Digital Measurement
What, Whereby, How?

Embedded Systems Engineering WS10
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Overview

• **What?**
  - Measurement Units
  - Signals
    (Classification, Sampling Theorem, Noise)

• **Whereby?**
  - Sensors …

• **How?**
  - Measurement Error
  - Measurement with microcontroller
    (analog comparator, ADC, DAC, Codes and value representation)
  - Data processing and filtering
Measurement Units

A measurement consists of the product of the *measurand value* and its *unit*.

\[ x = v \cdot u \]

- \( x \): the measurement
- \( v \): a number representing the measurand value (the physical or chemical quantity, property or condition that is measured)
- \( u \): the respective unit

- Standardized by the international system of units *(Système International d’Unités)* **SI-System**
SI-System - Units

• 7 Base units
  kg, m, s, A, K, mol, cd

• Derived Units (examples)
  Hz [1/s], N [(kg·m)/s²]
  W [(kg·m²)/s], Pa [kg/(m·s²)]
  °C [T_kelvin – 273.15], Joule [(kg·m²)/s²]
<table>
<thead>
<tr>
<th>SI-System - Unit-Prefix</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>kilo</td>
<td>k</td>
<td>$10^3$</td>
<td>milli</td>
</tr>
<tr>
<td>mega</td>
<td>M</td>
<td>$10^6$</td>
<td>micro</td>
</tr>
<tr>
<td>giga</td>
<td>G</td>
<td>$10^9$</td>
<td>nano</td>
</tr>
<tr>
<td>tera</td>
<td>T</td>
<td>$10^{12}$</td>
<td>pico</td>
</tr>
<tr>
<td>peta</td>
<td>P</td>
<td>$10^{15}$</td>
<td>femto</td>
</tr>
<tr>
<td>exa</td>
<td>E</td>
<td>$10^{18}$</td>
<td>atto</td>
</tr>
<tr>
<td>zetta</td>
<td>Z</td>
<td>$10^{21}$</td>
<td>zepto</td>
</tr>
<tr>
<td>yotta</td>
<td>Y</td>
<td>$10^{24}$</td>
<td>yocto</td>
</tr>
</tbody>
</table>
Signals - Classification

Signals

- Deterministic
  - Periodic
    - Sine
    - Non-Sine
  - Aperiodic
    - Quasi-Periodic
    - Transient

- Stochastic
Signals – Sampling Theorem

• Sampling is the process of converting an signal into a numeric sequence. (analog value to a discrete value)

• A band-limited \((0-f_{\text{max}})\), time dependent function \(f(t)\) can be reconstructed by sample-points if sampling frequency is more than the twice of \(f_{\text{max}}\).

\[ f_{\text{sample}} > 2 \cdot f_{\text{max}} \]
Signals - Noise

• **Noise is a stochastic changing** of current/voltage of a signal, which is caused by several affects:
  – Thermal noise
  – Atmospheric and Galactic/Cosmic noise

• **Impact of noise** on the measurement **should be minimized** by appropriate design measures, e.g.:
  – Shielding to reduce the impact of *external noise*
  – Appropriate hardware layout to eliminate avoidable sources of *internal noise*

(more details are given in the lecture „Hardware Design for Embedded Systems“)
### Signals – Noise Types

<table>
<thead>
<tr>
<th>Noise Type</th>
<th>Frequency Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Noise</td>
<td>( 0 ) dB</td>
</tr>
<tr>
<td>Pink Noise</td>
<td>( -40 ) dB, ( -3 ) dB/Octave</td>
</tr>
<tr>
<td>Brown/Red Noise</td>
<td>( -40 ) dB, ( -6 ) dB/Octave</td>
</tr>
<tr>
<td>Blue Noise</td>
<td>( +40 ) dB, ( +3 ) dB/Octave</td>
</tr>
<tr>
<td>Purple Noise</td>
<td>( +40 ) dB, ( +6 ) dB/Octave</td>
</tr>
</tbody>
</table>

**White Noise**  
(constant)

**Gray Noise**  
(approx. to const. psychoacoustic loudness)

**Pink Noise**  
(-3 dB/Octave)

**Brown/Red N.**  
(-6 dB/Octave)

**Blue Noise**  
(+3 dB/Octave)

**Purple Noise**  
(+6 dB/Octave)
Sensors – Some Definitions

- A device that responds to a physical or chemical stimulus (such as heat, pressure, flow, acceleration, etc) and affects or generates an electrical signal.

- Facilitates to quantitatively or qualitatively acquire the physical or chemical properties of an object.

- A sensor is a transducer that converts the measurand into a signal carrying information.
Classification of Sensors (1)

- **Passive Sensors**
  - A sensor whose physical measurement variable controls or affects the energy of something/someone else.
  - e.g. strain gauge (“DMS”), capacitive sensors

- **Active Sensors**
  - A sensor that generates by itself some form of energy as its measurement signal.
  - e.g. photo transistor, piezo-electric sensors
Classification of Sensors (2)

• **Type of measurand:**
  – Mechanical quantities (e.g. pressure, position, force)
  – Thermal quantities (e.g. temperature, heat flow)
  – Electrostatic and magnetic fields
  – Radiation intensity (e.g. electromagnetic)
  – Chemical quantities (e.g. humidity, gas)
  – Biological quantities (e.g. antigens, antibodies)
Classification of Sensors (3)

• **Nature of Output Signal**
  – analog output: continuous signal in its magnitude and/or temporal (e.g. temperature)
  – digital output: output signal in the form of discrete steps or states (e.g. switch)

• **Physical Measurement Variable**
  – resistance
  – inductance
  – capacitance
  – etc.

*selecting the most appropriate sensor is not a trivial task*
Selecting a Sensor (1)

• What should be measured?
  – distance, brightness, …
  – sometimes it is easier to measure a related value (voltage instead of current)

• Can we access the physical/chemical property directly?
  – e.g. temperature within a melting pot

• How should it be measured?
  – measuring wheel, propagation delay, triangulation
  – required precision
Selecting a Sensor (2)

• **Interface**
  - digital, analog, restrictions, dynamics …

• **Requirements in the field of application**
  - mechanical stress (e.g. heat, pressure, etc)
  - costs (mass production vs. prototype setup)

• **Effects biasing the measurement:**
  - *Never forget the physics behind the sensor!*
  - Example:
    - two infrared sensors (triangulation)
    - almost all measurements are rubbish
    - beam from sensor A was detected by sensor B
## Some Common Sensing Methods

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement / Position</td>
<td>resistive, capacitive, opto-electronic, Hall effect, variable reluctance</td>
</tr>
<tr>
<td>Distance</td>
<td>triangulation, measuring wheel, radar, echelon, capacitive/inductive proximity</td>
</tr>
<tr>
<td>Temperature</td>
<td>Thermistor (NTC, PTC), infrared radiation, thermocouple</td>
</tr>
<tr>
<td>Pressure</td>
<td>piezoresisitive, capacitive, piezoelectric, strain gauge</td>
</tr>
<tr>
<td>Velocity</td>
<td>Hall effect, opto-electronic, variable reluctance</td>
</tr>
<tr>
<td>Luminance</td>
<td>photo-resistor, photo-diode, photo-transistor</td>
</tr>
</tbody>
</table>
Resistive Sensors

- Common: passive sensors, variation of resistance $R$
- Potentiometer – changing $L$ due to mechanical displacement (slide, rotation)
  - liquid level sensor, rotation and angle sensor
- Thermistor – change of resistance due to change of, NTC (negative $k$), PTC (positive $k$)
  - heat sensor, heat flow sensor
- Piezoresistive Sensors – resistor diffused in silicon, compression decreases resistance, tension increases resistance
  - mechanical stress
Resistive Sensors

- **Potentiometer**
  - e.g. angle sensor (105°), 5k Ohm linear

- **Thermistor**
  - e.g. PTC with range 0 … 55° C

(figures taken from RS components online catalogue)
Capacitive Sensors

• Common: passive sensors, variation of capacitance C
• Pressure sensor
  – typically capacitor diffused into silicon chip
  – distance between capacitor plates is varied due to mechanical stress
• Liquid level sensor
  – typically two or three electrodes (measured object itself forms one electrode)
• Capacitive proximity switch
  – contact-free detection of liquids or solid materials
Revolution Sensor

- Speed indicator signal provided by DC fan (ESE-LU board)
  - special kind of on/off switch
  - two pulses per revolution

(figure taken from ebmpapst DC fan data sheet)
Optical Sensors (1)

• Position Encoder
  – incremental position encoder (PC mouse)
    • two square waves 90° phase-delayed
  – absolute position encoder (parallel)
    • n wires
    • Gray encoded position
Optical Sensors (2)

- Incremental position encoder
Optical Sensors (3)

- Absolute position encoder (5 bit gray code)

(figures taken from www.informatik.uni-hamburg.de)
Optical Sensors (4)

• Luminance Sensor
  – photo electric effect (photo transistor, photo diode, photo resistor)
  – output signal mostly analog
  – characteristic: linear & non-linear
  – some luminance sensors are programmable (gain, alarm limit, …)
  – e.g. NSL-19M51 photo resistor (ESE-LU board):
    • photo conductive cell
    • resistance from 20-100K Ohm (light) to 20M Ohm (dark)
Piezoelectric Sensor

- Piezoelectric Effect (P. and J. Curie, 1880)
  - ability of crystals to generate voltage as a response to mechanical stress
  - materials: quartz (SiO$_2$), cane sugar, topaz
  - in static operation the behavior is similar to a capacitor
- Active sensor for measuring pressure, force, or acceleration (e.g. piezoelectric microphone)
- Above 846°K this piezoelectric effect is lost (Curie-Temperature)
Hall Effect Sensor

- Hall Effect (Edwin Hall 1879)
  - generation of potential difference (Hall voltage) in a conductive material located in a stationary magnetic field through which electrical current is flowing

- Active sensor for measuring
  - displacement
  - velocity
  - inductive proximity switch
Ideal Sensor vs. Real World

- **Ideal Sensor:**
  - transforms highly linearly a single physical or chemical measurand into an electrical signal while being resistant to environmental influences

- **Real World:**
  - gain error, clipping
  - offset (bias), drift
  - nonlinearity
  - hysteresis
  - digitization error
Measurement Error

Measurement error is the difference between the measured and the actual value.

\[ e = x - a \quad e_{\text{rel}} = \frac{x-a}{a} \]

- \( e \) ... measurement error (absolute)
- \( e_{\text{rel}} \) ... measurement error (relative)
- \( x \) ... measured value
- \( a \) ... actual value
Measurement Error - Types

• **Systematic errors**
  – reproducible (calculation, measurement) measurement deviation (e.g. bias, drift), which is in principle correctable (e.g. calibration)
  – e.g. zero point/offset, scaling, integral linearity, differential linearity, history dependent

• **Conditional errors**
  – caused by external influences, e.g. Electromagnetic interference/pulse (EMI, EMP)

• **Stochastic errors**
  – measurement error that is due to random causes (e.g. noise)
Systematic measurement errors 1

(a) Zero point/offset error
(b) Scaling error
Systematic measurement errors 2

History dependent error
(e.g. hysteresis error)

- Caused by the effects of static and dynamic signal history
- Demands an advanced strategy for measurement error calibration
Calibration

**Calibration** is the correction of sensor reading and physical outputs so they match a standard. [J.Berge]

- Adjusting the measurement to agree with value of the applied standard within a specified accuracy.

Measurement Triple:
- estimated value
- error bound
- value probability
Digital calibration model

Example: The RT-Image is afflicted with a measurement error from the ADC (quantization, linearization, scaling/offset, ..)
Analog to Digital Converter - ADC

- Changes a signal’s time and value into discrete domain
- Requires a sample and hold stage (S/H)
- Conversion techniques
  more details in „Tutorial Peripherals and I/O“
Digital to Analog Converter - DAC

- Transforms a digital value with discrete time domain into analog value and time.
- Conversion techniques
  - >more details in „Tutorial Peripherals and I/O“
Processing of Measured Data

- Classification of measured data:
  - Several measurements from the *same instant* from different sensors (*sample*)
  - Several measurements from *different instants* from the *same sensor* (*series*)

- Next: Sensor Fusion and Digital Filtering
Motivation for Sensor Fusion

• Sensor Deprivation
  – e.g. loss of perception on object due to sensor break down

• Limited spatial coverage
  – e.g. single measurement of water temperature returns temperature estimation near the thermometer

• Limited temporal coverage
  – e.g. set-up time of sensor limits achievable measurement frequency

• Imprecision
  – e.g. inherent imprecision of deployed sensing element

• Uncertainty
  – e.g. ambiguous observation due to missing features (occlusions)
Marzullo’s Algorithm

- Each sensor measurement is represented as an interval
- Maximum $t$ sensors (out of $n$) are expected to be faulty
- Result is a single interval $M$ that covers all intersections shared by at least $n - f$ intervals

$n=4$ sensors

$f = 1$ expected to be faulty

value range
Confidence-weighted averaging

- Each measurement is assigned a confidence marker indicating the uncertainty of the measurement value
- Use statistical variance as measure for uncertainty
- Fusion operations use both properties and yield a result of value and confidence marker
- Confidence marker corresponds to variances
Filtering a Series of Measurements

• A filter is a layer designed to block certain things whilst letting others through
• Primary filtering question: what is the intended information and what should be filtered out
• Typically filter out noise
• Careful design not to remove the intended information
• Digital filter: input and output are treated as time discrete signals
Moving Average Filter

\[ y[n] = \frac{1}{M} \sum_{j=0}^{M-1} x[n - j] \]

- Very simple implementation
- Filter kernel h[n] = 1/M
- Well-suited for signal restoration (e.g. noise reduction)
- But does not cut off unwanted frequencies very well
- Tradeoff: noise reduction versus rise time
Moving Average Filter (2)

M=11

M=33
Summary

• Measurements have (systematic, stochastic) errors
• Chosen sensor type has to be aligned to (physical) characteristics of the measurand
• Calibration (works on some of the systematic errors)
• Signal and noise types
• Fusing samples with Marzullo‘s algorithm, Confidence-Weighted Averaging…
• Filtering series with Moving Average, …
THE END

Thanks for your attention!