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
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

(a) Diagram showing the components of an inductive sensor:
- Magnet
- Container
- Coil
- Resin
- Connector

(b) Diagram illustrating the magnetic flux lines:
- Coil
- Magnet
- Magnetic flux lines

(c) Diagram highlighting the steel or iron body:
- Steel or iron body
Proximity sensor: Hall effect sensor
Range sensor: Ultrasonic sensor
Touch sensor
Pressure sensor
**Force sensors**

![Diagram of a force sensor with strain gage and transformation matrix](image)

**Transformation Matrix Under Ideal Conditions**

\[
\begin{bmatrix}
    F_x \\
    F_y \\
    F_z \\
    M_x \\
    M_y \\
    M_z
\end{bmatrix}
= 
\begin{bmatrix}
    0 & 0 & k_{13} & 0 & 0 & 0 & k_{17} & 0 \\
    k_{21} & 0 & 0 & 0 & k_{25} & 0 & 0 & 0 \\
    0 & k_{32} & 0 & k_{34} & 0 & k_{36} & 0 & k_{38} \\
    0 & 0 & 0 & k_{44} & 0 & 0 & 0 & k_{48} \\
    0 & k_{52} & 0 & 0 & 0 & k_{56} & 0 & 0 \\
    k_{61} & 0 & k_{63} & 0 & k_{65} & 0 & k_{67} & 0
\end{bmatrix}
\]

\[
\begin{bmatrix}
    W_1 \\
    W_2 \\
    W_3 \\
    W_4 \\
    W_5 \\
    W_6 \\
    W_7 \\
    W_8
\end{bmatrix}
\]

**Forces and Torques**

**Forces and Torques Referenced to X-Y-Z Sensor Coordinates**
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 strains, slower response times.
- (power) IPMC = \( \frac{1}{100} \) Natural Muscle.

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

- Movement of ions and creations of micro channels.
IPMC motion
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
Fig. 9. Bending of an Ionic Gel Strip Due to an Imposed Electric Field Gradient
\[\rho^*(x,y,z,t) = (\rho_{M+}(x,y,z,t) - \rho_{s03}(x,y,z,t))N_e\]  

(2)

where \(\phi(x,y,z,t)\) is an electric potential, \(\rho(x,y,z,t)\) is an electric charge density and \(\epsilon\) is the dielectric constant of the composite. \(\rho^*(x,y,z,t)\) 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:

\[\rho^*(x,y,z,t) = (\rho_{M+}(x,y,z,t) - \rho_{s03}(x,y,z,t))N_e\]

(3)

where \(\rho_{M+}(x,y,z,t)\) and \(\rho_{s03}(x,y,z,t)\) are, respectively, the molar density of cations and sulfons, \(N\) is the Avogadro's number (6.023x10^{26} molecules per kilogram-mole in mks units), and \(e\) is the elementary charge of an electron (-1.602x10^{-19} coulomb). The electric field within the ionic polymeric structure is:

\[E(x,y,z,t) = -\nabla \phi(x,y,z,t)\]

(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:

\[N_e\rho_{M+}E_x(x,y,z,t) = N\left(\rho_{M+}M_{M+} + n\rho_wM_w\right)\left(\frac{dv_x}{dt}\right) + N\rho_{M+}\eta v_x + N\rho_{M+}kT\left(\frac{\partial \ln (\rho_{M+} + n\rho_w)}{\partial x}\right) + \left(\frac{\partial P}{\partial x}\right)\]

(5)

\[N_e\rho_{M+}E_y(x,y,z,t) = N\left(\rho_{M+}M_{M+} + n\rho_wM_w\right)\left(\frac{dv_y}{dt}\right) + N\rho_{M+}\eta v_y + N\rho_{M+}kT\left(\frac{\partial \ln (\rho_{M+} + n\rho_w)}{\partial y}\right) + \left(\frac{\partial P}{\partial y}\right)\]

(6)

\[N_e\rho_{M+}E_z(x,y,z,t) = N\left(\rho_{M+}M_{M+} + n\rho_wM_w\right)\left(\frac{dv_z}{dt}\right) + N\rho_{M+}\eta v_z + N\rho_{M+}kT\left(\frac{\partial \ln (\rho_{M+} + n\rho_w)}{\partial z}\right) + \left(\frac{\partial P}{\partial z}\right)\]

(7)
\[ kT \left( \frac{\partial \ln [\rho\, (x, y, z, t) + n\rho\, (x, y, z, t)]}{\partial y} \right) \]

\[ kT \left( \frac{\partial \ln [\rho\, (x, y, z, t) + n\rho\, (x, y, z, t)]}{\partial z} \right) \]

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

\[ (M_{M+} + nM_w) \left( \frac{dv}{dt} \right) \]

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

\[ N_c \rho\, E = N \left( \rho\, M_{M+} + n\rho\, M_w \right) \left( \frac{dv}{dt} \right) + N\rho\, \eta v + \]

\[ N\rho\, kT\nabla \ln (\rho\, + n\rho_w) + \nabla P\, \cdot \, \sigma^* \]

where the stress tensor \( \sigma^* \) 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:

\[ \zeta = \left[ \rho\,(x, y, z, t) + \eta\rho\, (x, y, z, t) \right] \psi(x, y, z, t) \]

Such that the equation of continuity becomes:

\[ \left( \frac{\partial [\rho\, (x, y, z, t) + n\rho\, (x, y, z, t)]}{\partial t} \right) = -\nabla \zeta \]
$$e\mathbf{E}(x,y,z,t) = \begin{bmatrix} eE(x,y,z,t)_x, eE(x,y,z,t)_y, eE(x,y,z,t)_z \end{bmatrix}^t$$  \hspace{1cm} (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,

$$\mathbf{v}(x,y,z,t) = \begin{bmatrix} v_x(x,y,z,t), v_y(x,y,z,t), v_z(x,y,z,t) \end{bmatrix}^t$$  \hspace{1cm} (9)$$

is the velocity vector of the hydrated cations, and

$$\nabla p(x,y,z,t) = \frac{L}{K} E(x,y,z,t)$$  \hspace{1cm} (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 $\eta$, and

$$kT \nabla \left[ \ln(\rho_{M^+}(x,y,z,t) + n\rho_w(x,y,z,t)) \right]$$  \hspace{1cm} (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:

$$kT \left( \frac{\partial \ln[\rho_{M^+}(x,y,z,t) + n\rho_w(x,y,z,t)]}{\partial x} \right)$$  \hspace{1cm} (12)$$
\[ \nabla p(x, y, z, t) = \frac{L}{K} \varepsilon(x, y, z, t) \]  

This \( \nabla p(x, y, z, t) \) will, in turn, induce a curvature \( \xi \) proportional to \( \nabla p(x, y, z, t) \). The relationships between the curvature \( \xi \) and pressure gradient \( \nabla p(x, y, z, t) \) 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:

\[ \nabla \nabla p(x, y, z, t) = \left( \frac{2P}{t^*} \right) = \left( \frac{M}{I} \right) = \frac{Y}{\rho_c} = Y \xi \]  

Now from equation (22) it is clear that the vectorial form of curvature \( \xi_E \) is related to the imposed electric field \( E \) by:

\[ k_{\xi_E} \equiv \frac{2 \delta_{\text{max}}}{l_g^2 + \delta_{\text{max}}^2} \cong \frac{2 \delta_{\text{max}}}{l_g^2} \cong \frac{L}{KY} E \]  

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

\[ k_{\xi_E} \equiv \frac{2 \delta_{\text{max}}}{l_g^2 + \delta_{\text{max}}^2} \cong \frac{2 \delta_{\text{max}}}{l_g^2} \cong \frac{L}{KY} E \]
Displacement verses voltage

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

Fig. Hand.

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