EE 252: Measurement and Instrumentation

Lecture 1: Analog-to-Digital and Digital-to-Analog Converter

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Digital to analog (D/A) and analog to digital (A/D) conversion are very important aspects in sensor data processing in digital form. Whereas D/A involves translating digital information into equivalent analog information, A/D converters are used for the reverse process of changing analog signals to equivalent binary signals. D/A converters can be used to drive actuators according to the control output generated by microprocessors. Thus, D/A can also be considered as a decoding device. A/D converters are used to convert analog signal generated by transducers into digital form to feed them into microprocessor system. A/D is referred to as an encoding device. A D/A converter is usually an integral part of any A/D conversion.

1.1 Digital-to-Analog Converter

1.1.1 Variable resistor network

The basic problem in converting a digital signal into an equivalent analog signal is to change the n digital voltage levels into one equivalent analog voltage. This can be achieved most easily by designing a resistive network which changes each of the digital levels into an equivalent binary weight voltage.

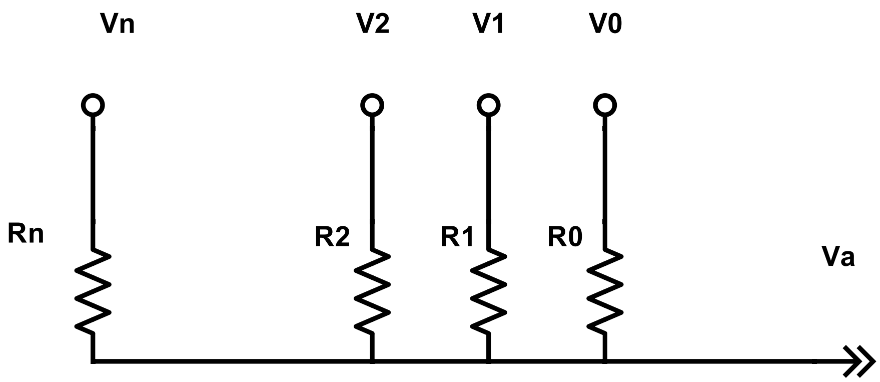


Figure 1.1

Consider a 3 bit digital signal that need to be converted into equivalent analog voltage signal. As we know with $n = 3$ bits, there are 8 distinct states. We wish to represent each of them with an equivalent analog voltage. The smallest increment change in the digital signal is represented by LSB (least significant bit). The binary equivalent weight associated with the LSB is $1/(2^n - 1)$. Thus, the next LSB has the weight of $2/(2^n - 1)$ and so on. Finally, the MSB has binary equivalent weight of $2^{n-1}/(2^n - 1)$. In the D/A converter, we would like to represent the n bit digital signal into equivalent analog signal between say 0 to $+V$ volts. The resistive divider circuit shown in Fig. 1.1 performs the D/A conversion. The output impedance is considered to be very high compared to $R_0, R_1, \cdots R_{n-1}$. The digital inputs are applied at $V_{n-1}, \cdots V_2, V_1, V_0$ with V_0 as LSB. According to Millman's theorem, the voltage V_a is given as

$$V_a = \frac{V_{n-1}/R_{n-1} + \cdots + V_2/R_2 + V_1/R_1 + V_0/R_0}{1/R_{n-1} + \cdots 1/R_2 + 1/R_1 + 1/R_0} \tag{1.1}$$

We choose, $R_1 = R_0/2$, $R_2 = R_0/4$, and $R_{n-1} = R_0/2^{n-1}$. The digital input voltage levels are 0 and $+V$. As a result we obtain

$$Va = \frac{V_{n-1}2^{n-1} + \cdots + V_2 2^2 + V_1 2^1 + V_0 2^0}{2^n - 1} \tag{1.2}$$

This type of resistive network has two basic drawbacks.

1. Each resistance in the network has a different value. Since the dividers are usually constructed using precision resistor, their cost factor increases.

2. The resistance used in the MSB is required to handle a much higher current than the LSB resistor.

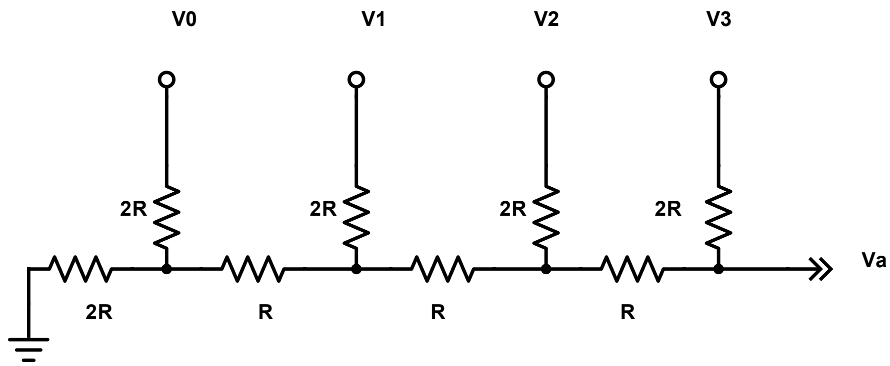


Figure 1.2

The solution for these limitation is another resistor network, ladder type. Figure 1.2 shows a binary ladder which is constructed of resistors having only two values. The figure shows the example of 4-bit ladder which can be easily extended to n-bit D/A. Here V_0 and V_3 represent LSB and MSB, respectively. Let $V_3 = V$ and $V_2 = V_1 = V_0 = 0$. In that case, we can easily compute $V_a = V/2$. For another condition, let $V_2 = V$ and $V_3 = V_1 = V_0 = 0$. In that case, we can compute $V_a = V/4$. Since this ladder is composed of linear resistors, it is a linear network and the principle of superposition can be used. Accordingly, the total voltage can be obtained as

$$V_a = \frac{V_3 2^3 + V_2 2^2 + V_1 2^1 + V_0 2^0}{2^4} \tag{1.3}$$

For the general case of n-bit D/A, we obtain

$$V_a = \frac{\sum_{k=0}^{n-1} V_k 2^k}{2^n} \tag{1.4}$$

The resolution of D/A converter is $V_{LSB} = V/2^n$ and its accuracy is $\pm(1/2)V_{LSB}$

1.1.2 OpAmp based D/A Converter

We have discussed summing amplifier configuration in previous lecture. The same can be used as op-amp based D/A converter. One need to select the series input resistances such that appropriate weights are set to each input. I leave it to you to think over it.

1.1.3 Practical D/A converter

Practical D/A converter consists of additional circuitry along with ladder network. Register is an integral part of D/A converter which is formed using an RS flip-flop, with one F/F per bit. There

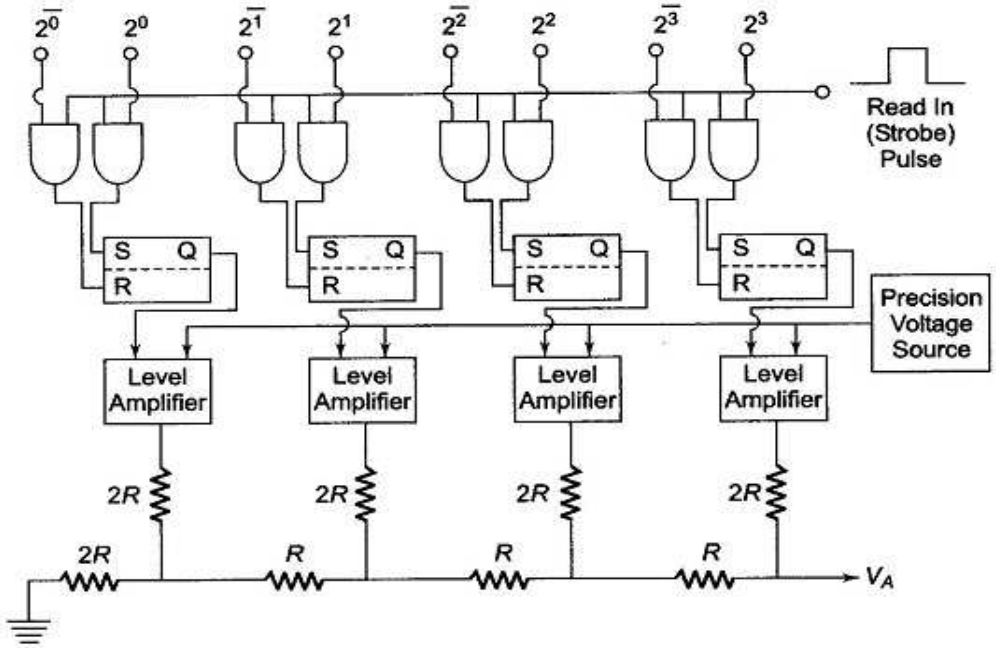


Figure 1.3

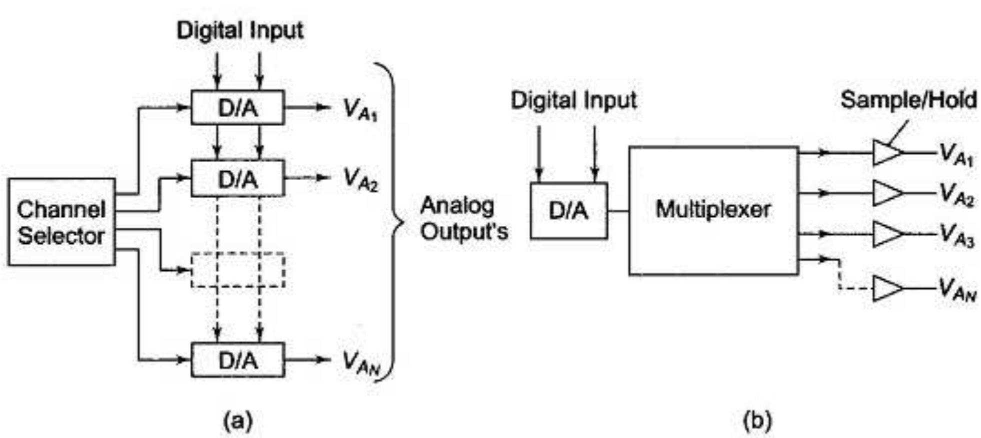


Figure 1.4

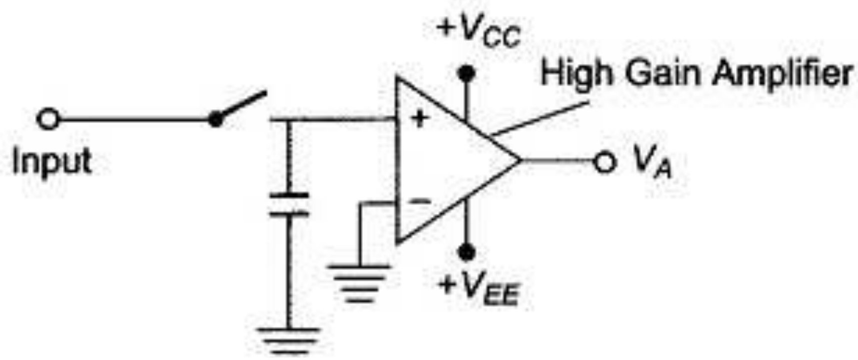
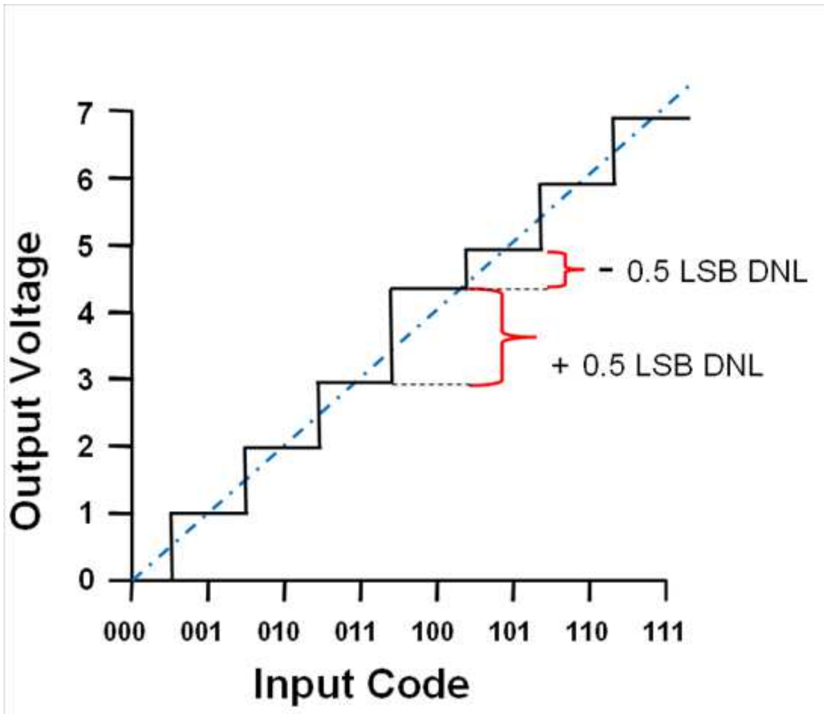


Figure 1.5

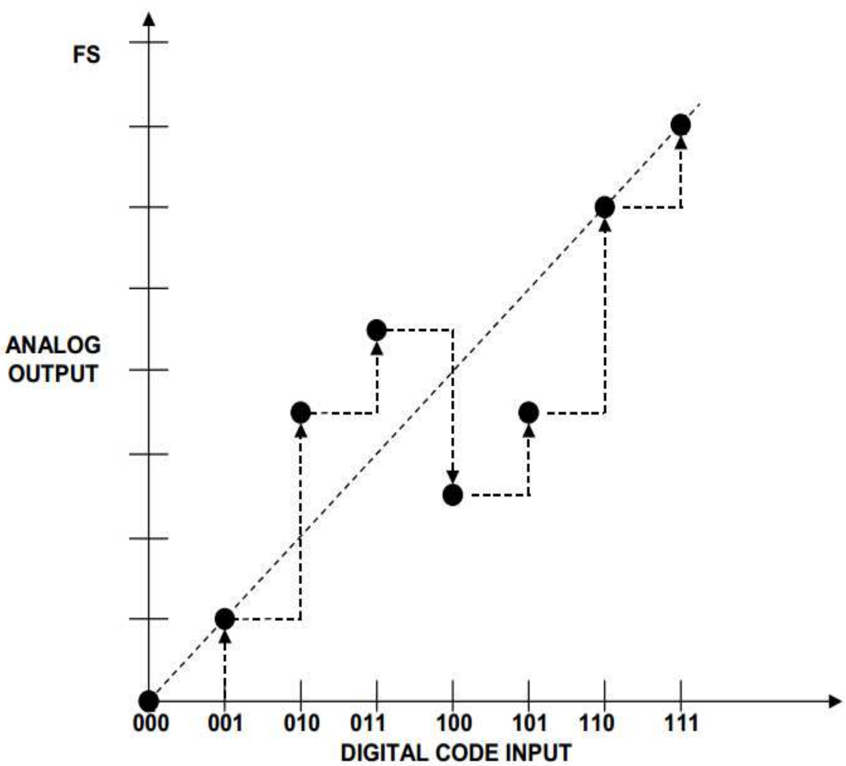
must also be a level amplifier between the register and the resistive network, to ensure that the digital signals presented to the network are all of the same levels and are constant. Finally there must be some form of gating on the input of the register, such that the F/F's can be set with the proper information from the digital system. A complete block diagram of 4-bit D/A converter is shown in Fig. 1.3. The F/F on the right represents the MSB and the F/F on the left LSB. When the real line goes high, one of the two gates connected to the F/F is true (enabled) and the F/F sets or resets accordingly. Hence the data are entered into the register each time the read in pulse occurs. When two or more digital signal conversion is required, one of the following two methods are used. In the first method, an individual D/A converter is used for each signal as shown in Fig. 1.4(a). The digital input line is connected to these converters in parallel. A channel selector is used for selecting the output line. The advantage of this method is that each signal to be decoded is held in its the register and analog output voltage is then held fixed. The second method consists of only one D/A converter and a multiplexer for switching its output as shown in Fig. 1.4(b). The disadvantage of this method is that the analog output signal must be held between sampling periods and the outputs must therefore be equipped with the sample hold circuits.

Figure 1.5 shows a sample hold amplifier. When the switch is closed (the output signal line is selected by the channel selector), the capacitor charges to the D/A converter output voltage. When the switch is opened, the capacitor holds the voltage level until next sampling time. The opamp high input impedance ensures that the capacitor is not discharges appreciably. When a D/A converter is used in conjunction with a multiplexer, the maximum rate at which the converter can operate must be considered. Each time data is shifted into the register, transients appear at the output of the converter. A settling time must be allowed between the time data is shifted into the register, and the time the analog voltage is read out. The settling time is the main factor in determining the maximum rate at which the output can be multiplexed.

Two important errors associated with a D/A converter are *non-linearity* and *non-monotonicity*. In the first image in Fig.1.6, the plot of analog voltage versus digital input code. For an ideal



Output Voltage
7
6
5
4
3
2
1
0
000
001
010
011
100
101
110
111
Input Code
- 0.5 LSB DNL
+ 0.5 LSB DNL



FS
ANALOG
OUTPUT
000
001
010
011
100
101
110
111
DIGITAL CODE INPUT

Figure 1.6

D/A converter, an a single increase in digital input should produce an output voltage change by V_{LSB}. However, in some cases, this step change is not equal to V_{LSB} a shown in the figure. This is called as D/A non-linearity. In some situations, a monotonic increase in digital input does not produce monotonic increase in the analog output voltage. This aspect of D/A is called as its non-monotonicity. For a D/A converter, the non-linearity error is quantified as differential non-linearity error (DNL) as

$$DNL_{error} = |V_a(i+1) - V_a(i)| - V_{LSB} \tag{1.5}$$

where i indicates the digital input level. Dynamic range of a D/A converter is defined as the number of usable values. For example, for n-bit D/A converter, there are 2^n possible values. The dynamic range is given as $20\log 2^n = 6.02n$ dB.

References

1. Electronics Instrumentation, second edition, H S Kalsi.