A/D Programming

LISTA/UFSC

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Signals

- Signal
  - Detectable transmitted energy that can be used to carry information

- Analog signals
  - Continuous nature
  - May take any value within a range
  - Information carried in (variations of) amplitude, frequency, or phase
Signals

- Digital signals
  - Discrete nature
  - Finite number of possible states within a range
  - Information carried in discrete signal states
Signals: Computers and the Real World

- The world is analog by nature
- Digital computers are... well, digital (and usually binary)!
- Interfacing analog signals to digital processors or microcontrollers is inevitable
  - Digital music and video
  - Digital telephony
  - Sensors and actuators
Analog to Digital Conversion

- The analog signal is sampled (i.e. measured) at a regular interval and each sample is quantized (i.e. converted to discrete numeric values) by a given value that approximates to the analog value.
Sampling

- The analog signal is measured periodically
- Sampling rate
  - Number of samples that are taken on a time period (e.g. a second)
Sampling

- Nyquist's theorem
  - “The sampling frequency must be greater than twice the highest frequency of the input signal in order to be able to reconstruct the original perfectly from the sampled version”
  - f Hz analog signal => 2 x f Hz sampling rate
  - Example: Hi-Fi audio
    - 20-20000 Hz signal => 40 kHz sampling frequency

- The sampling rate determines the speed of the conversion device
  - Fast devices cost more
Irregular Sampling

- Sampling must be performed on a regular basis with exactly the same time between samples
  - Irregular sampling leads to conversion errors
    - Early or late sampling, jitter, delayed sampling
Quantization

- The sampled signal is quantized (converted to discrete numeric values)
- The number of quantization steps determine how many discrete values a given sample may take
Quantization

- The size of the quantization step determines the resolution of the conversion
  - Dependent on the number of bits used to represent the analog value and the analog signal's amplitude

- Example (analog signal range 0-1):
  
<table>
<thead>
<tr>
<th>Size</th>
<th>Resolution (Size of each quantization step)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 bit</td>
<td>0.06250000</td>
</tr>
<tr>
<td>8 bit</td>
<td>0.00390625</td>
</tr>
<tr>
<td>16 bit</td>
<td>0.00001525</td>
</tr>
</tbody>
</table>

- Higher resolution means more precise conversions
  - High resolution devices cost more
Codification

- A digital value is associated with each quantized sample
- The maximum error in codification for a “perfect ADC” is +/- 1/2 LSB, where LSB is the size in volts of each quantization step
Digital Representation of Signals

- **PCM (Pulse Code Modulation)**
  - Linear quantization step
  - Encoded value correspond to the quantized value

- **DPCM**
  - Encoded value is the difference between the current sample and the previous sample
  - May improve accuracy and resolution (e.g. having a 16-bit dynamic range without having to encode 16-bit samples)

- **ADPCM**
  - DPCM with a non-linear quantization step
  - May achieve better SNR (Signal/Noise Ratio)
Analog / Digital Conversion Trade-offs

- Low sampling rates and small precision mean conversion errors
  - Lower cost
  - Enough for some applications
Analog / Digital Conversion Tradeoffs

- High sampling rates and resolution mean better conversion
  - High cost
  - Higher bandwidth
  - Bandwidth example (in bytes/sec):
    - Remember: resolution = amplitude / size
    - Nyquist: sampling rate > 2 x f

<table>
<thead>
<tr>
<th>Sampling Rate (Hz)</th>
<th>1000</th>
<th>10000</th>
<th>20000</th>
<th>44100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (Bytes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>5000</td>
<td>10000</td>
<td>22050</td>
</tr>
<tr>
<td>6</td>
<td>750</td>
<td>7500</td>
<td>15000</td>
<td>33075</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>10000</td>
<td>20000</td>
<td>44100</td>
</tr>
<tr>
<td>10</td>
<td>1250</td>
<td>12500</td>
<td>25000</td>
<td>55125</td>
</tr>
<tr>
<td>16</td>
<td>2000</td>
<td>20000</td>
<td>40000</td>
<td>88200</td>
</tr>
</tbody>
</table>
Flash ADC

- One comparator associating each tension level with an output digital word
- A 2-bit Flash ADC needs 4 comparators, a 4-bit, 16, and so forth
- Very fast, but limited precision
Successive-approximation ADC

- Uses a comparator to reject ranges of voltages, eventually settling on a final voltage range.
Delta-Sigma ADC

- Analog input signal connected to integrator
- Ramping voltage compared to ground
  - 1-bit ADC
- Comparator output latched through a D-type flip-flop clocked at a high frequency
- Fed back to integrator
Ramp-Compate ADC

- For each sample, the ADC produces a saw-tooth signal that ramps up, then quickly falls to zero. When the ramp starts, a timer starts counting. When the ramp voltage matches the input, the timer's value is recorded.
# Analog / Digital Converters

<table>
<thead>
<tr>
<th>Conversion Type</th>
<th>Typical Sampling Rate</th>
<th>Typical Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash</td>
<td>5Mhz – 500Mhz</td>
<td>4-8 bits</td>
</tr>
<tr>
<td>Successive Approx.</td>
<td>50Khz – 5Mhz</td>
<td>8-10 bits</td>
</tr>
<tr>
<td>Sigma-Delta</td>
<td>10Khz – 10Mhz</td>
<td>10-16 bits</td>
</tr>
<tr>
<td>Ramp-Compare</td>
<td>1Hz – 1 Khz</td>
<td>10-20 bits</td>
</tr>
</tbody>
</table>
ADC: Operational Parameters

- **Conversion range**
  - Determines the amplitude of the analog signal
  - May be fixed or selectable
  - Usually determined by a GND and a Vref voltage
  - An analog value that is equal to GND will determine a 0 output in the ADC
  - A Vref analog value will determine a MAX output in the ADC
  - The larger the analog signal amplitude, the bigger the quantization step

- **Differential and Single-ended conversion**
  - The first measures the difference between signals
  - The second measures a single analog signal
ADC: Operational Parameters

- **Operation Frequency**
  - Maximum is determined by the manufacturer
  - Internal or external clocks
  - Determines sampling rate
  - High frequencies imply on higher temperatures

- **Bandwidth**
  - Output speed
  - Sampling Rate = Frequency / Conversion Cycles
  - $BW = \frac{\text{Sampling rate}}{2}$ (Nyquist)
ADC: Errors

- **Absolute error**
  - Maximum deviation between the actual and the ideal ADC transfer functions. Composed by:
    - quantization error (+/- ½ LSB)
    - offset error
    - gain error
    - non-linearity

- **Offset error**
  - When a transition from 0 to 1 does not occur at an input value of ½ LSB
  - Offset error = Input voltage at the first 0 to 1 transition - Ideal transfer function value at first 0 to 1
ADC: Errors

- Gain error
  - Transfer function slope deviates from the ideal slope
- Non-linearity
  - Variation in the width of quantization steps
  - Maximum difference between the ideal width and each step width
- Calibration and compensation
  - Offset, gain and non-linearity errors may be measured and compensated
  - Important for high-precision devices
Digital / Analog Conversion

- Translates a binary input code to an analog output voltage
- Similar principle to ADCs
- Different conversion speeds and input rates
  - Expensive devices x glitches
- Examples
  - Pulse Width Modulator (PWM)
  - Delta-Sigma
  - R-2R Ladder
ADCs and DACs in Embedded Systems

- Devices
  - External
    - Parallel (GPIO)
    - Serial (SPI, I2C)
    - Myriad of choices, Requires additional circuitry
  - Internal (MCU-embedded)
    - Register-controlled
    - Limited choices, Easy to interface
  - Software ADCs
    - Built with an internal analog comparator and some additional circuitry
    - Limited precision/sampling rate, cheap
ADC Case Study: Analog Devices AD9260

- 16-bit, Single-channel, up to 2.5 Mhz ADC
- General Purpose, medium/high precision device
- Parallel output
- Additional pins for signals
  - Data available, Overflow
- Configuration
  - Sampling rate (via Input Clock)
  - Conversion range (via Analog Reference Inputs)
ADC Case Study: AVR ATmega ADC

- 10-bit, 8-channel, up to 1 Mhz ADC
  - Conversion
    - 0.5 LSB integral non-linearity, ±2 LSB absolute accuracy
    - 13 - 260 μs conversion time
  - 2 differential input channels
    - Optional gain of 10x and 200x
  - 0 - VCC ADC input voltage range
    - Selectable 2.56V ADC reference voltage

- Operation
  - Analog inputs shared with GPIO ports
  - Clock prescaling (sampling rate)
  - Optional left adjustment for ADC result readout
  - Free running or single conversion modes
    - Interrupt on completion