A/D and D/A Conversion Methods

Chapter 7

INTRODUCTION

In order for the microcomputer to communicate with its environment, it is usually necessary to convert analog input signals to the microcomputer into digital format so that they can be manipulated by the microcomputer in its own "language". Similarly, digital output signals from the microcomputer often have to be converted into analog form so that they can be used and acted upon by external circuits. This chapter is concerned with the most common techniques used to achieve analog-to-digital (A/D) and digital-to-analog (D/A) conversion.

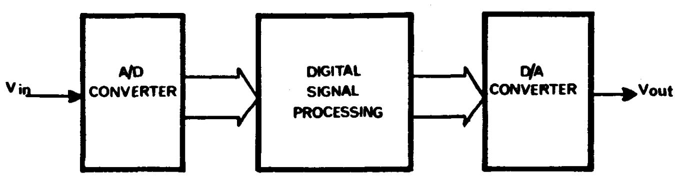

Figure 7-1. Basic method of using A/D and D/A converters

The relationship between analog and digital circuits is usually defined in terms of the number of bits used to specify a given range of signal values. For example, an 8-bit D/A converter can specify voltages in the range 0 to +10 volts with a resolution of 10×2^{-8} volts so that:

00000000	=	0 volts
00000001	=	0.03906 volts
00000010	=	0.07813 volts
	⋮	
11111110	=	9.9219 volts
11111111	=	$10(1\text{-}2^{-8})$ volts = 9.9961 volts

A D/A converter is a circuit which, when presented with a binary number at its input, gives an output voltage proportional to that binary number. An A/D converter performs the reverse operation; an analog input gives rise to a digital output whose numerical value is a representation of the analog input. The analog/digital relationship is not usually one-to-one (e.g., 5 volts is not usually represented by 00000101), but some scaled relationship such as:

Full-scale analog input = $2^n - 1$ when n is the number of bits available in the digital representation.

This chapter attempts to give a brief review of conversion methods and their applications to microcomputers.

DIGITAL-TO-ANALOG CONVERSION USING RESISTIVE NETWORKS

The resistive network is perhaps the classical digital-to-analog converter. Figure 7-2 shows an elementary form of D/A converter using binary weighted resistor values. It consists of a series of switches and an operational amplifier used as an adder. The switch for a particular bit is closed for logic "1" and is opened for logic "0." The diagram shows the position of the switches for the binary number 0011.

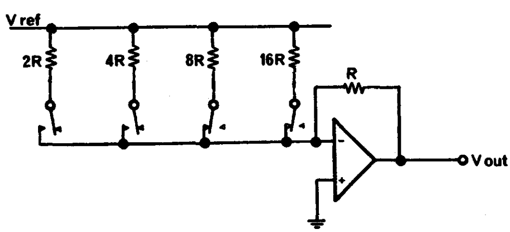

Figure 7-2. Binary weighted D/A converter

Unfortunately the system of Figure 7-2 is only suited to relatively low-resolution systems (5 bits) because it involves a wide range of resistor values, and it is difficult to match resistors in ratios greater than about 20 : 1. The R-2R ladder network shown in Figure 7-3 is more commonly used because the network can be constructed from only two values of registor. Each switch is a single-pole double-throw type which connects the 2R leg to either the reference voltage V_{REF} or ground. This design has the disadvantage that the switches, which are usually semiconductor devices, need to be high voltage units capable of operating under difficult bias conditions. As a result the inverted R-2R ladder shown in Figure 7-4 is used in most contemporary designs because the switches run with a small constant voltage across them which makes for easier design and fabrication.

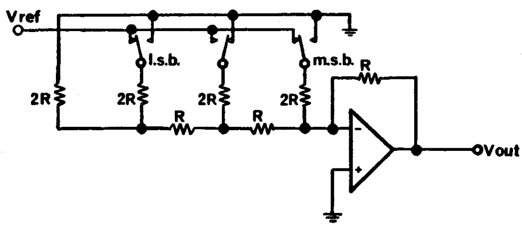

Figure 7-3. Standard R-2R D/A converter

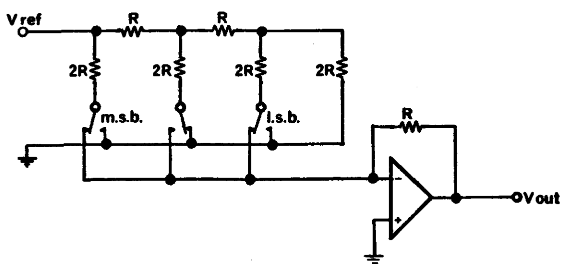

Figure 7-4. Inverted R-2R D/A converter

It is important to note that the D/A converter gives out a voltage which is proportional to the product of the digital input and the reference voltage V_{REF}.

If the reference input is connected to some analog voltage of interest, the D/A converter behaves as a variable attenuator (or multiplier) which is set digitally. In general, D/A converters which use bipolar IC components can only function with positive values of V_{REF} and then may only be used to attenuate a limited range of positive signals. Properly designed D/A converters using MOS analog switches can be used with both positive and negative values of V_{REF} and therefore are more suited for true multiplying applications where it is desired to multiply an analog signal at the V_{REF} input by some digital number.

DIGITAL-TO-ANALOG CONVERSION USING PULSE-WIDTH MODULATION

It is possible to perform digital-to-analog conversion by creating a series of pulses whose mark-space ratio is proportional to the digital values (see Figure 7-5). For example, in a simple 6-bit pulse-width modulated D/A, the binary number 011010 (=26) would be represented at the output as a continuous rectangular waveform with a "mark" width of 26 units and a "space" width of 63-26 = 37 units. The rectangular waveform is passed through a low-pass filter to obtain the dc signal output. A simple pulse-width modulator would be a continuously running binary counter feeding a comparator, the other side of which is connected to the binary value to be converted (see Figure 7-6). The comparator gives an output when the counter value is less than the binary value. The system has only limited resolution and a very slow response time due to the low-pass filter. It can be improved somewhat by replacing the counter with a pseudo-random binary sequence generator that generates exactly the same range of

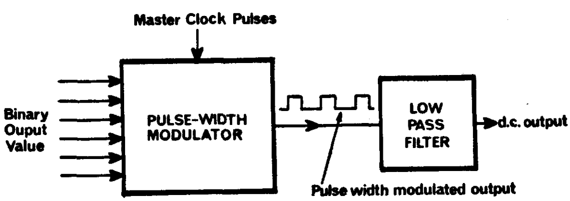

Figure 7-5. Pulse-width modulation D/A converter

numbers but in a random fashion. In this way the low-pass filter cut-off frequency can be raised and better resolution up to about 8 bits can be obtained.

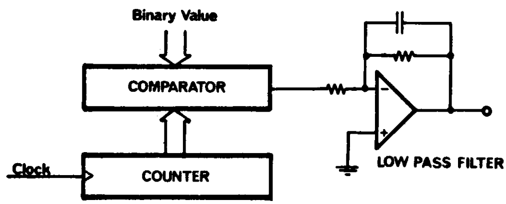

Figure 7-6. Possible hardware circuit for pulse-width modulated D/A converter

TRACKING A/D CONVERTERS

Figure 7-7 shows a tracking A/D converter. It consists of an up/down counter which drives a resistive ladder type D/A converter. The output from the D/A feeds one side of a comparator and the analog input V_{IN} feeds the other side. If the D/A output is less than V_{IN} the comparator causes the counter to count up on the next clock pulse and if the D/A output is greater than V_{IN}, the counter counts down. In this scheme the maximum track rate of the A/D is governed by the settling time of the comparator and the clock frequency. Tracking A/D converters can normally be used up to low-audio frequencies although it is possible to speed-up the conversion process by using "panic-mode" tracking where the counter is incremented in steps of, say, 4 units until the converter is in the correct range.

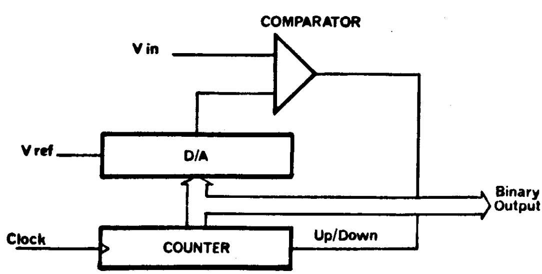

Figure 7-7. Tracking A/D converter

SUCCESSIVE-APPROXIMATIONS A/D CONVERTER

The successive-approximations A/D converter (see Figure 7-8) uses much the same logic configuration as the tracking A/D converter but the counter is replaced by a successive-approximations register (SAR). Successive-approximations is essentially a "try it and see" method. Initially the most significant bit of the SAR is set to "1" causing the D/A converter to give-out a half-range analog value. If the comparator output is high, the MSB of the result is set to a "1", and if it is low, the MSB is set to "0." The resulting MSB

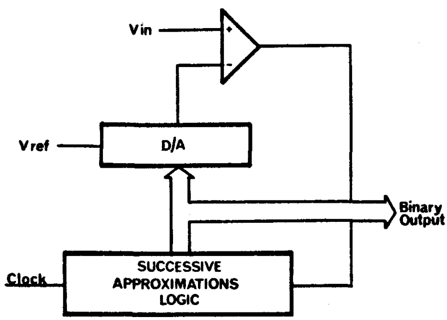

Figure 7-8. Successive-approximations A/D converter

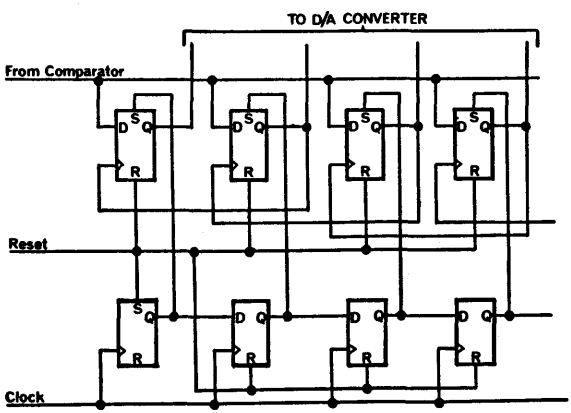

Figure 7-9. Successive-approximations logic

determines the D/A converter input and the logic proceeds to test the next lower bit in the same way (see Figure 7-9). This series of approximations continues until all bits have been determined. Successive-approximations is a very fast method of A/D conversion because for an n-bit conversion the conversion time is only n times the D/A and comparator settling time. A monolithic 10-bit converter like the AD571 can achieve a 10-bit conversion in less than 20μs.

DUAL-SLOPE INTEGRATING TYPE A/D CONVERTERS

An integrating dual-slope D/A converter performs the conversion process by feeding the unknown signal to an analog integrator for a fixed period of time. The unknown signal is then removed from the integrator input and a reference voltage of opposite polarity is applied. The time taken for the integrator to ramp back to its starting point is a measure of the magnitude of the unknown analog input. Figure 7-10 shows the basic circuit for a dual-slope converter.

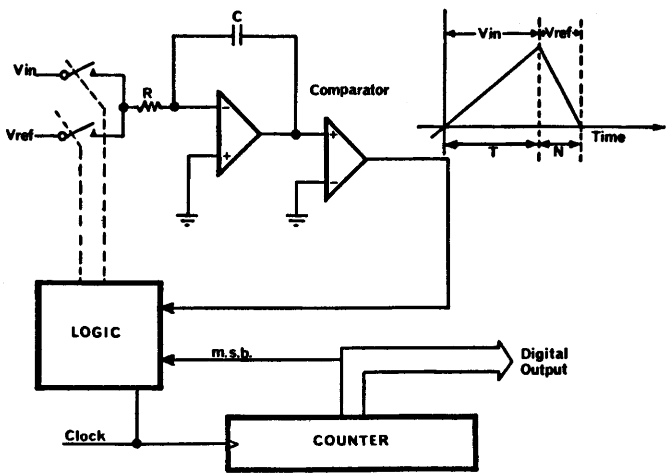

Figure 7-10. Simplified block diagram of dual-slope A/D converter

In practice, the counter is usually set to zero at the start of the conversion. When the counter has reached the all "ones" state and

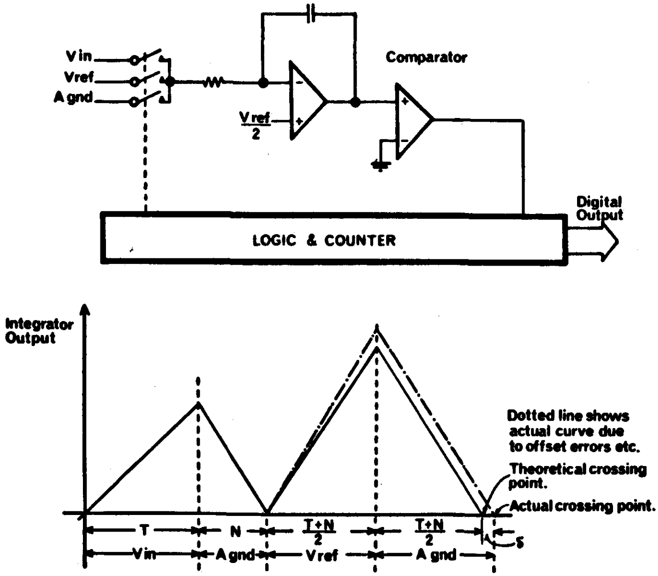

Figure 7-11. Simplified quad-slope converter

is about to proceed to the all "zero" state, the switches change over. Thus the counter is set to zero at the beginning of the ramp-down period and its accumulated count N is a direct measure of the analog input. Dual-slope has the advantage that errors are minimised because the same analog loop is used for both the V_{IN} and V_{REF} signals. In this way long term variations in the values of R and C do not affect the overall accuracy (see Figure 7-10). Unfortunately the circuit is sensitive to zero offset and drift in the integrator and comparator. It is normal to supplement the basic dual-slope with some additional circuits or logic to achieve compensation for these effects. One method is the Quad-Slope* approach shown in Figure 7-11. The circuit initially makes a dual-slope conversion on the unknown analog input and then repeats the conversion *over exactly the same period of time* using reference inputs. If there is no error in the analog circuits then the final ramp should hit the comparator crossing point after time (T+N),

*Analog Devices – U.S. Patent No. 3872466.

but if there is error then the crossing point will occur at some other time. Since this error δ has been accumulated over period (T+N), it is a measure of the error incurred in the first conversion process, and therefore the true value of N can be obtained by subtracting δ from N. The actual implementation of the quad-slope process is rather more complicated than would appear from the above description. There is increasing emphasis on methods which, like the quad-slope method, supplement the basic dual-slope process with addition calibration phases to measure the error and then use a microcomputer to remove this error from the original measured value. The error corrected dual-slope conversion technique enables high resolution to be obtained (the Analog Devices AD7550 achieves 13 bits), but because of the integration process, it suffers from the disadvantage of low conversion speed.

OTHER TYPES OF INTEGRATING A/D CONVERTERS

The concept of charging a capacitor from an unknown signal and then discharging the capacitor with a reference source can be applied in many ways. Some of the available techniques are considered here.

Charge-balancing A/D converters. With charge-balancing A/D converters (see Figure 7-12), the integrator input is switched repetitively between the unknown analog input and a reference source. This enables the integrator's output to be held within certain limits defined by the comparator hysteresis. The analog input value is found from the proportion of time within a given

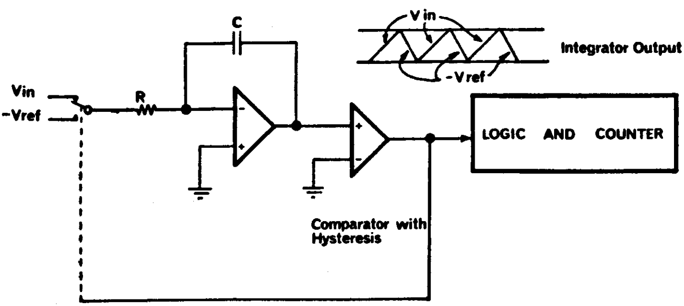

Figure 7-12. Basic charge-balancing converter

time frame that the reference signal has to be connected to the integrator input. In practice it is necessary to include a zeroing period prior to the measuring period. The charge-balancing method has the advantage that, as analog signal swings are small, the integrator operates over a small dynamic range. However, since the switches open and close frequently during a measuring period, errors that occur at switching points are magnified.

Voltage-to-frequency conversion. The previous charge-balancing circuit is a form of voltage-to-frequency converter since, as the input voltage increases, the ramp frequency increases. Voltage-to-frequency converters take several forms, but in principle most of them are of the charge-balance type. They operate by charging a capacitor from a current source which is proportional to the input voltage, and then discharging the capacitor with a precise current each time the charge on the capacitor reaches a pre-set level. This technique is shown in figure 7-13. Voltage-to-frequency converters have relatively poor performance for low input voltages due to offset voltage errors. In addition, there is an upper frequency limit imposed by the slew rate and settling time of the amplifier, but with careful design it is possible to achieve a dynamic range of better than 10^4. In order to accomplish A/D conversion, it is normal to feed the comparator output pulses into a counter for a fixed period of time. The accumulated count is proportional to the input voltage.

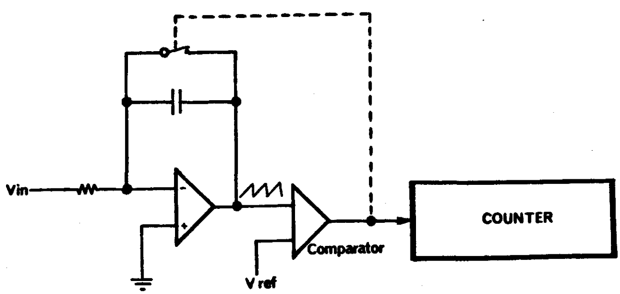

Figure 7-13. Voltage-to-frequency converter

MULTI-COMPARATOR LADDER

For high-speed low-resolution applications, it is possible perform the A/D conversion function by using one comparator for each possible level and feeding the input signal to all comparators. This method is shown schematically in Figure 7-14. Unfortunately it requires ($2^n - 1$) comparators for an n-bit binary word. The comparator outputs have to be encoded into the appropriate binary word.

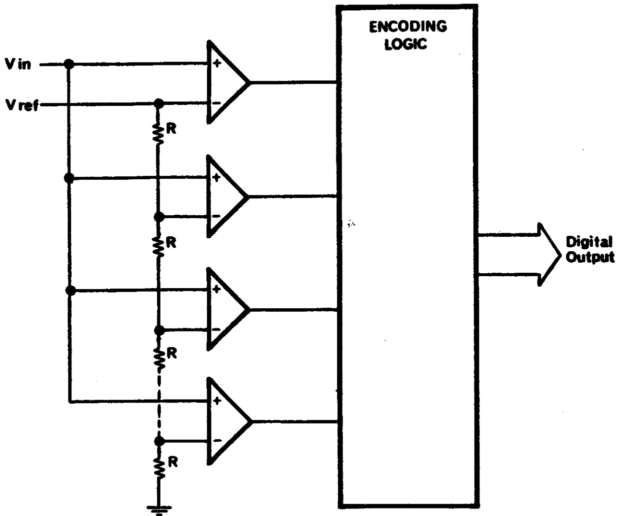

Figure 7-14. High-speed A/D converter using multiple comparators

D/A CONVERTERS USING MICROCOMPUTERS

In very low cost applications it is sometimes desirable to use the microcomputer for the D/A conversion function in order to avoid the expense of the D/A circuit. The pulse-width modulation type of D/A converter is particularly suitable for implementing on a microcomputer because it only requires 1 bit of output plus a low pass filter as shown in Figure 7-15. The microcomputer achieves the counter and comparator function of Figure 7-6 by means of software and it increments the counter at regular intervals. Usually the increment points are determined by a real-time clock which drives the microcomputer interrupt system. As long as the "counter" contents are less than the desired output value, the output bit is set to a "1" and once the counter is greater than the desired value, the output bit is set to a "0".

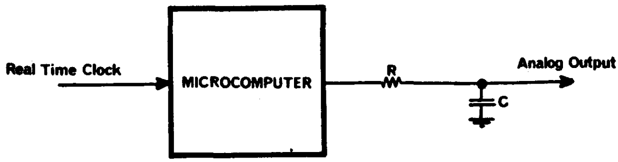

Figure 7-15. Pulse-width modulation D/A conversion using a single bit output from a microcomputer

This method of D/A conversion involves a significant amount of software time and can only be used where the microcomputer is not heavily taxed with other tasks. In addition, it has poor resolution and the apparent saving in external circuits is usually lost by the requirement for analog buffering of the signal. Nevertheless, it does have some uses and the domestic temperature control circuit of Chapter 9 is an example of one application.

A parallel output port can be used to drive a binary weighted resistor network such as shown in Figure 7-2, but limitations are imposed by the output impedance of the port and sensitivity to logic supply levels.

A/D CONVERTERS USING MICROCOMPUTERS

Figure 7-16 shows the basic method for implementing analog-to digital conversion using a D/A converter, a comparator and a microcomputer. The A/D conversion logic is implemented in software by the microcomputer, and can be programmed to emulate either the successive-approximations or tracking methods discussed earlier. However, there are some important speed limitations incurred by using the microcomputer to carry-out the required logic.

Successive-approximations is primarily a high-speed A/D conversion technique, and it requires the analog input to be absolutely steady whilst a conversion is made if gross errors are not to occur. For this reason successive-approximation converters are often

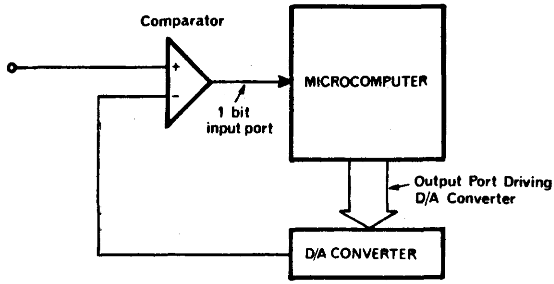

Figure 7-16. A/D converter using microcomputer to implement logic

preceded by a sample-and-hold circuit. Unfortunately, most microcomputer designs are not well-suited to carrying out the successive-approximations method and as a result conversion times are unduly long. This, in turn, places more stringent emphasis on the analog signal remaining steady over the whole conversion period, and therefore the use of a sample-and-hold circuit becomes more essential.

The tracking type of A/D converter is more suitable for software implementation because only a single instruction is required to increment a value. However, conversion times are inherently slow and this can lead to a loss in valuable software time. Nevertheless, in applications where the A/D conversion is used to monitor and follow a fairly low-frequency signal, the tracking method has much to recommend it.

In any A/D conversion process the microcomputer can, in principle, be used to replace the conversion logic. However, in practice, this is often not feasible because the conversion uses valuable software time which the microcomputer can ill afford. Also, many converters like successive-approximations require the undivided attention of the microcomputer during the conversion process and it is not always possible to mask-off all interrupts for a whole conversion period.

SUMMARY

This chapter has, of necessity, given a brief coverage of the type of D/A and A/D converters in common use. These are:

D/A – Weighted resistors
– R-2R ladder
– Pulse-width modulation

A/D – Tracking
– Successive-approximation
– Dual-slope integrating type
– Charge-balancing
– Voltage-to-frequency conversion
– Multiple comparator.

The choice of conversion technique is governed by many factors and Chapter 8 attempts to show some of the design parameters that should be considered when using data converters.