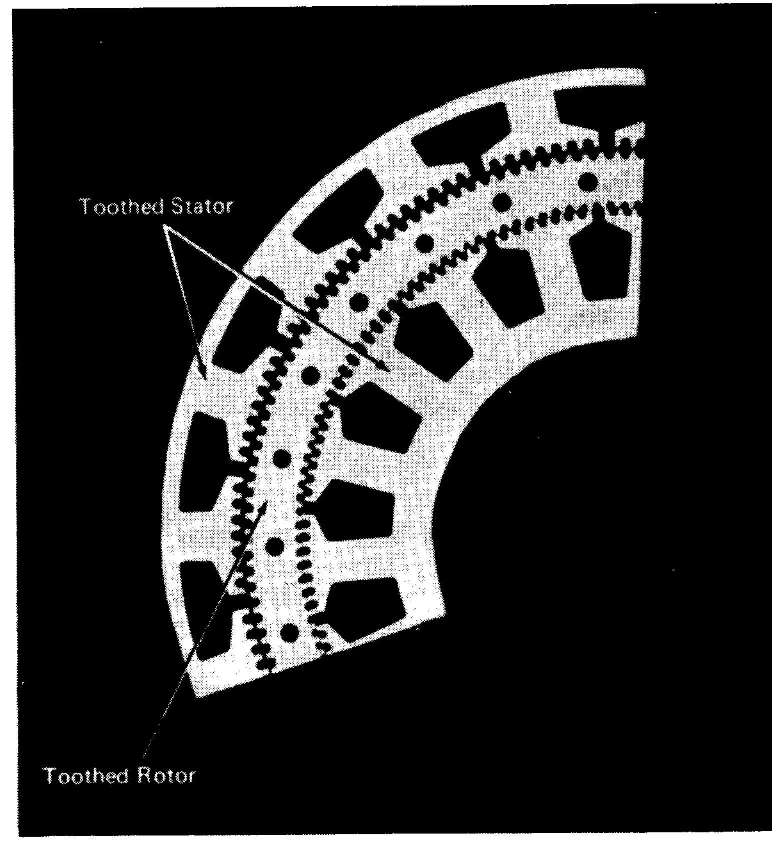
Working of a stepper motor

Sequence of rotation (CW): B – C – D - A’

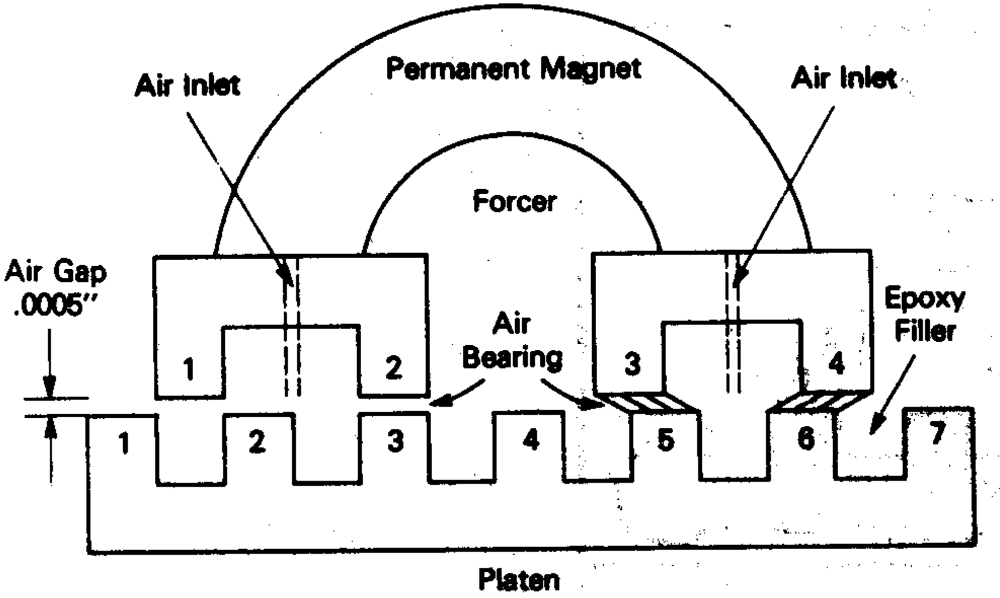


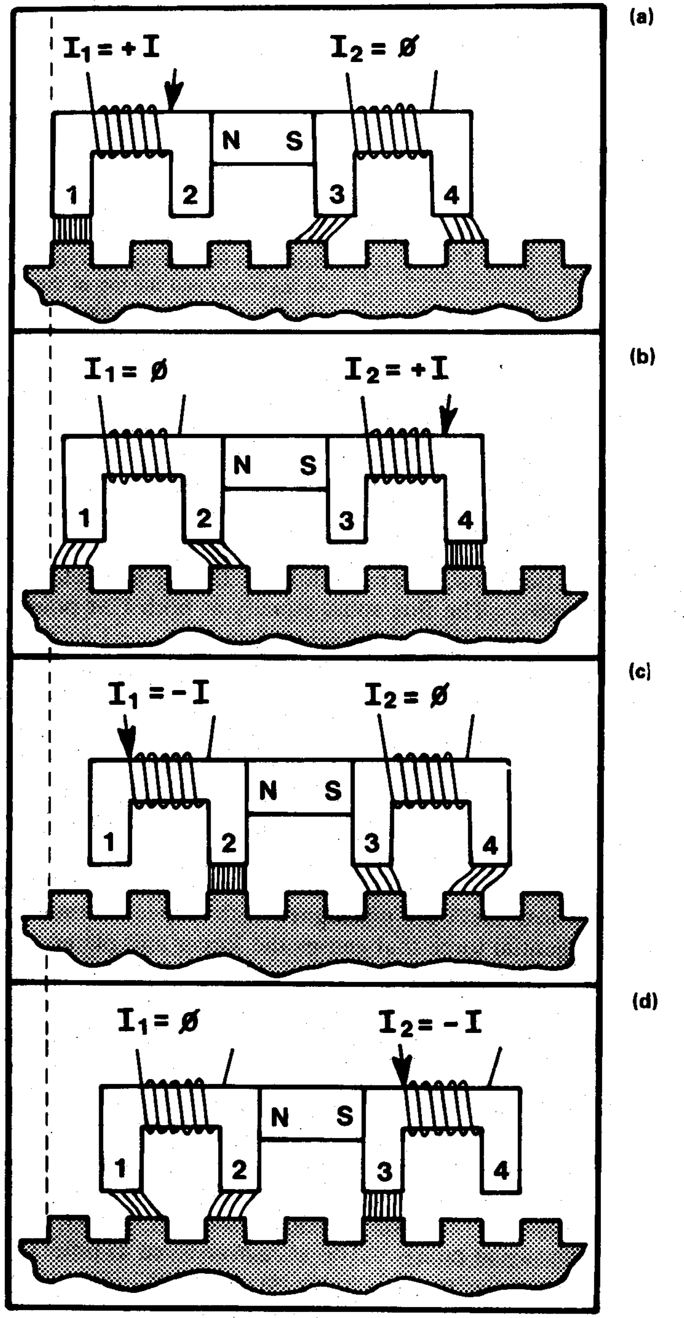
Mega-torque motors



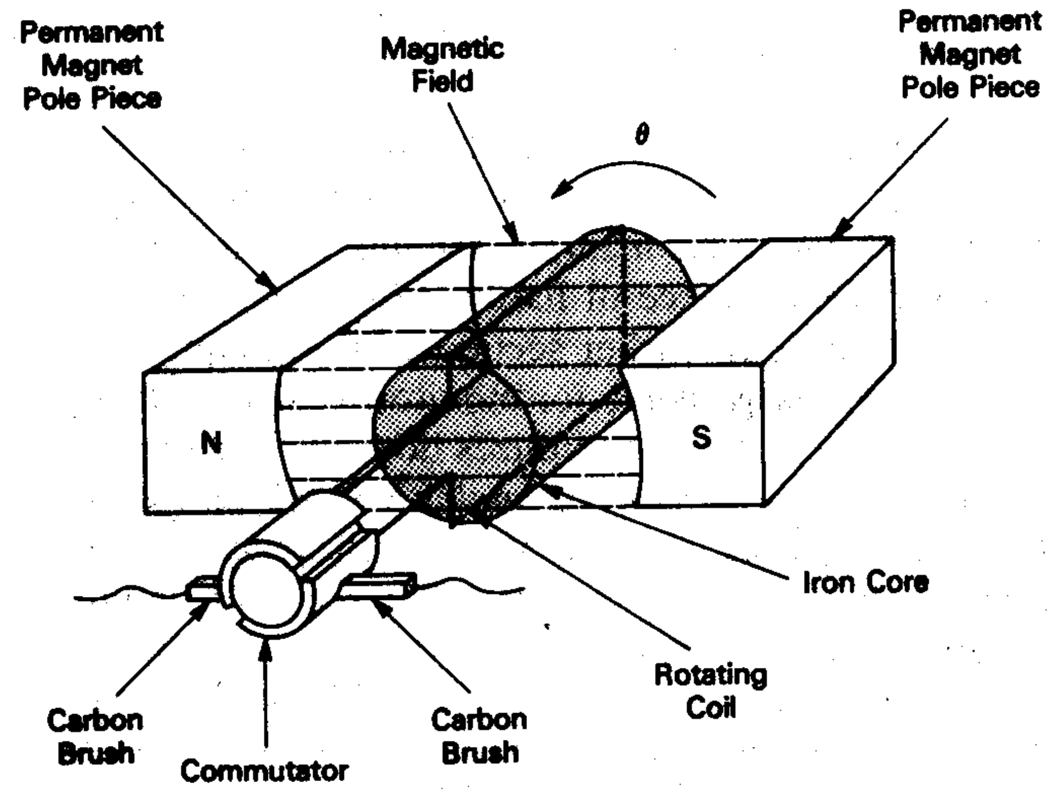


Linear stepper motor





DC Motors : basic working



Brushless DC motors

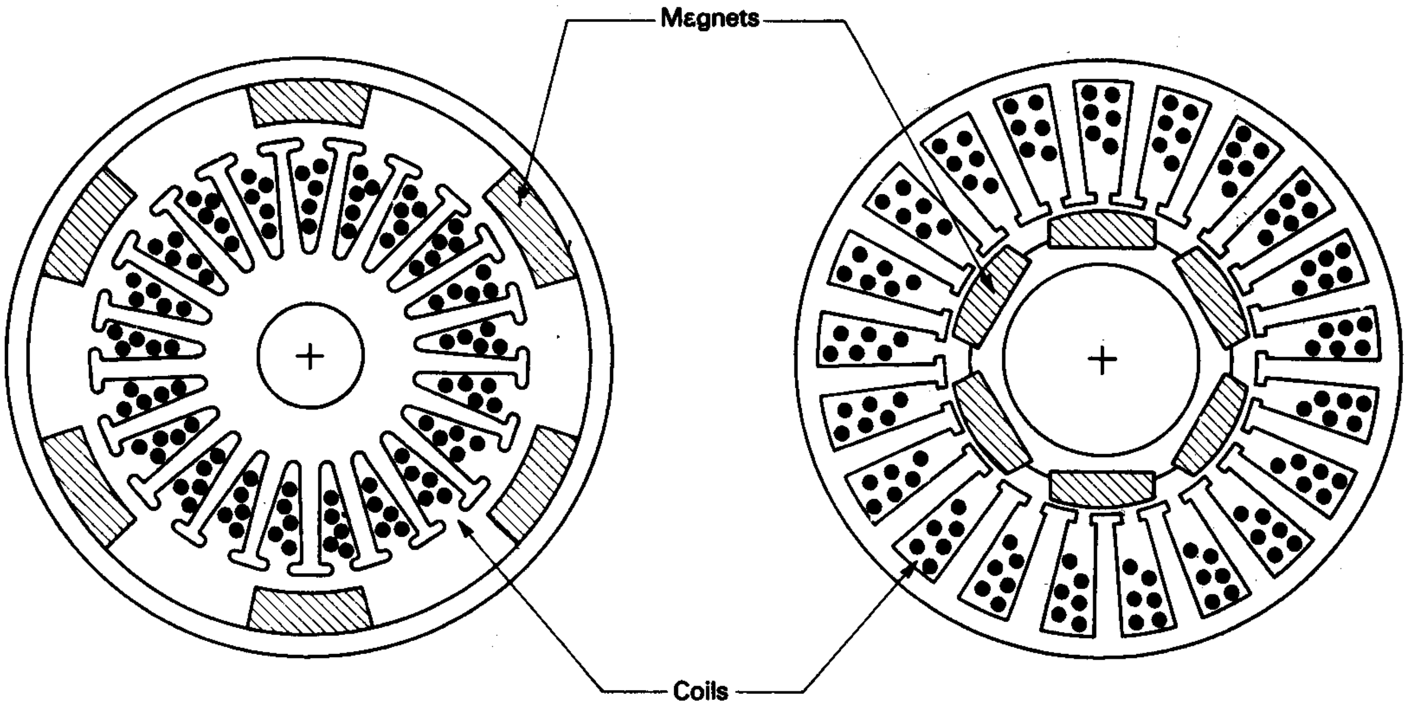
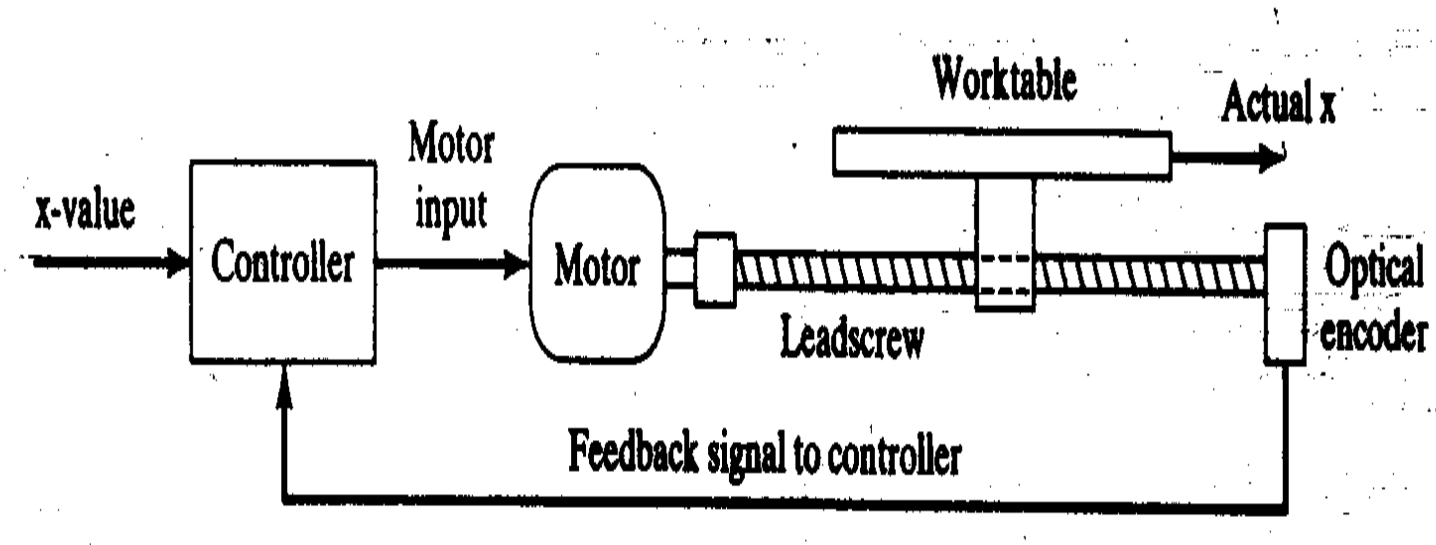


Fig. Brush type DC motor

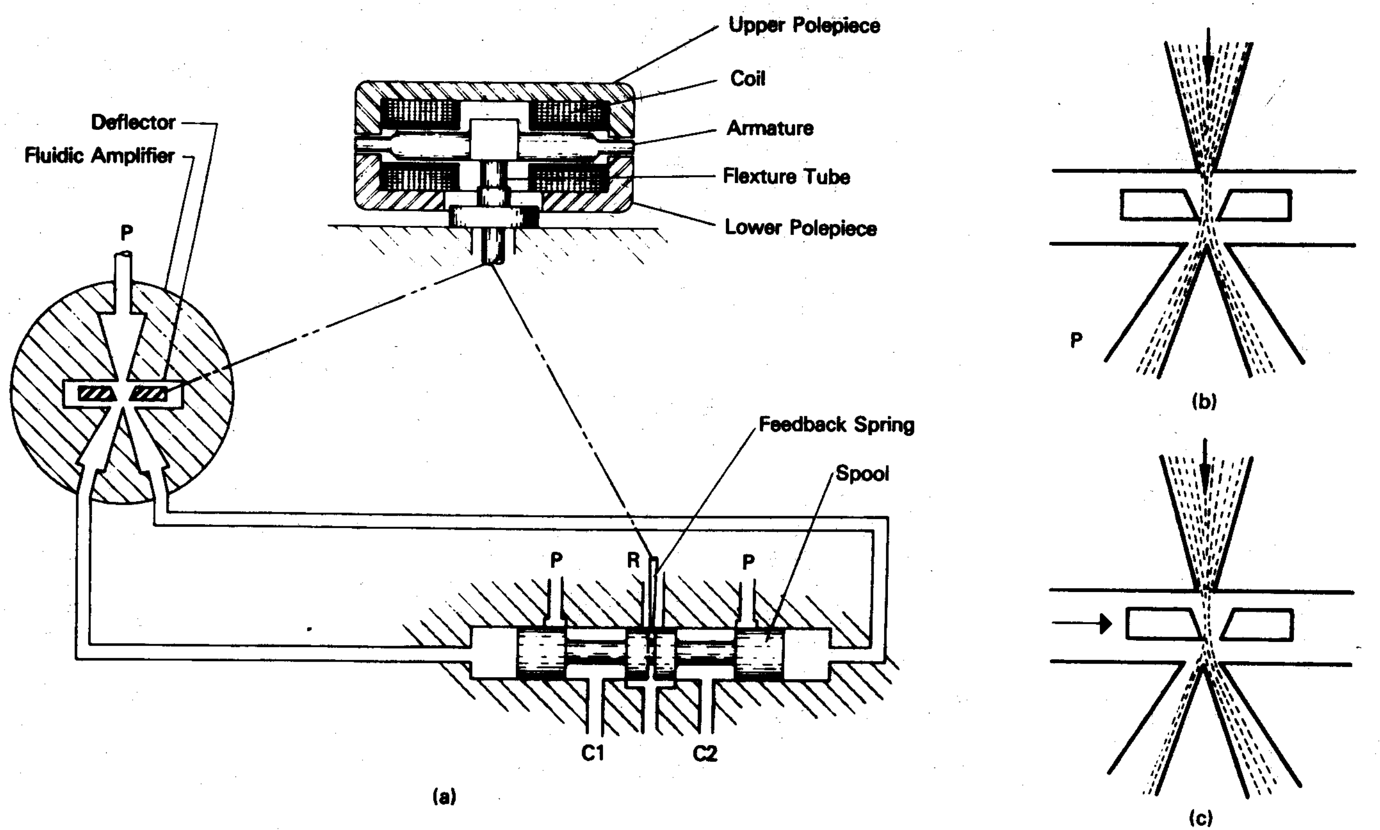
Fig. Brushless DC motor

DC servo motors

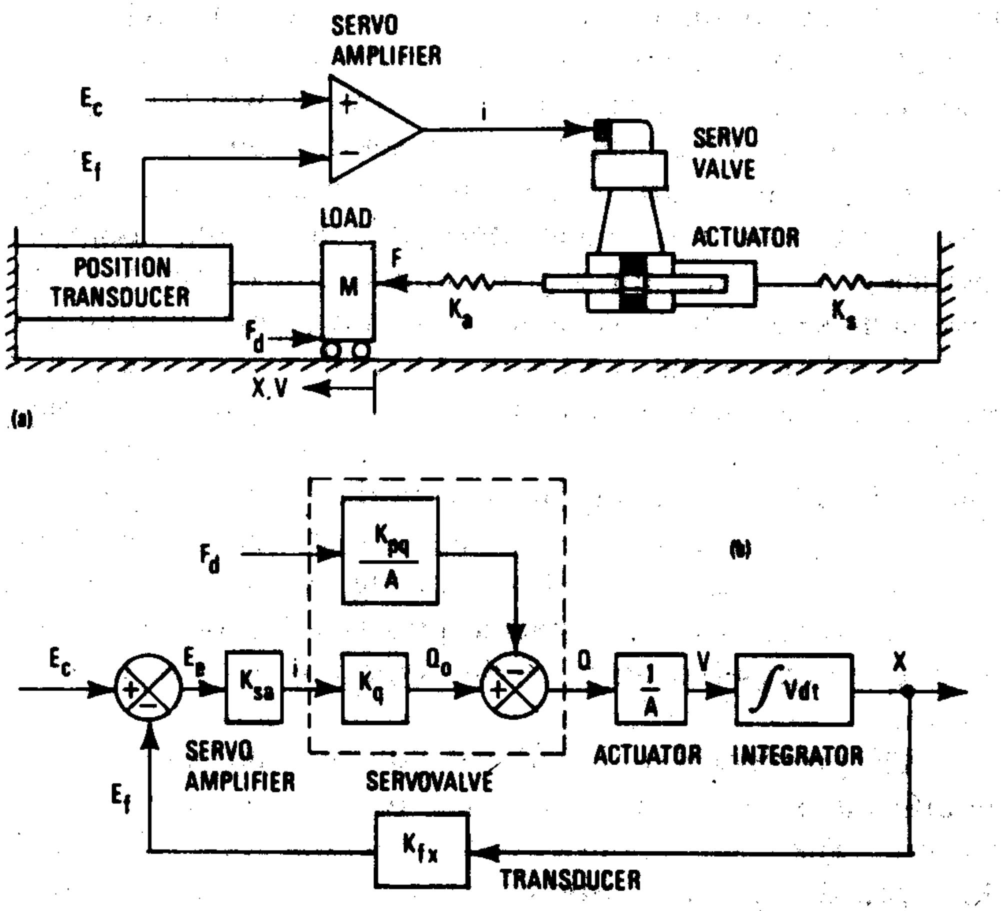
- DC motors working in closed loop position control.



Pneumatic actuators



Hydraulic actuators: piston cylinder mechanism



Advanced actuators: small, low power consumption, micro motion

- **Ultrasonic motors : micro robots, cameras, micro motion devices ..**
- **Artificial muscles : prosthetic, bio applications..**
- **Molecular motors : bio applications**

Ultrasonic motors

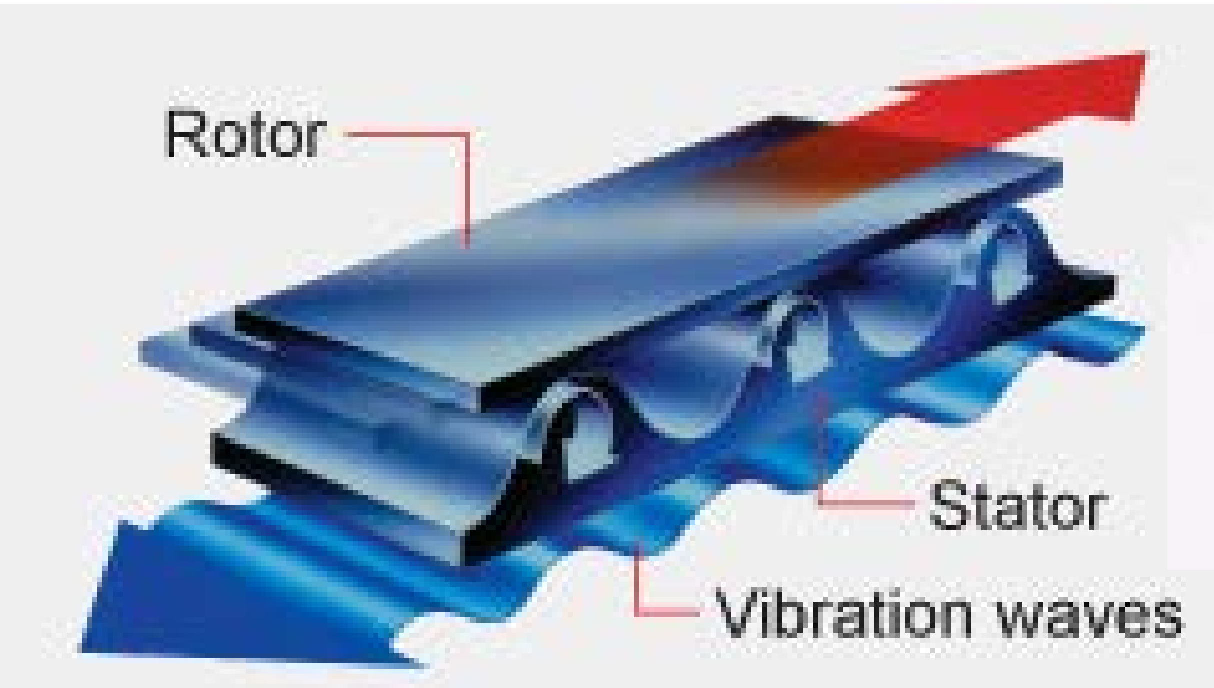


Fig. Motion due to dry friction and vibration.

Fig. Ring motors used in cameras.

Comparison of smart actuators

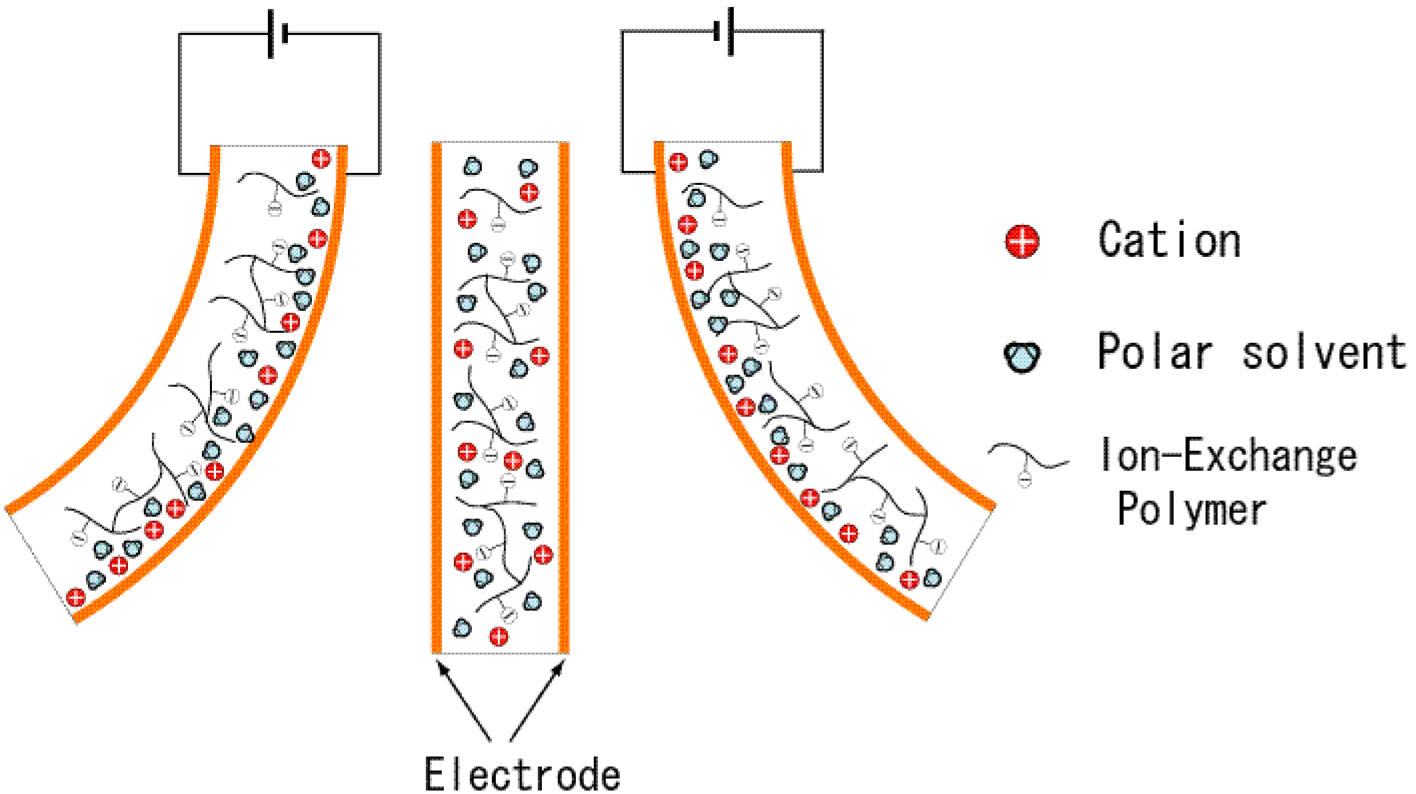
- **Piezo electric materials- large forces, small strains and fast response time.**
- **IPMCs- small forces, large straines, slower response times.**
- **(power) IPMC = (1/100) Natural Muscle.**

TABLE 1: Comparison of the properties of IPMC, SMA and EAC

Property	Ionic polymer-Metal Composites (IPMC)	Shape Memory Alloys (SMA)	Electroactive Ceramics (EAC)
Actuation displacement	>10%	<8% short fatigue life	0.1 - 0.3 %
Force (MPa)	10 - 30	about 700	30-40
Reaction speed	µsec to sec	sec to min	µsec to sec
Density	1- 2.5 g/cc	5 - 6 g/cc	6-8 g/cc
Drive voltage	4 - 7 V	NA	50 - 800 V
Power consumption	watts	watts	watts
Fracture toughness	resilient, elastic	elastic	fragile

Electro active Polymers

- Movement of ions and creations of micro channels.



IPMC motion

IPMC

- Ionomeric polymer metal composite (IPMC)

  - a polymer coated with a metal electrode.

  Material – Nafion 117

  Electrode – Platinum, Gold

  Electroplating by electrolysis

Working Mechanism

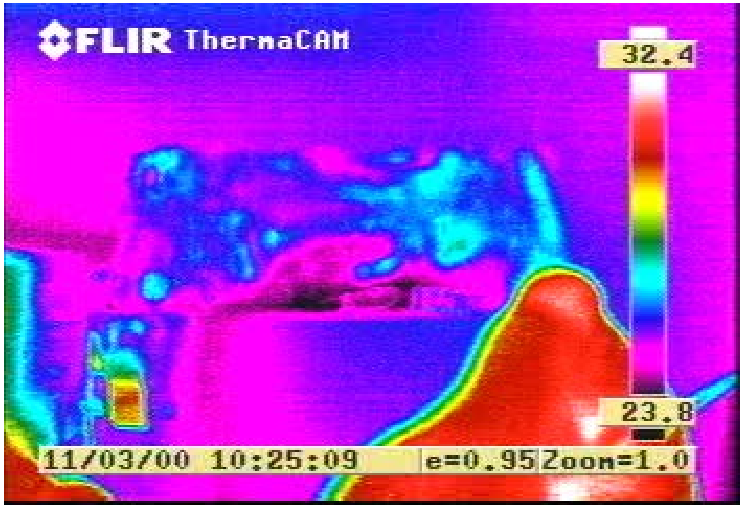
The actual mechanism at work in the polymers is debated.

- **Pressure gradients, electric fields, elastic deformation, ion transport etc.**

Two Theories

A. **Movement of Ions.**
B. **Creation of Micro- channels.**

Motion of Water in the IPMC



Modeling

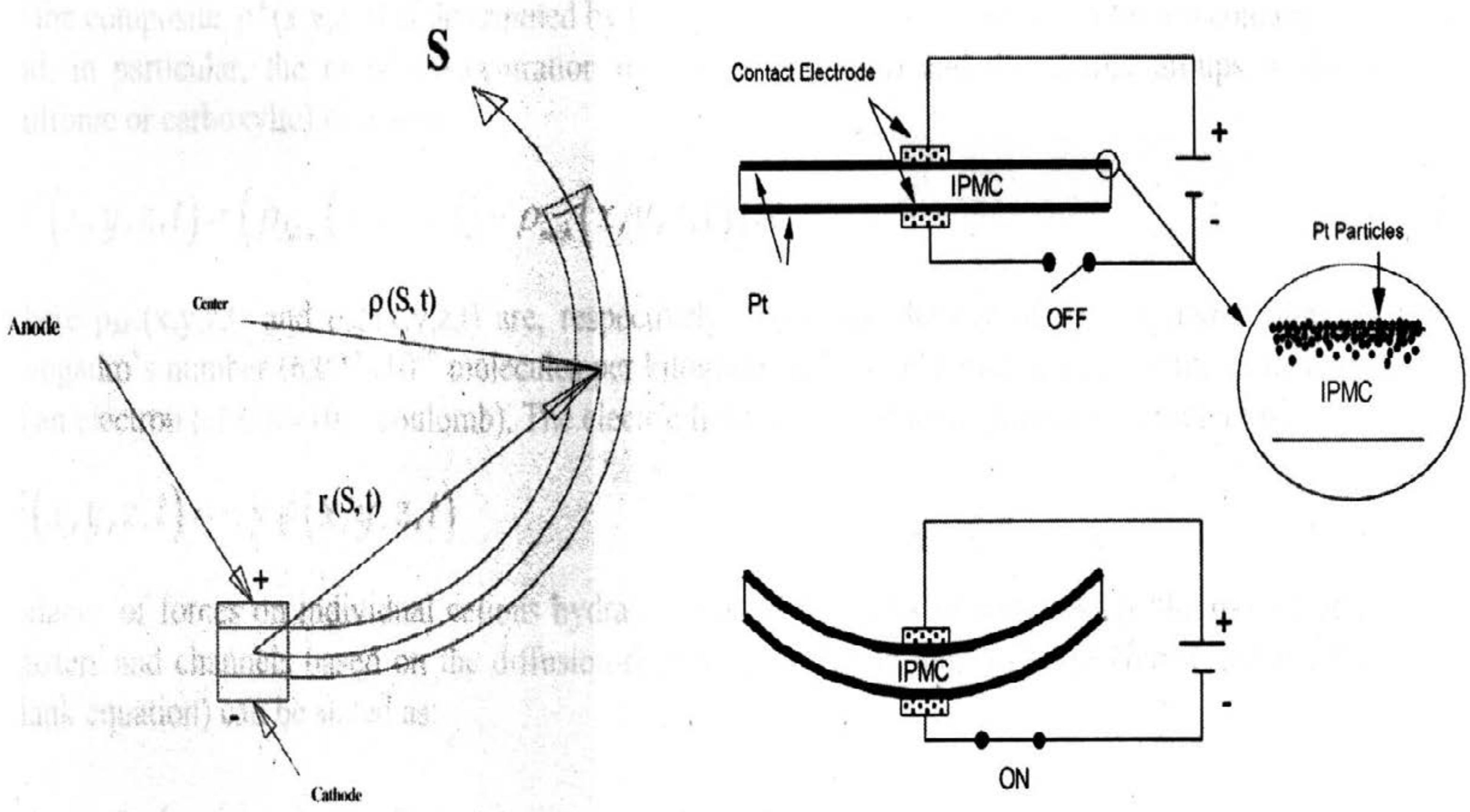


Fig. 9. Bending of an Ionic Gel Strip Due to an Imposed Electric Field Gradient

$$\rho^{*}(x,y,z,t)=\left(\rho_{M+}(x,y,z,t)-\rho_{so3}(x,y,z,t)\right)N_{e} \tag{2}$$

where φ(x,y,z,t) is an electric potential, ρ(x,y,z,t) is an electric charge density and ε is the dielectric constant of the composite. ρ*(x,y,z, t) is determined by the equivalent weight of the precursor ion containing polymer and, in particular, the molar concentration of cations (Lithium) and the charge groups in the polymer (sulfonic or carboxylic) such that:

$$\rho^{*}(x,y,z,t)=\left(\rho_{M+}(x,y,z,t)-\rho_{so3}(x,y,z,t)\right)N_{e} \tag{3}$$

where $\rho_{M+}(x,y,z,t)$ and $\rho_{so3}(x,y,z,t)$ are, respectively, the molal density of cations and sulfons, N is the Avogadro's number (6.023×10^{26} molecules per kilogram-mole in mks units), and e is the elementary charge of an electron (-1.602×10^{-19} coulomb). The electric field within the ionic polymeric structure is:

$$\underset{\sim}{E}(x,y,z,t)=-\nabla\phi(x,y,z,t) \tag{4}$$

Balance of forces on individual cations hydrated with n molecules of water inside the molecular network, clusters and channels based on the diffusion-drift model of ionic media due to Nernst and Plank (Nernst-Plank equation) can be stated as:

$$\begin{aligned} N_{e}\rho_{M+}E_{x}(x,y,z,t) &= N\left(\rho_{M+}M_{M+}+n\rho_{w}M_{w}\right)\left(\frac{dv_{x}}{dt}\right)+N\rho_{M+}\eta v_{x}+ \\ & N\rho_{M+}kT\left(\frac{\partial\ln(\rho_{M+}+n\rho_{w})}{\partial x}\right)+\left(\frac{\partial P}{\partial x}\right) \end{aligned} \tag{5}$$

$$\begin{aligned} N_{e}\rho_{M+}E_{y}(x,y,z,t) &= N\left(\rho_{M+}M_{M+}+n\rho_{w}M_{w}\right)\left(\frac{dv_{y}}{dt}\right)+N\rho_{M+}\eta v_{y}+ \\ & N\rho_{M+}kT\left(\frac{\partial\ln(\rho_{M+}+n\rho_{w})}{\partial y}\right)+\left(\frac{\partial P}{\partial y}\right) \end{aligned} \tag{6}$$

$$\begin{aligned} N_{e}\rho_{M+}E_{z}(x,y,z,t) &= N\left(\rho_{M+}M_{M+}+n\rho_{w}M_{w}\right)\left(\frac{dv_{z}}{dt}\right)+N\rho_{M+}\eta v_{z}+ \\ & N\rho_{M+}kT\left(\frac{\partial\ln(\rho_{M+}+n\rho_{w})}{\partial z}\right)+\left(\frac{\partial P}{\partial z}\right) \end{aligned} \tag{7}$$

$$kT\left(\frac{\partial \ln\left[\rho_{M+}(x,y,z,t)+n\rho_w(x,y,z,t)\right]}{\partial y}\right) \tag{13}$$

$$kT\left(\frac{\partial \ln\left[\rho_{M+}(x,y,z,t)+n\rho_w(x,y,z,t)\right]}{\partial z}\right) \tag{14}$$

and the force vector due to inertial effects on an individual hydrated cation is:

$$\left(M_{M+}+nM_w\right)\left(\frac{dv}{dt}\right) \tag{15}$$

such that in a compact vectorial form the force balance equation reads:

$$N_e\rho_{M+}\underset{\sim}{E}=N\left(\rho_{M+}M_{M+}+n\rho_w M_w\right)\left(\frac{d\underset{\sim}{v}}{dt}\right)+N\rho_{M+}\eta\underset{\sim}{v}+ \\ N\rho_{M+}kT\underset{\sim}{\nabla}\ln(\rho_M+n\rho_w)+\underset{\sim}{\nabla}P_f\cdot\underset{\approx}{\sigma}^* \tag{16}$$

where the stress tensor $\underset{\approx}{\sigma}^*$ can be expressed in terms of the deformation gradients in a non-linear manner such as in Neo-Hookean or Mooney-Rivlin type constitutive equations as suggested by Segalman, Adolf, Witkowski and Shahinpoor, [1991- 1993]. The flux of hydrated cations is given by:

$$\underset{\sim}{Q}=\left[\rho_{M+}(x,y,z,t)+\eta\rho_w(x,y,z,t)\right]\underset{\sim}{v}(x,y,z,t) \tag{17}$$

Such that the equation of continuity becomes:

$$\left(\frac{\partial\left[\rho_{M+}(x,y,z,t)+n\rho_w(x,y,z,t)\right]}{\partial t}\right)=-\underset{\sim}{\nabla}\underset{\sim}{Q} \tag{18}$$

$$e\underset{\sim}{E}(x,y,z,t)=\left[eE(x,y,z,t)_x,eE(x,y,z,t)_y,eE(x,y,z,t)_z\right]^t \tag{8}$$

is the force vector on an individual cation due to electro-osmotic motion of an ion in an electric field, k is the Boltzmann's constant and ,

$$\underset{\sim}{v}(x,y,z,t)=\left[v_x(x,y,z,t),v_y(x,y,z,t),v_z(x,y,z,t)_z\right]^T \tag{9}$$

is the velocity vector of the hydrated cations, and

$$\underset{\sim}{\nabla}p(x,y,z,t)=\frac{L}{K}\underset{\sim}{E}(x,y,z,t) \tag{10}$$

is the force vector of the viscous resistance to the motion of individual hydrated cations in the presence of a viscous fluid medium with a viscosity of η, and

$$kT\underset{\sim}{\nabla}\left[\ln(\rho_{M+}(x,y,z,t)+n\rho_w(x,y,z,t)\right] \tag{11}$$

is the force vector due to diffusion of individual cations and accompanying molecules of hydrated water in the polymer network with the following x, y, and z components, respectively:

$$kT\left(\frac{\partial\ln\left[\rho_{M+}(x,y,z,t)+n\rho_w(x,y,z,t)\right]}{\partial x}\right) \tag{12}$$

$$\underset{\sim}{\nabla} p(x,y,z,t) = \frac{L}{K} \underset{\sim}{E}(x,y,z,t) \tag{21}$$

This $\underset{\sim}{\nabla} p(x,y,z,t)$ will, in turn, induce a curvature $\underset{\sim}{\kappa}$ proportional to $\underset{\sim}{\nabla} p(x,y,z,t)$ The relationships between the curvature $\underset{\sim}{\kappa}$ and pressure gradient $\underset{\sim}{\nabla} p(x,y,z,t)$ are fully derived and described in de Gennes, Okumura, Shahinpoor and Kim [2000]. Let us just mention that $(1/\rho_c)$=**M**(**E**)/YI, where **M**(**E**) is the local induced bending moment and is a function of the imposed electric field E, Y is the Young's modulus (elastic stiffness) of the strip which is a function of the hydration H of the IPMC and I is the moment of inertia of the strip. Note that locally M(**E**) is related to the pressure gradient such that in a simplified scalar format:

$$\nabla\nabla p(x,y,z,t) = \left(\frac{2P}{t^*}\right) = \left(\frac{M}{I}\right) = \frac{Y}{\rho_c} = Y_{\underset{\sim}{K}} \tag{22}$$

Now from equation (22) it is clear that the vectorial form of curvature $\underset{\sim}{k}_E$ is related to the imposed electric field **E** by:

$$\underset{\sim}{k}_E \cong \left[\frac{2\underset{\sim}{\delta}_{\max}}{l_g^2 + \underset{\sim}{\delta}_{\max}^2}\right] \cong \frac{2\underset{\sim}{\delta}_{\max}}{l_g^2} \cong \left(\frac{L}{KY}\right)\underset{\sim}{E} \tag{23}$$

Based on this simplified model the tip bending deflection δ_{max} of an IPMC strip of length l_g should be almost linearly related to the imposed electric field due to the fact that:

$$\underset{\sim}{k}_E \cong \left[\frac{2\underset{\sim}{\delta}_{\max}}{l_g^2 + \underset{\sim}{\delta}_{\max}^2}\right] \cong \frac{2\underset{\sim}{\delta}_{\max}}{l_g^2} \cong \left(\frac{L}{KY}\right)\underset{\sim}{E} \tag{24}$$

Displacement verses voltage

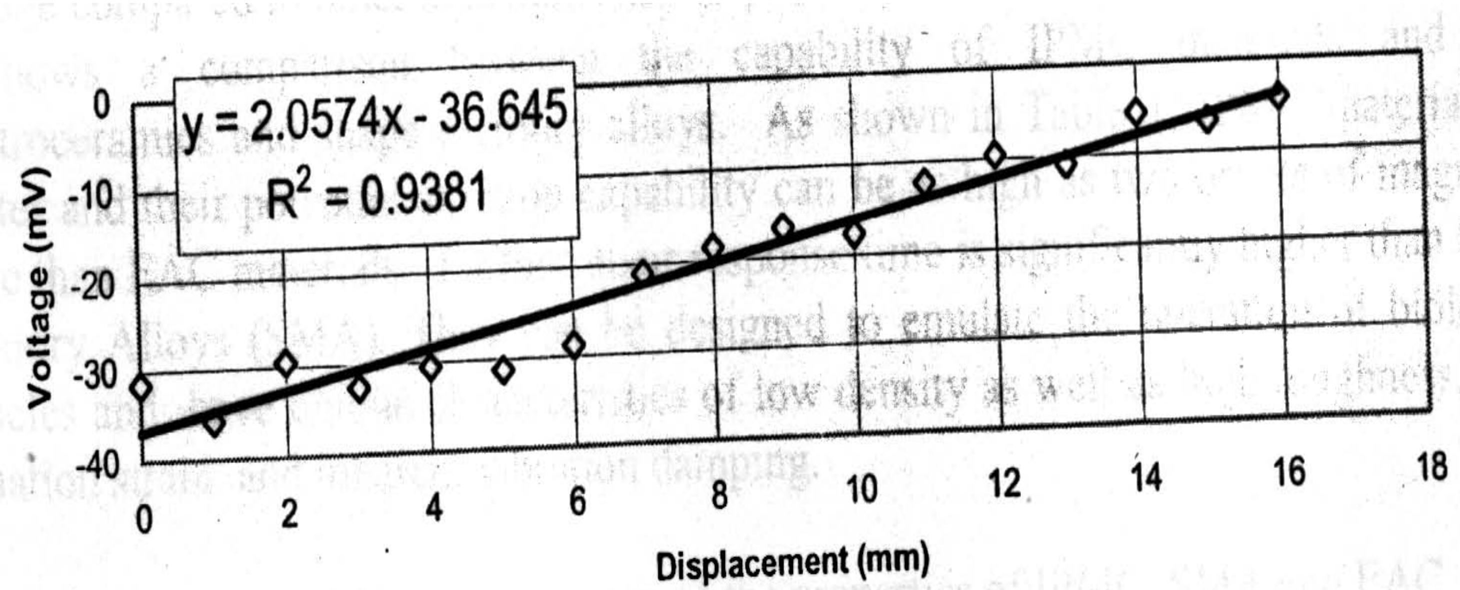


Figure 3. Inverted IPMC film sensor response for positive displacement input.

Artificial muscles

Fig. Hand.

Fig. Flying robot.

END

Molecular motors

Protein-based molecular motors harness the chemical free energy released by the hydrolysis of ATP in order to perform mechanical work.