Lecture 22
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Analog/Digital Converters

• Introduction to A/D Converters
• The Analog Comparator
• The Flash A/D Converter
• A/D Converter Resolution and Quantization
• A/D Sampling Rates – Nyquist Theorem
• D/A Converters
• Slope A/D Converters
• Successive Approximation A/D Converters
Analog/Digital Converters

- An Analog-to-Digital (A/D) converter converts an analog voltage into a digital number.
- There are a wide variety of methods used for A/D converters. Examples are:
  - Flash (Parallel)
  - Successive Approximation
  - Sigma-Delta
  - Dual Slope Converter
- A/D converters are classified according to several characteristics:
  - Resolution (number of bits) — typically 8 bits to 24 bits
  - Speed (number of samples per second) — several samples/sec to several billion samples/sec
  - Accuracy — how much error there is in the conversion
- High-resolution converters are usually slower than low-resolution converters.
- The MC9S12 has a 10-bit charge redistribution successive approximation A/D converter (which can be used in 8-bit mode for faster conversions).
- The MC9S12 uses an analog multiplexer to allow eight input pins to connect to the A/D converter.
Comparator

- A comparator is used in many types of A/D converters.
- A comparator is the simplest interface from an analog signal to a digital signal
- A comparator compares two voltage values on its two inputs
- If the voltage on the + input is greater than the voltage on the - input, the output will be a logic high
- If the voltage on the + input is less than the voltage on the - input, the output will be a logic low

\[
\begin{align*}
\text{If } V_{\text{in}} &> V_{\text{ref}} \text{ then } V_{\text{out}} = V_{\text{cc}} \\
\text{If } V_{\text{in}} &< V_{\text{ref}} \text{ then } V_{\text{out}} = 0
\end{align*}
\]
Flash (Parallel) A/D Converter

- A flash A/D converter is the simplest to understand.
- A flash A/D converter compares an input voltage to a large number of reference voltages.
- An $n$-bit flash converter uses $2^n - 1$ comparators.
- The output of the A/D converter is determined by which of the two reference voltages the input signal is between.
- Here is a 3-bit A/D converter.
Flash A/D Converter

- A $B$-bit Flash A/D converter requires $2^B - 1$ comparators
- An 8-bit Flash A/D requires 255 comparators
- A 12-bit Flash A/D converter would require 4,095 comparators
  - Hard to integrate 4,095 comparators onto an IC
- The largest flash A/D converter is 8 bits
- Flash A/D converters can sample at several billion samples/sec
A/D Converter Resolution and Quantization

- If the voltage input voltage is 3.2516 V, the lowest 5 comparators will be turned on, and the highest 2 comparators will be turned off.
- The output of the 3-bit flash A/D converter will be 5 (101).
- For a 3-bit A/D converter, which has a range from 0 to 5 V, an output of 5 indicates that the input voltage is between 3.125 V and 3.750 V.
- A 3-bit A/D converter with a 5 V input range has a quantization value of 0.625 V.
- The quantization value of an A/D converter can be found by
  \[ \Delta V = \frac{V_{RH} - V_{RL}}{2^b} \]
  where \( V_{RH} \) is the highest voltage the A/D converter can handle, \( V_{RL} \) is the lowest voltage the A/D converter can handle, and \( b \) is the number of bits of the A/D converter.
- The MC9S12 has a 10-bit A/D converter. The typical voltage range used for the MC9S12 A/D is \( V_{RH} = 5 \) V and \( V_{RL} = 0 \) V, so the MC9S12 has a quantization value of
  \[ \Delta V = \frac{5 \text{ V} - 0 \text{ V}}{2^{10}} = 4.88 \text{ mV} \]
- The dynamic range of an A/D converter is given in decibels (dB):
  \[ DR(\text{dB}) = 20 \log 2^b = 20 \log 2 = 6.02b \]
- A 10-bit A/D converter has a dynamic range of
  \[ DR(\text{dB}) = 6.02 \times 10 = 60.2 \text{ dB} \]
A/D Sampling Rate

- The rate at which you sample a signal depends on how rapidly the signal is changing.
- If you sample a signal too slowly, the information about the signal may be inaccurate.
A 1050 Hz signal sampled at 500 Hz
• A 1,050 Hz signal sampled at 500 Hz looks like a 50 Hz signal

• To get full information about a signal you must sample more than twice the highest frequency in the signal
  
  – This is called the Nyquist theorem

• Practical systems typically use a sampling rate of at least four times the highest frequency in the signal
Digital-to-Analog (D/A) Converters

- Many A/D converters use a D/A converter internally
- A D/A converter converts a digital signal to an analog voltage or current
- To understand how most A/D converters work, it is necessary to understand D/A converters
- The heart of a D/A converter is an inverting op amp circuit
- The output voltage of an inverting op amp circuit is proportional to the input voltage:

\[
V_{\text{out}} = \frac{-R_F}{R_0} V_{R_0}
\]
Digital-to-Analog (D/A) Converters

• An inverting op amp can produce an output voltage which is a linear combination of several input voltages

\[ V_{\text{out}} = -\frac{R_F}{R_0} V_{R0} - \frac{R_F}{R_1} V_{R1} - \frac{R_F}{R_2} V_{R2} - \frac{R_F}{R_3} V_{R3} \]
Digital-to-Analog (D/A) Converters

- By using input resistors which scale by factors of 2, a summing op amp can produce an output which follows a binary pattern
Digital-to-Analog (D/A) Converters

- By using switches on the input resistors, a summing op amp can produce an output which is a binary number (representing which switches are closed) times a reference voltage.

4-Bit Digital-to-Analog Converter

\[
V_{\text{out}} = \frac{-R_F}{R_0} V_{\text{Ref}} 
\]

\[
B = B_3 B_2 B_1 B_0
\]

\[
B = B_0 + 2 B_1 + 4 B_2 + 8 B_3
\]
Slope A/D Converter

- A simple A/D converter can be constructed with a counter and a D/A converter
- The counter counts from 0 to $2^b - 1$
- The counter drives the input of the D/A converter
- The output of the D/A converter is compared to the input voltage
- When the output of the comparator switches logic level, the generated voltage passed the input voltage
- By latching the output of the counter at this time, the input voltage can be determined (with the accuracy of the quantization value of the converter)
- Problem with Slope A/D converter: Takes $2^b$ clock cycles to test all possible values of reference voltages
SLOPE A/D CONVERTER

$2^n$ Clock Cycles per Conversion

V_in

D/A

CLK

COUNTER

LATCH

V

V_in

D/A

Latch Here

Time
Successive Approximation A/D Converter

- A successive approximation (SA) A/D converter uses an intelligent scheme to determine the input voltage.
- It first tries a voltage halfway between $V_{RH}$ and $V_{RL}$.
- It determines if the signal is in the lower half or the upper half of the voltage range.
  - If the input is in the upper half of the range, it sets the most significant bit of the output.
  - If the input is in the lower half of the range, it clears the most significant bit of the output.
- The first clock cycle eliminates half of the possible values.
- On the next clock cycle, the SA A/D tries a voltage in the middle of the remaining possible values.
- The second clock cycle allows the SA A/D to determine the second most significant bit of the result.
- Each successive clock cycle reduces the range another factor of two.
- For a $B$-bit SA A/D converter, it takes $B$ clock cycles to determine the value of the input voltage.
SUCCESSIVE APPROXIMATION A/D CONVERTER

N Clock Cycles per Conversion

D/A

High/Low
Successive Approximation Register

Conversion Complete

LATCH

A/D Value

V in

Start
Clk

D/A

V

110000
101000
100100
100110
100111
100110
100110

100000
100100
100110
100111
100110

Time

V

D/A

V

Conversion Complete

LATCH

A/D Value

V in

Start
Clk

D/A

V

110000
101000
100100
100110
100111
100110

100000
100100
100110
100111
100110

Time
**Successive Approximation A/D Converter**

- An SA A/D converter can give the wrong output if the voltage changes during a conversion.
- An SA A/D converter needs an input buffer which holds the input voltage constant during the conversion.
- This input buffer is called a Track/Hold or Sample/Hold circuit.
- It usually works by charging a capacitor to the input voltage, then disconnecting the capacitor from the input voltage during conversion.
- The voltage on the capacitor remains constant during conversion.
- The MC9S12 has a Track/Hold amplifier built in.
- SA A/D converters have resolutions of up to 16 bits.
- SA A/D converters have speeds up to several million samples per second.
SUCCESSION APPROXIMATION A/D CONVERTER

V_{in} \rightarrow \text{Track/Hold} \rightarrow + \rightarrow \text{Successive Approximation Register} \rightarrow \text{Conversion Complete} \rightarrow \text{LATCH} \rightarrow \text{A/D Value} \rightarrow \text{D/A} \rightarrow \text{Successive Approximation Register} \rightarrow \text{Start} \rightarrow \text{Cik} \rightarrow \text{Track/Hold} \rightarrow V_{in}