High-resolution A/D converters

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Designers' seemingly insatiable appetite for higher resolution and faster conversion speed has spawned a new generation of A/D converters that provide a flexibility not previously available. The new 22-bit converters combine high accuracy, an extremely wide dynamic range, and microprocessor compatibility in a modular package. These features make them an attractive alternative to bulky benchtop DVMs. In addition, new oversampling techniques have significantly reduced the cost of 16- to 20-bit converters over those using more traditional techniques.

Three manufacturers currently offer oversampling (also known as sigma-delta and delta-sigma) converters and others are planning to enter the market soon (see box, "Converters couple analog and digital filtering"). Many of the manufacturers of high-resolution products are mainstream players in the data-converter marketplace. Analog Devices, Analogic, Burr-Brown, and Micro Networks all have experience designing high-resolution ADCs. However, Thaler Corp's first converter is a 20-bit high-accuracy ADC, and Motorola has entered the field with an oversampling converter. Prema Precision electronics, a West German manufacturer of precision multimeters, produces a 25-bit ADC that is the highest-resolution converter available. These high-resolution converters are dedicated ADCs, not products that include internal ADCs and DACs and function as analog interface circuits.

According to many ADC manufacturers, the main reason for the movement toward higher and higher resolution is that data-acquisition-system designers want to make use of every bit of their transducers' resolution. They feel that if there has to be a limiting factor in the system it should be the transducer, not the ADC. Another reason is that higher-resolution converters can provide additional and often critical details about a set of data.

Ensuring the accuracy of this data is a very tough design task. Even a small amount of system noise can corrupt a high-resolution converter's data. The usual solution to this problem is careful layout and grounding, which will improve systems accuracy to the limits of the ADC. However, it's difficult to find a truly accurate 16-bit converter. Many 16-bit converters, for instance, have only 14 bits of accuracy. This level of accuracy is especially true of many of the successive-approximation types. Although a converter's integral nonlinearity may be 14 bits (equivalent to ±0.003% FSR), it may still provide no-missing-codes performance at 16 bits. Note that the linearity of some 14-bit ADCs matches that of many of the 16-bit products.
The world of high-resolution A/D converters is somewhat fragmented. Many converters are intended for very specialized markets. The successive-approximation converters serve many general-purpose data-acquisition systems. Other converters are closely tied to specific applications. Fortunately, every converter fits into one of two general classifications: those designed for the highest-possible dc accuracy in the dc sense, and those designed for signal processing and good ac specs. Two general applications are associated with these categories: precise measuring systems and DSP applications.

Many oversampling converters are intended for signal-processing applications, therefore their data sheets usually quote complete dynamic specifications. But this trend isn't confined to oversampling converters. As DSP applications proliferate, so does the number of high-resolution converters specifically aimed at these applications. To help designers evaluate and compare converters' ac performance, many new converters are fully tested and specified for dynamic characteristics such as S/N ratio and THD.

For applications that require the highest possible dynamic range, take a look at the high-resolution integrating converters. These high-accuracy converters are a world unto themselves. ATE, process control, and weighing systems are typical application areas for them. These ultrahigh-resolution converters are also used in medical and scientific instrumentation that must be able to distinguish extremely small differences in element or chemical concentrations.

**Achieving high resolution and high accuracy**

Prema Precision electronics' 25-bit converter with its 0.001% nonlinearity and typical temperature coefficient of 0.5 ppm/°C suits weighing systems and precise data collection. The converter utilizes a patented multiple-ramp method that continuously integrates the measured signal to cancel interference. In order to use this ADC you must develop your own microprocessor control. For integration times of 20 msec, 200 msec, 2 sec, and 20 sec, you can achieve a 15-, 18-, 21-, and 25-bit result, respectively. The software also controls the handling of gain and offset adjustments. A key feature of the ADC 5601 is its compact 2× 2×0.4 in. size.

Analog Devices' 22-bit AD1175 was designed for data-acquisition systems that had relied on DVMs and DMMs to make dedicated measurements. Its resolution and accuracy compete with 6.5-digit DVMs. The AD1175 data sheet quotes a wide dynamic range of 133 dB. This range is higher than what $2^{22}$ indicates because the part's accuracy is guaranteed for inputs to 10% above the nominal full-scale input range.

Unlike Prema's ADC 5601, the AD1175 is a complete microcomputer-based measurement subsystem. It consists of three major elements: a linearized, autozeroed integrator, a single-chip microcomputer, and a custom CMOS controller/bus interface chip.

You don't need any external components for the AD1175, and all its digital inputs and outputs are LSTTL compatible. The analog input is a high-impedance, 1-GΩ, high-CMRR, true differential-input pair. The AD1175 interfaces to any microprocessor-based system via an 8-bit data bus. Analog Devices recently announced a PC-compatible evaluation card for the AD1175 priced at $495. This card comes with simple Basic software that allows you to send commands to the AD1175 and test its performance.

The AD1175 utilizes a multislope-integrating principle that's similar to the classic dual-slope technique. The input signal is integrated during an integer number of line cycles, then the ADC makes a digital measurement of the time required for a known reference voltage to drive the integrator output back to zero. You can select the integration time for maximum line-frequency noise
rejection at either 60 or 50 Hz. Internal autozeroing occurs at every conversion, without reducing the throughput rate. During each autozero cycle, the device offsets and low-frequency noise of the converter's main elements are acquired and held; they will be cancelled in the conversion. This circuitry holds the AD1175's input-offset drifts to less than 0.5 µV/°C.

**High accuracy requires stability**

The ADC100 is Thaler's first entry in the A/D converter market. Their design focus in the past has been reference technology. Like the AD1175, the ADC100 has an onboard microprocessor that controls all internal functions, and a PC evaluation card for it will be available soon. You need two external parts to apply the ADC100: a 25-MHz crystal and an integration capacitor, both of which Thaler supplies. The company quotes the ADC100's analog-input impedance as 200 GΩ.

Thaler's ADC100 has some advantages over the AD1175 in offset and gain stability. Although the ADC100 has lower accuracy and throughput, it is fully specified for operation from -25 to +85°C. The AD1175's range is 0 to 70°C. In addition, the ADC100's maximum offset and scale-factor error of 0.1 and 0.5 ppm/°C compare favorably with the AD1175's ±0.5 µV/°C and ±1-ppm/°C errors. The ADC100's onboard microprocessor performs autozeroing automatically at start-up, but Thaler recommends that you repeat it after the ADC is fully warmed up to ensure maximum accuracy.

Thaler stresses that you must take temperature effects into account when calculating system accuracy (Ref 1). The company warns that even in a standard laboratory environment, temperature effects can significantly degrade a system's accuracy. In order to calculate the accuracy, you must take both the converter's and the internal or external reference's gain error into account. The maximum error over temperature is the converter's linearity error plus the product of the combined gain TC and the temperature.

V/F converters can also offer high resolution. A V/F converter coupled with a counter/time IC allows you to trade resolution for conversion time and vice versa. Dymec's 32824 instrumentation A/D converter and the 5024 programmable counter/timer ($15) together form an A/D system that supports both frequency-counting and period-averaging measurement techniques. At 10 conversions/sec this ADC achieves a sensitivity of 10 µV, which is the equivalent of 20 bits of resolution in a 10v signal. For a conversion time of 1 sec, the sensitivity of this system is 1.1 µV or 23 bits. The analog front end is completely isolated from the rest of the system. This isolation guarantees that the ADC is free of ground loops and digital noise in the analog section, two absolute requirements if the system is to achieve sensitivities of 10 µV or better.

**500-kHz conversion rates are possible**

These high-accuracy, high-resolution parts represent only a segment of the marketplace. There are plenty of applications that require the highest speed available. High speed, however, is relative. You won't find any high-resolution converters with megahertz conversion rates. The current state-of-the-art high-speed plus high-resolution converters have conversion rates of 500 kHz. But you'll pay a lot for this speed. Analogic's, Analog Solutions', Burr-Brown's, and Datel's high-speed products cost between $500 to $900. Both Analogic and Burr-Brown introduced 500-kHz converters at the beginning of 1989.

Analogic's AM40016/40116 and AM41016/41116/41216 modular 16-bit converters are based on a multipass flash architecture that includes internal S/H amplifiers. The AM40016 is tailored for the digitization of several multiplexed channels, such as in automatic test equipment. The AM41016 series features low distortion and was designed for frequency domain applications. Both converter families have an input impedance of 10¹⁰Ω and guarantee no missing codes from 0 to 60°C.
Because the AM41016 series is designed to digitize fast, time-varying signals, its data sheets include complete dynamic specifications. The S/N ratio with an input of 10 kHz is 88 dB; the peak distortion at 10 kHz is -93 dB; the total harmonic distortion at 10 kHz is -89 dB. Analog provides dynamic testing on most of their products, and it publishes a technical note to explain the procedure.

Burr-Brown hopes to capture the market for those high-speed, high-resolution applications where small size and low power consumption are especially important. Burr-Brown's ADC 701 and companion SHC702 S/H amplifier ($168) are both hybrid designs characterized as an ADC-S/H pair. Together, the ADC and S/H pair consume 2.8W. The S/H timing is provided directly by the ADC. No other timing circuitry is necessary. Only two connections are required between the SHC702 and the ADC701: the SHC702 analog output to the ADC701 input and the digital hold command from the ADC701 input.

Like Analogic's converters, the ADC701 is based on a 3-step architecture, and Burr-Brown provides dynamic specs for the ADC/SHC pair. The S/N ratio with an input frequency of 5 kHz is 93 dB. Total harmonic distortion at 20 kHz is 0.00068%. The spurious-free dynamic range with a 20-kHz input is 107 dB. Two temperature ranges are available: 15 to 55°C and 0 to 70°C.

**Oversampling technology grows rapidly**

Although these high-accuracy and high-speed converters have advanced the state of the art, there has been a tremendous amount of activity in the oversampling converter marketplace. This trend is likely to continue. Because of their monolithic construction, these converters are an extremely low-cost, high-resolution alternative. Although they can't compete with integrating converters for absolute accuracy, they're ideal for high-resolution, mid-range accuracy and signal-processing applications.

Crystal Semiconductor, a pioneer in 16-bit oversampling converters, has a variety of new products targeted for specific applications. Motorola introduced its first oversampling converter recently, and Carillon Technology, a manufacturer of professional audio equipment, has also announced a 3-chip set based on the sigma-delta architecture.

One of Crystal Semiconductor's three new delta-sigma parts is an upgrade of its CS5501. Designated the CS5503, it's the first 20-bit monolithic A/D converter designed for precision measurement applications. The CS5503's ±0.0003% typical linearity error and its offset and full-scale errors of ±4 LSB max make this converter, priced at $27.70, an extremely low-cost alternative. The CS5503 continuously samples at a rate set by a CMOS clock or a crystal.

The other new products from Crystal, the CS5317 and CS5326, are aimed at the telecommunications and audio markets, respectively. The CS5317 is suitable for high-end voice-band applications such as V.32 modems, speech-recognition systems, telephone-system line cards, and high-resolution sonar. This converter features an internal PLL, which simplifies clock synchronization in complex data systems. The internal PLL makes recovering the master clock transparent to the user. The CS5317 has a total harmonic distortion of 80 dB across its 10-kHz bandwidth, and intermodulation distortion is less than 84 dB. The CS5326 is a stereo 16-bit ADC with a 25-kHz bandwidth. Its output word rate is adjustable from 30 to 50 kHz. It has an S/N ratio of 92 dB and a total harmonic distortion of 0.0015%.

These products from Crystal illustrate the application-specific nature of this marketplace. Motorola is taking a different approach. Its new 56ADC is a versatile converter, aimed at general signal-processing users. The 56ADC provides a complete set of analog-to-digital conversion functions on one chip. It requires a single 5V supply. No glue logic is needed to interface the 56ADC to
Motorola's, TI's, NEC's, or AT&T's DSPs. Its dynamic specs include a 90-dB S/N ratio and a 90-dB signal-to-THD ratio for input signals of 0 to 45.5 kHz.

The 56ADC's versatility stems from the implementation of its internal digital filtering. The decimation process is split between a comb filter and a FIR filter. The outputs of both filters are accessible. Depending on which output you choose, the part performs as either a 12-bit, 400-kHz converter or a 16-bit, 100-kHz converter. This 2-stage design removes the multiplexing restriction.

**Oversampling and muxing seldom mix**

There are some applications for which oversampling converters are not well suited. Systems that have only one ADC to measure a variety of transducer outputs and, therefore, require signal muxing before the ADC, can't take advantage of these converters. The oversampling technique involves a long pipeline delay, which makes multiplexing between channels impractical. Depending on the cost of your system this lack of multiplexing capability may not be a significant disadvantage. You could replace an expensive ADC and mux with individual oversampling converters.

Motorola's 56ADC is not suited for a multiplexed situation when you need 16 bits of resolution. The pipeline delay through the second digital filter is approximately 325 µsec. However, if 12 bits of resolution is enough for your system, you can use the comb-filter output. The pipeline delay between the input and the comb-filter output is approximately 15 µsec. This conversion time is competitive with that of other 12-bit products, so you can use the comb-filter output in the same multiplexing situations.

Integrating, subranging, and sigma-delta converters are usually targeted for either precision dc or signal-processing applications. The rest of the high-resolution market is rounded out by a variety of 16-bvit successive-approximation converters. Successive approximation is the workhorse architecture because it provides moderate speed coupled with moderate accuracy. These converters serve the majority of standard data-acquisition systems. The many successive-approximation types available feature variations in cost, speed, size, power consumption, and internal functions.

Many of the newer successive-approximation converters, the so-called sampling converters, include internal S/H amplifiers that are designed for compatibility with their companion ADC. The advantages of choosing a sampling ADC are straightforward: you won't have to do as much front-end analog design; the joint performance of the ADC and S/H amplifier is guaranteed by the manufacturer; and internal S/H amplifiers save board space. If your system requires external S/H amplifiers—for example, if you're muxing between different amplifiers—it's important to choose an S/H amplifier that is compatible with your ADC and your system objectives (Ref 2).

Many successive-approximation converters feature self- or autocalibration circuitry. The standard calibration approach uses laser-trimmed resistors for the internal DAC. However, Crystal's CS5101 and CS5102 DACs are composed of an array of binary-weighted capacitors. To ensure accuracy, these capacitors are calibrated on chip with digital logic upon reset or power-up. This calibration enables the converter to guarantee 16-bit no missing codes and provides an inherent S/H function—the analog input's value is always held by at least one capacitor.

Successive-approximation converters have the highest number of internal features, including references, clocks, S/H amplifiers, multiplexers, and serial and parallel ports. Some newer converters are also microprocessor compatible and feature short-cycle capability. You can decrease the conversion time if you only require a 14-bit-accurate result.

Burr-Brown's ADC700 includes a reference, a clock, and an 8-bit microprocessor interface. Sipex
Corp's Hybrid Systems Div has a variety of 16-bit successive-approximation hybrid converters. Its newest one is a 16-bit µP-controlled data-acquisition system, the SP9488. It includes an internal multiplexer, an instrumentation amplifier, and a 16-bit sampling ADC. The mux is user selectable. You can configure the converter to accept either eight differential inputs or 16 single-ended inputs. You can use the 16-bit data bus to read the result of a conversion or the status word of the ADC, to write control bits to the ADC, and to select a new input signal.

For military and harsh environment applications, most manufacturers offer successive approximation converters rated for extended temperature performance. Micro Networks' converters are specified in terms of no missing codes over temperature. The company also produces converters screened to MIL-STD-883. Its new MN6295/6296 ADC family includes converters rated at four electrical performance grades and two operating temperature ranges. The MN6295T/6296T guarantees 14 bits of resolution with no missing codes from -55 to _125°C and is fully specified for dynamic performance. The S/N ratio is 82 dB over temperature; the harmonics and spurious noise spec if -85 dB. This dynamic performance is guaranteed with an input frequency as high as 25 kHz—the Nyquist frequency of the converter.

There's no doubt that the high-resolution ADC market will continue to grow. Future 16-bit converter designs will focus on increasing speed and lowering costs. More products will feature 16 to 20 bits of resolution, and oversampling converters will continue to provide low-cost solutions. The ties between DSP and A/D converters will become even stronger, and devices that integrate A/D and DSP functions may not be far in the future.

References


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Converters couple analog and digital filtering

The fundamental function of oversampling converters, also called delta-sigma or sigma-delta converters, is to perform a simple, low-resolution conversion and reduce the resulting quantization noise with analog and digital filtering. To accomplish this task, these converters utilize an analog modulator and a digital filter. The modulator simultaneously samples the analog signal and shapes the large amount of quantization noise.

A simplified model of a first-order modulator (Fig A) illustrates the noise-shaping principle. The summing node to the right of the integrator represents a comparator. It's here that sampling occurs and quantization noise is injected into the model.

The signal and noise transfer functions that correspond to this block diagram, also shown in Fig A, illustrate the modulator's main action. As the loop integrates the error between the sampled signal and the input signal, it low-pass filters the signal and high-pass filters the noise. In other words, the signal is left unchanged as long as its frequency content doesn't exceed the filter's cutoff frequency, but the loop pushes the noise into a higher frequency band. Grossly oversampling the input causes the quantization noise to spread over a wide bandwidth and the noise density in the bandwidth of interest to significantly decrease.

Filtering noise is the primary purpose of the digital filtering stage. Its secondary purpose is to take a 1-bit data stream that has a high sample-rate and transform it into a 16-bit data stream at a lower rate. This process is known as decimation. Essentially, decimation is both an averaging function and a rate reduction function performed simultaneously. The output word rate will be some ratio of the internal sampling rate.

Fig B is a spectral representation of the sigma-delta conversion process. Note that a delta-sigma ADC doesn't provide noise rejection in the region around integer multiples of the sampling rate. If system noise exists in these bands, you can usually remove it at the converter's input with a simple, single-pole RC filter.

Although all sigma-delta converters perform the same functions, each does them with its own, generally proprietary circuit. For instance, the modulator stage can be second order, such as in Crystal's CS5317 and CS5503; third order, as in Motorola's 56ADC; or fourth order, as in Crystal's CS5326. The ratio of the internal sampling rate to the input signal's maximum bandwidth can also vary. The CS5317 samples at 2.5 MHz—500 times the input bandwidth of 5 kHz. The 56ADC samples at 6.4 MHz, which is equivalent to 64 times the converter's output rate. A converter's S/N ratio and distortion specs are derived from the combination of oversampling rate and modulator order. You shouldn't judge an oversampling converter exclusively on either one of these internal-architecture features.

There are many advantages inherent in this new converting technique. Digital filtering removes the need for external antialiasing filters. Because this filtering resides behind the A/D conversion, noise injected during the conversion process, such as power-supply ripple, voltage-reference noise, or noise in the ADC itself, is rejected. Because of the high sampling rate and the low precision A/D conversion, an S/H circuit is not needed. Sigma-delta converters are inherently linear and don't suffer from appreciable differential nonlinearity; the S/N ratio is independent of the input signal level. The last, but certainly not the least, consideration is cost. Attaining a high level of performance at a fraction of the cost of hybrid and modular designs is probably the greatest advantage of all.