I Data-System Components

Chapter I-1

This book is basically about A/D and D/A converters: understanding them, applying them, testing them, choosing them, and using them in systems.

When used in systems, they are often accompanied by an impressive panoply of other devices, both analog and digital, to measure input signals and perform intermediate processing with varying degrees of sophistication.

This chapter provides what might be termed a brief biographical "thumbnail" sketch of the main role players. Their general characteristics and aptitudes are summarized, and their roles in further conversion activity are hinted at within the short discussions devoted to each device.

In this book, the reader will quickly find that by far the greater weight of discussion is given to the properties and uses of *analog* circuits and their characteristics in the performance of system functions. The reasons for this lie primarily in the extreme fine-structure and the many degrees of freedom associated with analog circuits. They must labor in the real world, where noise immunity is a function of resolution and signal level, speed is a function of signal level, accuracy is a function of component tolerance and signal level, and the challenges to the designer's knowledge and ingenuity are many and unrelenting. On the other hand, their basic promise, in favorable environments, is functional simplicity, speed, and overall low cost.

With digital techniques, on the other hand, the principal challenges are to combinational ingenuity, equipment architecture, decreasing the cost and complexity of interconnections, and – in common with analog techniques – anticipating where Murphy's Law will strike next, and debugging where anticipation has failed. Digital circuits have high noise immunity, no drift, high speed (individually) and low cost (individually), and the rules for using them are few and simple.

With the exception of pre-amplification, a great many of the functions described here in analog form could be performed digitally, after the conversion. That they are not often is (so far) the result of favorable tradeoffs in cost, speed, and complexity. However, reductions in cost of digital integrated circuits and the increase of chip complexity are rapidly making feasible the development of devices that are intended to perform analog functions, but contain digital components. Examples of these include analog function generation with read-only memories (ROM's) and the universe of arithmetic, logic, and control possibilities with microprocessors.

Figure 1 illustrates the relationships of the principal components of a data system in a "global" perspective. Those to be introduced in this chapter include the following:

Sensors
Operational Amplifiers
Instrumentation Amplifiers
Isolation Amplifiers

Function Modules
Multiplexers
Sample-Hold Circuits
Analog-to-Digital Converters
Digital-to-Analog Converters
Up-Down Counters
Filters
Power Supplies
Comparators
DPM's
Digital Displays

Rarely will a system use all of the above components; on the other hand, the more-complex systems will often use appreciable quantites of one or another of them. Furthermore, as components shrink in size and cost and become available as integral parts of subsystems with specified performance (and perhaps even a modicum of software), the designer may not even have to think of them as individual components, but rather as sub-blocks in a supplier's diagram (examples may be found in Chapter I-4).

SENSORS

One might imagine that the systems designer has very little say in the choice of sensor, that he accepts whatever data signals exist without protest and gets on with the interface system design without further ado. However, if the systems engineer can have a say in the selection of the original transducer, he can go a long way towards easing his own conversion-design task.

For example, in monitoring or controlling mechanical shafts, the designer may be confronted with signals obtained by three radically-different position-sensing approaches: digital shaft encoders, synchros, and potentiometers, plus variations on all three.

Likewise, temperature measurements may be accomplished with thermocouple and thermistor, while mechanical force may be measured directly by load cells and strain gauges, or obtained indirectly by integrating the output from accelerometers, or even by counting interference fringes in an optical system.

Although it is not our role to recommend any particular type of signal transducer for a particular application, we thoroughly endorse the idea of getting the systems-design engineer into the act before the signal sources are settled upon, instead of later, when it is found that the designer is painted into a corner by the few options allowed.

AMPLIFIERS

If the transducer signals must simply be scaled up from millivolt levels to an A/D converter's typical ±10-volt full-scale input, an operational amplifier with appropriate closed-loop gain may be the first choice. Possibly, if the system involves many sources, each transducer can be provided with its own local amplifier so that the low-level signals are amplified before being "shipped" to the data center. Besides scaling, operational amplifiers are used for a host of linear and nonlinear, static and dynamic functions. Specialized amplifiers, such as instrumentation and isolation amplifiers, are always worthy of consideration, because they are frequently the most cost-effective option.

COMMON-MODE PROBLEMS

If analog data must be transmitted over long distances (and often, over quite short distances), differences in ground potential between signal site and data center will add spice to the interface systems design problem. In order to separate common-mode interference from the signal to be recorded or processed, devices designed for the purpose (i.e., instrumentation amplifiers) may be introduced. Typically, an instrumentation amplifier is characterized by good common-mode-rejection capability, high input impedance, low drift, adjustable gain, and somewhat greater cost than operational amplifiers. They range in form from the monolithic AD521 and hybrid AD522 to potted modules.

ISOLATION

In the event of either very-high common-mode voltage level or the need for extremely-low common-mode leakage current, or both (as might be mandatory for many clinical medical-electronics applications), an *isolation amplifier* is required to interpose a break in the common-mode path from the signal source to the data center. Isolation amplifiers involve optical isolation or transformer-coupled carrier isolation techniques, and (for a given technology) they typically cost about the same as instrumentation amplifiers. Though most-often used for isolating input data from system level, they may also be used for communicating system outputs to devices at other levels.

FUNCTION MODULES

These are special-purpose analog devices and circuits used for a wide variety of signal conditioning operations on signals that are in analog form. Where their accuracy is adequate, they can simply, and at low cost, relieve a processor of an expensive and time-consuming software and computational burden. This category is large and open-ended, but some of the more popular operations performed are multiplication; taking ratios; raising to powers; taking roots; performing special-purpose nonlinear functions such as linearizing transducers; performing rms measurements; computing vector sums; integration and differentiation; current-to-voltage or voltage-to-current transformations, etc. Some of these operations can be purchased in the form of such readily-available devices as multiplier/dividers, log/antilog amplifiers, etc. Others represent but a sampling of the vast potential inherent in operational-amplifier circuitry, available to the designer at low parts cost, and limited only by his ingenuity.

ANALOG MULTIPLEXERS

If data from many independent signal sources must be processed by the same computer or communications channel, a multiplexer is usually introduced to couple the input signals into the A-D converter in some sequence. Additional logic keeps track of which data source is coupled to the converter at any instant.

Multiplexers are also used in reverse. For example, when the converter must distribute analog information to many different channels, the multiplexer, fed by a high-speed output D/A converter, continually refreshes the various output channels with computer-generated information.

DIGITAL MULTIPLEXING

Often, a digital distribution system uses no device that specifically goes under the label of "digital multiplexer." Unlike the comparable process of shunting analog information from computer to many output channels via a single D/A converter, or from many sources to a single A/D converter, the digital multiplexing function is often delegated to the devices being multiplexed, as they share a set of common inputs.

For example, if many digital sources must be multiplexed into a computer or data-transmission channel, they are usually tied to the computer by a common set of parallel "bus" lines.

Commands from the computer then instruct the individual sources which one among them must feed its burden of data into the common bus, thence to the computer. Conversely, if the computer is bent on updating a number of digital output registers (each of which might be connected to a D/A converter), the updating process is accomplished by computer commands that strobe the selected register to accept the data being transmitted over the common output bus lines. Only that register instructed to receive the data can do so; the remaining registers simply ignore the data fed in parallel to their input terminals.

SAMPLE-HOLD CIRCUITS

In many interface systems, the original signal varies quite rapidly, calling for some subtlety in the interface linkage. Because an A/D converter takes a finite time to digitize the input signal, changes in this signal level during the actual conversion process could result in gross errors with some converter types. In any event, the lengthy conversion period would be completed some appreciable time following the conversion command, so that the final digital value would never truly represent the data level prevailing at the instant at which the conversion command was transmitted.

Sample-hold devices are typically introduced into the data link to make a fast "acquisition" of the varying analog signal and "hold" this signal for the duration of the conversion process. Sample-hold circuits are also used in multi-channel distribution installations, where they enable each channel to receive and "hold" its own signal level for activation of different output processes. Usually, a data-acquisition sample-hold circuit must exhibit ultra-fast signal acquisition, with minimal droop for a matter of 1 to 50 microseconds. By contrast, an output data distribution sample-hold circuit can be updated more leisurely, but it is often required to "hold" an analog value for many milliseconds – or even seconds – in the interval between updates.

A/D CONVERTERS

These devices, which may range from monolithic IC's, such as the AD7570, to high performance modules such as the ADC1102, convert analog input data – usually voltage – into its equivalent digital form. Key characteristics of A/D converters may include absolute and relative accuracy, linearity, monotonicity, resolution, conversion speed, stability, and – of course – price. Other aspects open to choice include input ranges, digital output codes, and physical size.

Although the industry tends to converge upon the successive-approximations technique for a very large number of system applications, because of its inherently excellent compromise between speed and accuracy, other popular alternatives include counter-comparator types, and dual-ramp and "quad-slope" approaches. The dual-ramp has been widely-used in digital voltmeters. In addition, synchro-to-digital and resolver-to-digital converters are used where data from mechanical shafts must be converted into digital form.

D/A CONVERTERS

These devices "reconstitute" the original data after processing, storage, or even simple transmission from one location to another in digital form. The basic converter consists of an arrangement of weighted resistance values (or divider ratios), each controlled by a particular level or "significance" of digital input data, that develops varying output voltages or currents in accordance with the digital input code.

Although converters have fixed references, for most applications, a special class of D/A converters exists, having a capability of handling variable and even ac reference sources. These devices are termed *multiplying* DAC's, because their output value is the product of the number represented by the digital input code, and the analog reference voltage, which may vary from full scale to zero, and in some cases, even to negative values. In some instances, such as for ac measurements and resolver/synchro conversion, the multiplying converter's weighted divider circuitry is based on tapped transformers, instead of precision resistors, since turns ratios have excellent long-term stability and immunity to temperature effects.

REGISTERS

Digital registers are used to hold information in readiness for passing it along to computers, D/A's, and so forth. For example, a multi-channel interface system using an A/D converter for every input channel would store the digitized values in each converter's output register until called on by the computer to feed the stored value into the common input bus. The converse holds true for output multiplexing, where a number of D/A converters provide different voltage levels for the independent output channels. Each D/A is then fed by a storage register, which "holds" the digital input word until the computer feeds in the new, updating digital value.

Shift registers are used, for example, where the data is transmitted serially over a single pair of wires, instead of as parallel bits over many wires. In this case, the shift register accumulates a serial input word in much the same way that a train and its many carriages (bits) enters a station. When all the bits have entered the shift register, the data bits (passengers) may be read out (detrained) in parallel.

UP-DOWN COUNTERS

These devices, analogous to ramp generators, are quite useful for performing a variety of "tricks" with A/D and D/A converters. Specifically, they are used in forming electronic servo loops for automatic error correcting, offset adjusting, long-termed sample holds, etc.

In electronic servo applications, the up-down counter accumulates pulses representing the variable being controlled, adjusted, or measured, in much the same way that a servo-motor shaft accumulates rotational angle. The counter is often used in conjunction with a D/A converter to develop an analog value proportional to the accumulated count. The process is also used in tracking-A/D converters and resolver/synchro-to-digital converters.

FILTERS

Filters are used on the input side of an A/D converter to remove unwanted components of the input signal. Noise and line-frequency pickup are also attenuated in this way, but at the expense of reduced response to fast input-signal amplitude variations. Filters are also used on the analog output from D/A converters, in order to smooth out the "lumps" created by discrete digital values. Often, the electromechanical device being actuated by a D/A converter (examples include d'Arsonval meters, servo motors, magnet coils, loudspeakers, etc.) acts as a filter in its own right, owing to substantial electrical or mechanical inertia.

In high-speed information-processing systems, "anti-aliasing" low-pass filters are used ahead of A/D and following D/A converters to avoid errors caused by intermodulation of unwanted high-frequency components of the signal (and input noise) with harmonics of the sampling frequency.

COMPARATORS

Conversion systems involve both analog and digital comparators. For example, the A/D conversion process involves balancing the unknown input voltage against some form of internally-produced reference. A comparator responds to the polarity of the inequality between input and reference. More rarely, comparators are used as fast, high-gain (open-loop) amplifiers. Digital comparators, as their name implies, are used on digitized, rather than analog forms of data. For example, a digital comparator might be used in set-point control to provide considerably better accuracy, resolution, and stability, than is possible with an equivalent analog process.

POWER SUPPLIES

Accuracy of interface systems is steadily rising, to the point where 12-bit resolution is quite routine, and 16-bit operation is frequently involved for higher repeatability, resolution, linearity, and accuracy. Consequently, the design of the dc power system is no longer a trivial matter (it never really was!) since errors that remain second-order effects at 8-10 bits become menacing first-order effects at the 16-bit level. In many instances, careful separation of analog and digital grounds is required, demanding, in turn, considerable isolation between the various outputs that modern power supplies provide.

We certainly advocate raising the priority of power-supply engineering from the status of an "afterthought" to that of an item that should be eliminated as a concern early in the design process. Too often, the power supply design (or choice) is left until last, where it is presumed to be able to take up all the slack or tolerances that other design stages create. Instead, at least as much initial attention should be devoted to the power supply as selection of converters, amplifiers, sample-holds, multiplexers, and other devices. A related question is whether to use power supplies and/or regulators in large, medium, or small "chunks," for major portions of the system, for individual chassis, or perhaps even for mounting on individual boards. The issues involve space, cost, circuit independence vs. excessive lead length and wire size, avoidance of ground loops, allowable local dissipation levels, etc.

If continued operation despite loss of primary power is essential, either from considerations of overall system reliability or because of potential loss of data in volatile memory, the system design should include some arrangement for continuity of supply, for detection when standby power is in use, and for contingency decisions or alarm.

DIGITAL PANEL METERS (and DVM's)

These devices form a kind of self-contained digital processing system all on their own. They can, of course, be used in conjunction with computer or digital recorder, owing to the BCD output that most DPM's provide.

Basically, the DPM may be regarded as an analog-to-digital converter, complete with case, overrange capability, input protection, visual readout, and remote electrical output, usually in BCD format. Thus, the DPM may be used as an A/D converter, complete with visual displays for initial adjustments, in a multi-channel conversion system. Alternatively, it provides a very unambiguous and error-free component for quality-control systems, where human operators use the DPM with high resolution and repeatability in set-point applications for adjusting temperature, pressure, weight, and other industrial variables.

DIGITAL DISPLAYS

Decimal displays are often required in conversion systems for initial setup procedures. Although normal operation of the system involves data rates considerably too fast for the eye to follow, calibration, checkout, and other manual operations nonetheless require a display to be added, often in conjunction with a counter. Thus, manufacturers offer decimal displays in decade increments, and usually with input data compatible with conventional logic levels and prevailing codes.

ONE MORE IMPORTANT ELEMENT

As Figure 1 indicates, there is one additional element that is always present in a data system but seldom shown on a block diagram: *homo sapiens.* These systems are designed, built, programmed, tested, and perfected by humans to serve human purposes; and quite often humans interface with data systems in operation, reading displays and making adjustments–to, and within the system. It is to all these humans that this book is fraternally dedicated.