12-Bit DAC Design Can Be Routine . . . 16 Bits is More Difficult, But Achievable

by Cyril H. Brown and Wayne Marshall

Complete D/A Converters in modular form, characterized by virtually all practicable levels of resolution, are available commercially from Analog Devices* and an increasing number of other sources in the industry. The prices of complete units are highly competitive with the costs of "do-it-yourself," especially for resolutions of 10 bits or less.

For higher resolutions, the design problems (principally obtaining switch and resistor networks having adequate matching and tracking with temperature) can be solved at reasonable cost by purchasing complete units. Nevertheless, there are many applications for which the user has a compelling necessity to build-his-own (because of special form factor, interfacing, or company policy). Until recently, the effort of obtaining selected components was a major source of cost and inconvenience.

To serve the needs of such users, Analog now makes available μDAC components for D/A and A/D Converters. These are low-cost monolithically-matched sets of switches and resistors capable of 12-bit (and better) performance, the "secret ingredients" of our complete modular converters. The μDAC's bring 12-bit converter design – to fit a wide variety of physical forms – within the province of any competent circuit design engineer, at a cost he can afford. The details of the AD555 *voltage* switches and R-2R ladder networks were discussed in *Dialogue*, Vol. 5, No. 2. The details of the AD550 *current* switches have been spelled out in a number of publications.† In the pages that follow, we summarize a number of ideas about low-frequency aspects of the use of current switches in high-accuracy D/A conversion.

WHAT 12- AND 16-BIT ACCURACY MEAN

There are few electrical instruments in routine high-volume use of which we expect and demand the order of resolution and stability nominally specified for D/A and A/D converters (including DVM's, which are BCD A/D's with visual readout). 12-bit converters are now fairly commonplace, and it is with only slight discomfort that we remind ourselves that ½LSB nonlinearity (see Definitions on facing page) in a 12-bit binary converter means 1 part in 2^{13} (=8192), or 120 ppm! And we really have to shift our thinking into overdrive to contemplate 16-bit converters, in which ½LSB amounts to 7.6ppm! Interpreted in more tangible terms, the limits of error for an ideal DAC or ADC operating at 10V nominal full-scale are

	LSB value (resolution)	½LSB (relative accuracy)
16 bits	152μV	76μV
12 bits	2.4mV	1.2mV

The 16:1 difference in magnitude can appear startling: 1.2mV is already small enough, but 76μV can be well into the noise level for many kinds of equipment. At any rate, this brief preliminary consideration may suggest that, while 12-bit resolution is just at the threshold of "multiple influence" (many individually-negligible contributions affecting error), 16-bit resolution requires control (minimization or isolation) of a very large number of influences, including not only the quite stringent tolerances on switch and resistor matching, but also the op amp voltage and current offsets, stray leakages, thermocouples in lead junctions, power supply noise coupling, and other sources of both inherent and induced noise and drift. Even milliohms of series resistance now become important, and one must look with a jaundiced eye at one's calibration standards if "absolute accuracy" is a part of the specification.

We will discuss here new circuit design techniques and components that make 12-bit performance achievable for a careful circuit designer, freeing him from arduous matching; and we will attempt to provide a suggestion as to how limitations of the basic components are overcome in 16-bit converter design (without presuming to suggest that *anyone* can – or should – design his own, because of all the many unimportant characteristics of components, subassemblies, interfaces, wiring, and system environment that suddenly become very formidable.)

ELEMENTS OF 12-BIT-ACCURATE DAC's

Figure 1 is a schematic of the critical portions of a DAC having 4-bit resolution but capable of excellent linearity. The reference supply is shown at the left. Feedback amplifier A1 stabilizes the average resistance of zener diode Z1 by exciting the bridge, Z1, R7, R8, R9 (see *Dialogue*, Vol. 5, No. 1, page 13). With a reasonably good operational amplifier at A1, and metal-film resistors for R7, R8, and R9, the supply rejection of the reference zener will be about 10^6:1, and temperature and time stability will depend primarily on those properties of the zener itself. Performance appropriate for 12-bit DAC performance is not hard to find.

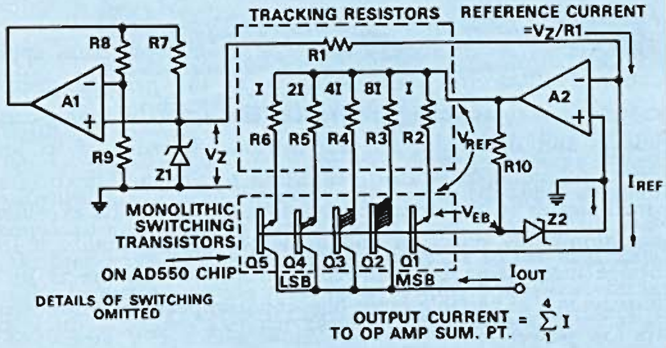

Figure 1. High-accuracy basic 4-bit D/A converter. Resistor chip also contains feedback resistor of output op amp (not shown).

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*For data on Analog's complete line of D/A and A/D Converters and conversion accessories, use the reply card. Circle C3

†See: "μDAC AD550 & AD850 *Application Note*" and detailed technical bulletins on μDAC AD550 and AD850. For further information on applications of current-switching D/A Converters, see "*MINIDAC Application Note.*" To receive a complete "package" of μDAC information, enveloped in a jacket outlining specific ordering information, use the reply card. Circle C4

Q2, Q3, Q4, and Q5 are switching transistors located close to one another on the chip, and also in close proximity to Q1, a reference compensation transistor. Because of the monolithic construction and identical transistor geometry, all five units are well matched, and they track well with temperature. Thin-film resistors, R1 through R6, are built on a single monolithic chip and are trimmed initially to high accuracy. They have inherently-excellent temperature tracking.

The details of the TTL/DTL-compatible switching circuitry need not be discussed here.* When the switches are open (logic "true"), output leakage current is negligible. When the switches are closed (logic "0"), they contribute binarily-weighted collector currents to the output bus, which is usually connected to the summing point of an operational amplifier. The resistor chip also contains a feedback resistor, which tracks the other resistors, for current-to-voltage conversion with minimal error.

Resistance R_1 is such that V_z produces a current of 1/8 mA through it. This is the basic reference current. Operational amplifier A2 maintains the voltage at its negative input at zero and causes I_{ref} to flow through the collector circuit of Q1. Augmented by Q1's base current, it develops a negative reference voltage across R2. The operational amplifier develops the necessary voltage to supply the baseline voltage, (via Z2) the emitter-base voltage, and the reference voltage developed by the emitter current of Q1. Because the switching transistors all share a common base line, and because their V_{EB}'s track, essentially identical voltages appear across R3, R4, R5, and R6. The resistance of R3 is 1/8 that of R2, and the emitter current of Q2 is thus 8x that of Q1 (i.e., 1mA). Because Q2 has 8 paralleled emitters, the current density is identical to that of Q1, and V_{BE} tracking is near-perfect; hence the voltage across R3 is identical to that across R2, both initially and as a function of temperature. The collector current contributed to the common output summing junction is thus very nearly 8x the reference current, since the base current (8-fold increased) tracks that of Q1. R3 tracks R2, tending to maintain the 8:1 ratio, independently of temperature variations.

Similarly, the collector current of Q3 = 4x that of Q1 (or $4I_{ref}$), and Q4 and Q5 contribute $2I_{ref}$ and I_{ref}, respectively. Thus, depending on which transistors are switched on and which are switched off, a range of precise currents from 0 to $15I_{ref}$ is available (i.e., from 0 to 1.875mA). Finally, because the feedback resistor of the output op amp also tracks R1, the output voltage depends almost solely on the stability of the basic zener reference, and not at all on the initial accuracy of the resistors, so long as they track one another.

To summarize, the absolute value of the output current *does not depend* on either the absolute value of the resistors or the parameters of the switching transistors; only the tracking, or ratio accuracy, is significant. For instance, if age or temperature should cause R2 to increase in value, then all resistors would tend to change in the same ratio, thanks to the monolithic construction. The only observable manifestation of change would be a decrease in reference current (which would be compensated for by an increase in feedback resistance around the output amplifier.

WHAT IS ACCURACY?

All too often, the many parameters which define the performance of a converter are lumped into something called "accuracy." We must be careful to define our terminology, especially when discussing high-performance devices. The following guidelines should be useful to those attempting to relate converter specifications to the intended usage.

Accuracy is the exactness with which any level of a D/A converter's output agrees with the reading of a working standard, which is itself traceable to a primary standard. Most commercially-sold devices are adjustable by the user to any desired zero and full-scale *absolute accuracy,* within the resolution of the adjustment, under a prescribed set of conditions.

Relative accuracy The closeness with which the ratio of the value of a point on the defining function to full scale approaches the ideal ratio. For linear functions, which are characteristic of most D/A converter types, *relative accuracy* and *linearity* are often (but not always) interchangeable. Note that the maximum analog value of the function is not "full scale," but is usually of the order of an LSB below full scale, depending on the digital code and its implementation.

Linearity is the closeness of the function at every point to a "best" straight line. Linearity within ±½LSB insures *uniqueness* and *monotonicity.*

Differential linearity is the closeness of each incremental step to the ideal 1 LSB. If the differential nonlinearity is $<|1\text{ LSB}|$ at all transitions, uniqueness and monotonicity are guaranteed.

Monotonicity and *uniqueness* mean that each and every consecutive step is in the same direction, that each digital code corresponds to a unique portion of the analog range (D/A's), and that all intermediate codes exist (A/D's).

Resolution. Nominal resolution ("resolution") is the relative value of the "least significant bit (LSB)" or 2^{-n} for binary devices, when n is specified by the manufacturer. It may be expressed as 1 part in 2^n, as a percentage, in parts per million . . . or simply by n. *Useful resolution* (not usually specified) is the smallest *uniquely distinguishable* bit for all conditions of operation (time, temperature, etc.). For example, a "12-bit" converter may have a useful resolution, over its temperature range, of only 10 bits.

Useful resolution is limited by the relative accuracy, but resolution need not limit accuracy. For example, the 4-bit converter used as an example in this article has only 16 levels but each step might have a relative accuracy of 0.01%, which would be useful if one were building a digitally-programmed high-accuracy power supply stepping from 2.5V to 10V in 0.5V increments. Note also that low-cost completely-monolithic "6-bit" (or even "8-bit") DAC's would not have sufficient accuracy for such an application, although their resolution is adequate.

For some inherently-monotonic applications, accuracy need not limit resolution. A good example is the integrating A/D converter, in which the less-significant bits may not be accurate, but they do provide useful resolution.

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*See second footnote on page 6. See also page 11.

A single quad switch and resistor set covers a range of 15 increments (i.e., 4-bit resolution). If an 8-bit converter is required, one adds another set of four switches and resistors (Q2′ - Q5′ and R3′ - R6′). Its output is connected to the current output bus via a 16:1 current divider. If 12-bit resolution is needed, a third set of quads is added, with another 16:1 divider in the output, etc. Since the output of these less-significant quads is attenuated, so are their errors; hence, less expensive grades may be used. The entire *resistance* complement needed for a 12-bit DAC is available in a single package, the AD850, to accompany the three graded AD550 quad switches.

For BCD (binary-coded decimal) networks (AD851), the inter-quad attenuators are 10:1 instead of 16:1. That's all!

APPROACHES FOR 16-BIT DAC'S

For a 16-bit converter, one LSB is 15ppm of full scale! Thus, we can allow only a few ppm to account for resistor errors, switch errors, and tracking errors. The AD850L thin-film resistor network is trimmed to relative magnitudes within 0.01% or so, but the tracking is to within 1ppm/°C. A selected AD550 current switch can maintain ½ppm/°C in output linearity in terms of the V_{EB} differential between switches. With these components, (everything else being perfect), a system can be built having linearity within 1.5ppm/°C and gain stability within 2ppm/°C, plus errors due to the reference. Zener aging will be the prime cause of long term drift, typically of the order (for some readily-available units) of 5 to 10 ppm/month.

Two practical problems that arise are these: finding a suitable method of trimming the most significant bit resistors to the needed accuracy, and overcoming errors caused by series resistance and thermal voltage drops in the output leads.

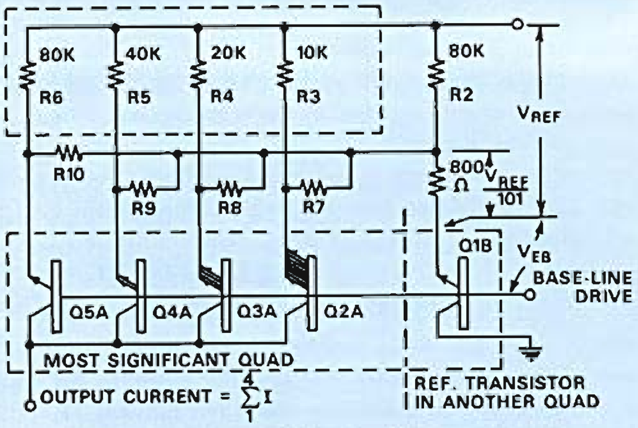

Figure 2. Resistance-Trimming Scheme, showing how practical resistance values can be used by attenuating the reference voltage

Trimming. First of all, it should be pointed out that ordinary lab test equipment, such as digital voltmeters, are almost never adequate in resolution and stability to perform as standards for the calibration. A resistance network of primary standard quality must be used, and ratiometric measurements must be applied.

It's also interesting to note that simple series or parallel trimming of the resistor network is *not* feasible. 5ppm of 10kΩ is only 0.05Ω in series or 2000MΩ in parallel, both impracticable values. Series trimming will be suitable for lower-order quads, since the resistance resolution needed will be of the order of 0.5 to 1. ohm. An interesting approach is shown in Figure 2. It is a shunt scheme in which a voltage divider is used to apply 1/101 of the reference voltage to the trim resistors, R7, R8, R9, and R10, thus magnifying them in the same ratio. In the circuit, as shown, a value of 10 megohms at R7 would cause a current change through Q2 of about 10ppm, equivalent to 1,000MΩ in parallel with R3.

External sensing Consider that, for a 16-bit converter operating with 10 volts full scale, one LSB is 152μV. If the load current is 10mA at full-scale output, and series wiring and connector resistance is only 15mΩ, the output will be in error by 1 LSB. To make output independent of lead resistance, the circuit may be slightly modified to provide sensing of the output (by the op amp's feedback circuit) at the load itself. Figure 3 shows one way of accomplishing this. For the circuit used in Analog's DAC-16QG, typical output impedance is 1 milliohm, low enough to cause negligible error.

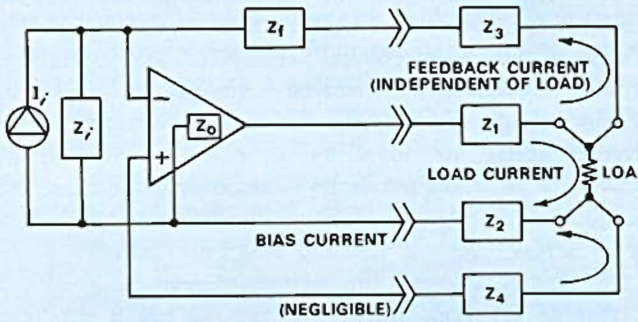

Figure 3. Sensing Scheme for making load voltage essentially independent of lead resistance and connector thermals; output resistance ($Z_o + Z_1 + Z_2$) is reduced by loop gain

The 4-terminal output configuration will have increased capacitance and inductance, which will adversely affect either loop stability or speed or both. Settling time of 25μs is not unfeasible with lead lengths of about 1 meter, in conservatively-designed practical units.

USES OF 16-BIT DAC'S

Uses of 16-bit DAC's are pretty much the same as those of lower-resolution converters, only with greater resolution and accuracy. However, there are some new applications that become feasible:

1. Testing lower-resolution converters by direct comparison
2. High-resolution histograms
3. High-resolution A/D converters to replace the combination of lower-resolution converters and programmable-gain amplifiers
4. High-accuracy programmable current or voltage sources

ERRATUM

In Volume 5, No. 2, of *Dialogue*, (green cover), on page 8, there is an error in Figure 3: The Z_{in} (3) and Z_o (9) terminal connections are interchanged. For multiplying, E_o (4) should be connected to Z_{in} (3), the offset trim to Z_o (9).