Analog-to-Digital Converters
Huang Sections 12.1-12.2
  o Review of MC9S12 PWM subsystem
  o Introduction to 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 two 10-bit successive approximation A/D converters (which can be used in 8-bit mode)

• The MC9S12 uses an analog multiplexer to allow eight input pins to connect to any of the A/D converters.
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 (Parallel) 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!
  - Cannot integrate 4,095 comparators onto an IC

- Such A/D are available in IC form up to 8-bit and 10-bit

- 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 HC12 has a 10-bit A/D converter. The typical voltage range used for the HC12 A/D is \( V_{RH} = 5 \) V and \( V_{RL} = 0 \) V, so the HC12 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):

\[ DR(\text{dB}) = 20 \log 2^b = 20 \log 2b = 6.02b \]

• 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 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

• 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:
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.

\[
\text{4-Bit Digital-to-Analog Converter}
\]

\[
\begin{align*}
\text{Output voltage } V_{\text{out}} &= \frac{-R_F}{R_0} \cdot V_{\text{Ref}} \\
B &= B_3 \cdot 8 + B_2 \cdot 4 + B_1 \cdot 2 + B_0
\end{align*}
\]
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: Could take $2^b$ clock cycles to test possible values of reference voltages
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 half way 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

\[ V_{in} \rightarrow + \rightarrow \text{Start} \rightarrow \text{Clock} \rightarrow \text{High/Low} \rightarrow \text{Successive Approximation Register} \rightarrow \text{Conversion Complete} \rightarrow \text{LATCH} \rightarrow \text{A/D Value} \]

\[ V \]

\[ V_{in} \rightarrow 110000 \rightarrow V_{D/A} \rightarrow 101000 \rightarrow 100110 \rightarrow 100111 \rightarrow 100110 \]

\[ \text{Time} \]
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 HC12 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