Biomedical Measurements in Embedded Applications
Electronic Measurements in Biomedical Engineering

**Electronic Measurement Systems**

**Analog domain systems**

Sensor (transducer)
- Physiological property of tissue $\rightarrow$ electrical signals

Amplifier
- Sensor output $\rightarrow$ input requirements of measuring system

Analog filter
- Amplifier output $\rightarrow$ information of interest

Analog to digital converter (A/D)
- Signal $\rightarrow$ binary coded sample sequence

**Digital domain systems**

Microcontroller
- Process automation: measurement $\rightarrow$ display process

Digital signal processing (DSP)
- Digital domain filtering

Storage
- Interface $\rightarrow$ information systems
Physiological Measurements

**Mechanical**

General physical measurement

Examples

Length, weight, pressure, temperature, motion

**Electrical / chemical**

Contact with tissue → electrical signal

Examples

EKG, EEG, blood glucose

**Imaging**

Stimulate tissue — pressure, sound, electromagnetic waves

Detect induced emissions

Examples

Ultrasound, X-ray, infrared, MRI
Electromagnetism

**Force on charged particle**

\[ \mathbf{F} = q[\mathbf{E} + \mathbf{u} \times \mathbf{B}] \], \quad \text{charge } q, \text{ electric field } \mathbf{E}, \text{ magnetic field } \mathbf{B}, \text{ velocity } \mathbf{u} 

**Voltage (potential)**

Measure of work performed against electric force \( \mathbf{F} \)

\[ v_{AB} = \text{work required to push unit charge (} q = 1 \text{) from A to B} \]

Analogous to pressure in a water pipe

**Ground**

Reference point for measuring voltage

\[ v_B = \text{voltage from ground to point } B \]

**Current**

Measure of motion of charged particles

\[ i = \text{total charge crossing unit area per second} \]

Analogous to flow in a water pipe
Electric Circuit Concepts

**Functions of time**

**Voltage** $v(t)$
- Measured from ground: $v_1 = v_{1G}$, $v_2 = v_{2G}$
- Current $i(t)$

**Voltage drop**
- Pushing current $\rightarrow$ perform work $\rightarrow$ loss of voltage

**Voltage source**
- Power supply = source of energy for work = – drop

**Kirchhoff laws (graph theory)**
- Sum of currents entering any node = 0
  $$i_1 - i_2 - i_3 = 0$$
- Sum of voltage drops around any loop = 0
  $$-v_1 + v_{\text{drop}} + v_2 = 0$$
Electrical Circuit Elements

**Conductor**
Carries current with voltage drop $\rightarrow 0$

**Resistor**
Current $i(t)$ causes voltage drop $v(t) = R \times i(t)$
Resistance $R$

**Capacitor**
Current $i = C \times \frac{dv}{dt}$
Capacitance $C$

**Inductor**
Voltage drop $v = L \times \frac{di}{dt}$
Inductance $L$

**Example — resistor elements $R_A$ and $R_B$**

\[
\begin{align*}
\phantom{\text{Example — resistor elements } R_A \text{ and } R_B} \\
i_1 &= i_2 = i \\
v_1 &= v_A + v_B = iR_A + iR_B \Rightarrow i = \frac{v_1}{R_A + R_B} \Rightarrow v_B = iR_B = \frac{R_B}{R_A + R_B} v_1 \\
\frac{v_B}{v_1} &= \frac{R_B}{R_A + R_B}
\end{align*}
\]
Frequency Domain Analysis

**General circuit**

Ordinary differential equations with respect to time

**Example**

Inductor $L_A$ and resistor $R_B$

\[ i_1 = i_2 = i \]

\[ v_1 = v_A + v_B = L_A \frac{di}{dt} + iR_B \]

**Fourier transform**

\[ v(t) = \int_{-\infty}^{\infty} V(\omega)e^{j\omega t} \, dt \iff V(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} v(t)e^{-j\omega t} \, d\omega \]

\[ i(t) = \int_{-\infty}^{\infty} I(\omega)e^{j\omega t} \, dt \iff I(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} i(t)e^{-j\omega t} \, d\omega \]

\[ v_1(t) = L_A \frac{di}{dt} + iR_B \rightarrow \quad V_1(\omega) = j\omega I(\omega)L_A + I(\omega)R_B \quad \Rightarrow \quad I(\omega) = \frac{V_1(\omega)}{R_B + j\omega L_A} \]

\[ V_B(\omega) = \frac{R_B}{R_B + j\omega} V_1(\omega) \quad \Rightarrow \quad \left| \frac{V_B(\omega)}{V_1(\omega)} \right| = \frac{R_B}{\sqrt{R_B^2 + \omega^2 L_A^2}} \]
Frequency and Analog Filters

**Low pass filter**

Transfer function

\[
|H(\omega)| = \left| \frac{V_B(\omega)}{V_1(\omega)} \right| = \frac{R_B}{\sqrt{R_B^2 + \omega^2 L_A^2}} = \frac{1}{\sqrt{1 + \frac{\omega^2}{\omega_0^2}}} , \quad \omega_0 = \frac{R_B}{L_A}
\]

Higher frequency \( \omega \Rightarrow \) lower transfer

**High pass filter**

Resistor \( R_A \) and inductor \( L_B \)

Transfer function

\[
|H(\omega)| = \left| \frac{V_B(\omega)}{V_1(\omega)} \right| = \frac{\omega L_B}{\sqrt{R_A^2 + \omega^2 L_B^2}} = \frac{\omega}{\sqrt{\omega_0^2 + \omega^2}} , \quad \omega_0 = \frac{R_A}{L_B}
\]

Higher frequency \( \omega \Rightarrow \) higher transfer

**Band pass filter**

Resistor \( R \), inductor \( L \), and capacitor \( C \)

\[
\omega = \omega_0 \Rightarrow \text{highest transfer}
\]

\[
|H(\omega)| = \frac{\omega}{\sqrt{\omega^2 + \omega_1^2 \left( 1 - \frac{\omega^2}{\omega_0^2} \right)^2}}
\]
Amplifiers

Operational amplifier (op amp)

Analog integrated circuit

Differential amplifier

\[ v_{out} = A(v_+ - v_-) \]

\[ i_{in} = \frac{v_+ - v_-}{R_{in}} \]

Simplified model

\[ A, R_{in} \to \infty \implies v_+ - v_- = \frac{v_{out}}{A} \to 0, \quad i_{in} = \frac{v_+ - v_-}{R_{in}} \to 0 \]

Feedback amplifier

\[ v_+ - v_- \to 0 \implies v_+ = 0 \]

\[ i_{in} \to 0 \implies i_1 + i_2 = 0 \implies i_2 = -i_1 \]

\[ i_1 = \frac{v_{in}}{R_1} \]

\[ v_{out} = i_2 R_2 = -i_1 R_2 = -\frac{R_2}{R_1} v_{in} \implies \frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1} \]

Set \( R_1 \) and \( R_2 \) to any convenient values for arbitrary amplification.
Analog to Digital Conversion — Sampling

**Nyquist Theorem**

Filter data signal to bandwidth \( f_{\text{max}} \)

Sample data signal at sample rate \( f_{\text{sample}} \geq 2 \times f_{\text{max}} \)

Reproduce data signal from samples without distortion

![Diagram showing analog to digital conversion]

- Data signal \( d(t) \)
- Sampling signal \( S(t) \)
- Sampled signal \( S(t)d(t) \)

Sequence of sample values
Convert Samples to Digital Form

Rounding-off

n-bit integer codes $2^n$ levels

Round-off samples to n-bit integer

Distorts data

Equivalent to added noise

Larger $n \Rightarrow$ more levels $\Rightarrow$ higher resolution $\Rightarrow$ less noise

Example

<table>
<thead>
<tr>
<th>Sampled values</th>
<th>158.276</th>
<th>158.879</th>
<th>159.724</th>
<th>159.821</th>
<th>159.312</th>
<th>158.791</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rounded values</td>
<td>158</td>
<td>159</td>
<td>160</td>
<td>159</td>
<td>159</td>
<td>159</td>
</tr>
</tbody>
</table>
Sampling for Standard Telephony

**Telephone line**
Filter audio frequencies 300 Hz to 3300 Hz

**Sample voice channel**
\[ f_{sample} = 8000 \text{ samples/second} > 2 \times 3300 \text{ Hz} \]

**Round-off samples**
Scale = \(2^8 = 256\) levels (0 to 255)
Each sample encoded as 8-bit byte

**DS-0 voice channel**
\[ 8000 \text{ samples/second} \times 8 \text{ bits/sample} = 64 \text{ kbps} \]
Sampling for Standard CD Audio

**CD audio**

Filter audio frequencies 20 Hz to 22,000 Hz

**Sample voice channel**

\[ f_{\text{sample}} = 44,100 \text{ samples/second} > 2 \times 22,000 \text{ Hz} \]

**Round-off samples**

Scale = \( 2^{16} = 65,536 \) levels (0 to 65,535)

Each sample encoded as 16-bit word

**CD audio channel**

\[ 44,100 \text{ samples/second} \times 16 \text{ bits/sample} = 705,600 \text{ bps} \]

**MP3 encoding \( \rightarrow \) 5 times compression rate**

\[ 705,600 \text{ bps} / 5 \approx 140 \text{ kbps} \approx 17,508 \text{ bytes/sec} \approx 1 \text{ MB/minute} \]
Biomedical Sensors

Classification by interaction type

Interaction → analog electrical signal (voltage / current)
  Physical / electrical / optical / chemical

Biosensor

Biological element — enzyme / antibody / receptor
Biochemical reaction → optical / electrical / physical signal

Packaging

Safe — biocompatibility
Reliable — long operational lifetime
Isolate sensor from body
  Polymer (plastic) covering / barrier layers
  Host body affects sensor function
  Sensor affects implantation site

Environmental factors

Interactions affected by temperature / pressure / noise ...
**Electrochemical concepts**

**Ion**

Atom / molecule with electrons ≠ protons

**Cation**

Electrons < protons ⇒ net + charge

**Anion**

Electrons > protons ⇒ net - charge

**Metal**

Material containing free electrons ⇒ electrical conductor

**Electrolyte**

Material containing free ions ⇒ electrical conductor

Typically ions in solution

**Ionization current**

![Diagram of ionization current]
Half-Cell Potential

**Metal / electrolyte interface**

Electrons flow to / from metal
Charge distribution near surface
Voltage between metal and electrolyte — half-cell potential

**Battery (cell)**

2 half-cells with different metals
Electrons flow from metal 1 ⇒ net +
Electrons flow into metal 2 ⇒ net −

**Biopotential electrodes**

Electrolyte = host tissue
2 half-cells with same metal
   Equal half-cell potentials (ideal model) ⇒ half-cell potentials cancel

Example

Two similar electrodes taped to chest near heart
Measure electrical potentials generated by heart
Differential amplifier → electrocardiogram (ECG = EKG) signals
Common Electrode Types

**Electrocardiogram (ECG) electrodes**
- Common electrode — flexible polymer + carbon / metal powder
- Pre-pasted electrolyte gel for application to skin

**Electromyographic (EMG) electrodes**
- Sense signals from muscles
- Surface EMG recording
  - 1 cm circular discs of silver / platinum
- Direct recording
  - Percutaneous (skin puncture) needle electrodes

**Electroencephalographic (EEG) electrodes**
- Sense signals from brain
- Cup electrodes
  - 5 – 10mm discs of platinum / tin with conducting gel attached to scalp
- Subdermal
  - Platinum / stainless-steel needle electrodes
  - 10mm long by 0.5mm wide
Magnetism

**Magnetic field**

Induced by accelerating charge

Example — electron in stable orbit around nucleus

**Permanent ferromagnet**

Metal (typically iron) with permanent magnetic field

Many atoms with electrons in stable parallel orbits

Compass aligns with earth's magnetic field

Earth's North Pole is a magnetic S

**Mechanical forces**

Opposite poles (N ↔ S) attract

Like poles (N ↔ N / S ↔ S) repel

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemag.html
Electromagnetic Effects

**Electromagnet**

Electric current in wire coil (winding) $\rightarrow$ magnetic field

Field configuration

Identical to permanent bar magnet

Current level + direction $\rightarrow$ field strength + polarity

**Induction**

Varying magnetic field $\rightarrow$ varying current in conductor

**Mutual induction**

Varying current in coil $\rightarrow$ magnetic field $\rightarrow$ current in second coil

**Hall effect**

Current in magnetic field

Charges spread to edges of conductor $\rightarrow$ induced voltage $V_{\text{Hall}}$

$$F = q(u \times B)$$

- $u$ along $x$
- $B$ along $z$
- $F$ along $y$

<table>
<thead>
<tr>
<th>+</th>
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</tr>
</thead>
<tbody>
<tr>
<td>charge separation</td>
<td>induced voltage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Physical Measurements — 1

**Linear Variable Differential Transformer (LVDT)**

- Mutual induction effect
  
  \[ L = \text{displacement of core from exact center} \]
  
  Secondary voltage \( V_S = k_{\text{geometry}} \times V_P \times L \)

- Precise measure of position

**Electromagnetic flow transducer**

- Magnetic field surrounds blood vessel
- Hall effect \(\rightarrow\) electrolytes separate to walls
- Transverse voltage measures blood flow
Elastic resistive transducer

Thin elastic tube containing conductor

Electrical resistance depends on length

Breathing → expanding chest → higher resistance → voltage change

Strain gauge

Similar to elastic resistive transducer

Stress (force) → strain (change in size) → higher resistance

Smaller range of expansion

Bonded

Single thin wire in flexible frame

Unbonded

Multiple thin wires in two-part frame
Variable Capacitance

**Capacitor**

Parallel metal plates

\[ A = \text{area of plate} \]

\[ D = \text{distance between plates} \]

Apply voltage → separate charges

Capacitance = charge stored per volt

\[ q = C \times V \]

\[ C = \text{constant} \times A \times D \]

**Capacitor current**

\[ i = \frac{dq}{dt} = C \frac{dV}{dt} + V \frac{dC}{dt} \]

**Measure small changes in displacement**

Varying \( D \) with constant \( V \)

\[ i = \text{constant} \times V \times A \times \frac{dD}{dt} \]
Pressure Transducers

**Piezoresistance effect**

Pressure on crystal $\rightarrow$ contraction $\rightarrow$ higher resistance

Used in portable blood pressure monitors

**Piezoelectric effect**

Voltage on crystal $\rightarrow$ contraction

Pressure on crystal $\rightarrow$ contraction $\rightarrow$ voltage

Sensitive to short mechanical pulses

Used in sensitive cardiac monitors

**Ultra-sound**

Apply high frequency (1 to 10 MHz) voltage to crystal

Crystal vibrates at voltage frequency $\rightarrow$ pressure wave $\rightarrow$ ultra-sound

Apply ultra-sound to crystal

Pressure wave $\rightarrow$ crystal vibrates $\rightarrow$ voltage at ultra-sound frequency
Temperature Measurement

Contact thermometer

Measure body temperature in direct contact with skin

Thermistor

Metallic mixtures change resistance with temperature T

\[ R = R_0 \exp \left[ \beta \left( \frac{1}{T} - \frac{1}{T_0} \right) \right] \]

Noncontact thermometer

Measure temperature of ear canal near tympanic membrane

Infrared (IR) radiation guided to sensor

Thermopile sensor

Two metal plates in contact

Heated plates → voltage depending on temperature

Used in standard thermostat

Pyroelectric sensor

Heated crystal → voltage depending on temperature
Blood Pressure Set

High Level Design

cuff

air hose

controller
display

switches

air pump

controller
display

switches

air pump

controller
display

switches

air pump

motor control

LCD control

digital input

A/D

microcontroller

cuff

air hose

pump

pressure sensor

amplifier

filter

LCD display

switches

A/D

microcontroller
Blood Pressure

**Pressure**

Force per unit area

Measured as mmHg

External pressure balances weight of Hg in column

**Pulse**

Heart muscle contracts

Internal surface area decreases $\Rightarrow$ pressure increases

**Systolic pressure**

Maximum BP at peak contraction

Normal range: 90 – 120 mmHg

**Diastolic pressure**

Minimum BP at minimum contraction

Normal range: 60 – 79 mmHg
Sphygmomanometer

**Cuff**

- Pump air into cuff
- Pressure measured in gauge
- Pressure on artery → restrict blood flow

**Blood flow**

- Unrestricted artery
  - Laminar (smooth) flow → silent
- Restricted (occluded) artery
  - Turbulent flow → BP oscillations → Korotkoff sounds

L. A. Geddes, *Handbook of Blood Pressure Measurement*
BP Measurement with Sphygmomanometer

**Inflate cuff on upper arm**

- Pump cuff to 160 – 200 mmHg
- Brachial artery occluded → no flow → silent

**Gradually deflate cuff**

- Listen to pulse with stethoscope

**Systolic BP**

- Onset of Korotkoff sounds
- Maximum contraction BP > cuff pressure

**Korotkoff sounds**

- Minimum contraction BP < cuff pressure < maximum contraction BP

**Diastolic BP**

- Silent flow ⇒ minimum contraction BP > cuff pressure
Oscillometric method

Filter + amplify oscillations

Cuff inflation

Cuff deflation

Pressure in cuff

High pass filter (at 1 Hz)

Amplify

SBP / DBP criteria determined by comparison with clinical data

Chua and Hin, Digital Blood Pressure Meter, Freescale Semiconductor