# I

# Applications of Converter Systems

## Chapter I-6

APPLICATIONS OF CONVERTER SYSTEMS

A. AUTOMATIC TESTING
B. COMMUNICATIONS AND SIGNAL ANALYSIS
C. DISPLAYS
D. COMMERCE, INDUSTRY, AND ELSEWHERE

Chapters I-5 have introduced the basic hardware elements of systems and equipment that involve converters, shown the basic configurations of data-acquisition and data-distribution systems, and indicated a few examples of the uses of digital and analog elements in intimate combination.

This chapter will illustrate the scope and breadth of systems and equipment that have been conceived of or built involving converters. The examples are drawn from a variety of sources, but they share the ideas, hardware, and circuit structures that have already been touched upon.

The intent is to inform the reader of what has been done, to suggest what can be done, and to arouse thoughts of what *might* be done by adding the conceptual tools described in this volume to the fund of knowledge and experience that he already possesses pertaining to his own field of endeavor.

### A. AUTOMATIC TESTING

> "Automatic testing of electronic devices has been a major factor not only in the overall improvement of product quality and reliability, but also in the dramatic lowering of product costs."[1]
>
> –Harold T. McAleer, General Radio Company

Although a major (and in some ways an obvious) market for electronic testing equipment, makers and users of electronic devices have not been the only beneficiaries of automatic testing. Anyone who has had his blood tested recently, has flown safely in a 747 jet aircraft, or has contemplated purchasing a new Volkswagen, has been exposed to the potential savings (and not only financial) inherent in automatic testing.

The cost savings, both immediate and long term, result from a number of characteristics of automatic testing:

*Human resources are conserved.* Fewer persons can conduct more (and more-thorough) tests of high complexity with minimal training.

*Volume.* Large numbers of tests can be performed in a short time: either many tests on complex devices or fewer tests on large number of devices.

*Reliability and consistency.* A well-designed test program will perform identical tests leading to consistent results, with no aberrations due to misreading, fatigue, etc. If failure occurs in mid-test and repairs are made, the entire test cycle can be repeated,

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[1] *IEEE Spectrum*, May, 1971, "A Look at Automatic Testing"

numerous times if necessary, with full confidence that the most recent test has "cut no corners."

*Multiplexing of adjustments and readouts.* An instrument designed for use in automatic testing bears little physical resemblance to conventional instruments, since it need have neither binding posts, knobs, readout, nor even "front panel;" it shares the system's readout devices; connections and adjustments are made by the system.

*Automatic Calibration.* Any necessary calibrations, zero-adjustments, nonlinear-device compensations, or other predicted allowances can be made under system command. Range-changing can also be fully automated.

*Measurement statistics.* The system can retain in memory the results of all tests, the results of discrepant tests, and/or histograms of specific parameters, and print them out upon request. Yield studies can lead to product improvements, elimination of sources of repeated rejections, and prediction or tracing of future failures.

In short, a well thought-out, designed, and implemented automated test facility can reliably perform large numbers of tests, around the clock, on a "100%" basis, consistently and without tiring, with accuracy and skill, and with feedback to the designer for the next generation of the product. Skilled test personnel can be applied to more-creative pursuits than routine manual testing of the ins-and-outs of complex systems.

Then, as mentioned above, there are the many intangible benefits, that pay off in human values as well as dollars-and-cents: the aircraft engine that didn't fail, the electrical chassis that didn't need field repair, the steel rolling mill that didn't run away, the hospital patient that survived, the vendor whose reputation remained consistently high.

## *USES FOR AUTOMATIC TESTING*

*The manufacturer of components,* such as integrated circuits, benefits greatly, because testing is a far-from-negligible cost in the integrated circuits business. Besides delivering a higher level of acceptable quality to the customer, he also develops more-accurate knowledge of yields and trends, and can serve needs for specific selection categories. For the producer of high-performance specialty IC's, such as Analog Devices, it is an indispensable tool. Such devices as the laser-trimmed AD510 low-offset op amps and the AD534 monolithic multiplier/divider would be so costly as to be infeasible if manual measurements and adjustments were involved. (Instead, the additional cost is a small fraction of the price of the standard unit.)

*The user of large number of identical components* can also benefit: He can weed out discrepant units in incoming inspection; measure, select, and grade units for different applications (rather then paying the manufacturer extra to do the same job); and keep comparative statistics from lot-to-lot and vendor-to-vendor. It may be noted, as a matter of perspective, that an average saving of 10¢ on 100,000 units is $10,000.

*The manufacturer of equipment and systems* can test subassemblies in-process, or as received from subcontractors; he can also test completed pieces of equipment thoroughly. In both cases, the test system can be programmed for GO/NO at points of discrepancy, and to either reject the device for later evaluation, or branch into a diagnostic mode, to isolate the portion of the circuit (or perhaps even the component or connection) that is faulty. Repaired units can be recycled and subjected to the same battery of tests as the new units.

*Highly-complex systems,* such as jet aircraft and their various subsystems, can be tested thoroughly on the ground by a small number of persons in a short time, with a high probability of finding any faults, or the discrepancies that might indicate incipient faults. In addition, the on-board test and monitoring system can provide warning to the crew of anomalous subsystem behavior, and, as the electronic portions become increasingly sophisticated, it can perform a degree of diagnostic testing.

## *INGREDIENTS OF TEST SYSTEMS*

For systems that test devices, the test begins with the *unit under test.* It must be handled, maneuvered into place, connected to. Then a *stimulus* is applied, and a *response* must be measured. The response is compared with a set of possible responses, and a *decision* is made (accept, reject, grade-and-sort, perform an adjustment) and communicated (print, store, mark, analyze), and a new instruction is given (next test, next set of connections, next device, wait for manual instruction, etc.). An outline of such a system is shown in the block diagram of Figure 1.

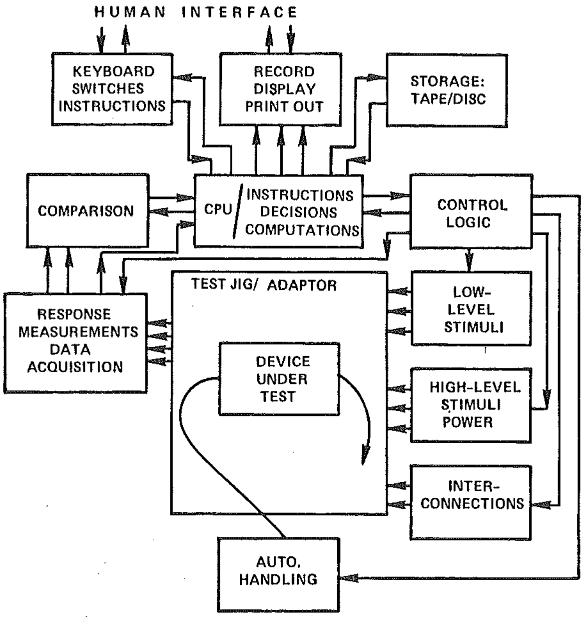


*Figure 1. Test system ingredients in typical configuration.*

Devices have at least two leads (resistors, capacitors), but they may have many more (op amps have at least six, printed-circuit boards may have 20 or more.) The instructions must call for connecting the appropriate stimulus generators and power sources to the appropriate terminals, and the appropriate measuring devices (bridges, amplifiers, etc.) to *their* appropriate terminals, and making all opens, shorts, "grounds," links, etc., as required for the test step. Some of these may be hard-wired in the adaptor; others must be called for by software, or manual setting. Minimal noise pickup, interference, and parasitic effects caused by lead resistance, capacitance, and inductance are absolutely essential.

### *Converters in Test Systems*

It may be fairly evident that much of the engineering and hardware cost of test systems goes into fixtures, switching devices, computers, peripherals, displays, wiring, and cabinetry. However, since the stimuli are digitally-controlled, and the responses must be returned to digital form for processing, it should be evident that converters and their accessories play a key role in ensuring test accuracy, speed, and reliability, yet represent but a small fraction of the cost of the system. For this reason, it may be false economy to use conversion devices that are anything but entirely adequate to do the job, or to seek to cut cost corners.

Typical uses of D/A converters in testing include: programmable power supplies, pulse generators, sweep generators, waveform generators (with appropriate digital inputs). They may be used as offset and gain "potentiometers" in calibration loops, as bridge-balancing voltage sources, and as part of A/D converters, sample-holds, peak-followers, etc.

A/D converters, either with multiplexing or per-channel, return the measurements to digital form, after processing by isolation or differential amplifiers, by op amps as electrometers, by multipliers, ratio devices, log devices, and all the other paraphernalia mentioned in Chapter 2.

An essential decision that must be made is the degree to which analog data reduction will be used, as compared with the performance of similar functions by digital software. Whatever the realities of the system itself, this consideration depends largely upon the background and experience of the designer; we suggest that analog-oriented designers not overlook the possibilities of software for reliable routine computation, and that digital designers consider the decreasing cost of functions that can be performed with analog modules and linear integrated circuits, and the balance between too much and too little data.

Much that could be said about system optimization, in terms of getting the best-possible interference-free measurements of suitable accuracy, has already been mentioned in several places in this book; and test systems are probably the most representative class of design problems requiring active application of these principles.

In component tests, where the lead-runs to the unit-under-test (UUT) are controllable, as is the local environment, the main sources of interference arise from the proximity of input, output, power, and logic leads in the vicinity of the test adaptor. In large-system testing, long leads, including multiconductor cables and connectors; the presence of electrical noise (RFI, power line and switching-transient spikes); and possibly unfavorable environmental conditions (temperature, humidity, vibration), may all make the measurement problem extremely difficult. It often turns out that, in the design of large systems, self-checking is an effective way of solving the interference problem, using a local $\mu$P-controlled test subsystem that communicates digitally with an external system tester. If this is too ambitious, local digitizing, as an integral part of system design – in anticipation of testing – may provide a large ratio of benefits to cost.

## B. COMMUNICATIONS AND SIGNAL ANALYSIS

In this section, we shall discuss briefly the class of converter applications that involve the generation, transmission, recovery, processing, storage, characterization, and synthesis of analog waveforms. Conceivable applications include:

Time expansion, compression, (relative) advance, and delay
Transient storage and recording
Synthesis and analysis of speech and music (and waveforms in general)
Transfer-function synthesis and analysis
Convolution
Digital filtering
Recovery of signals from noise by correlation techniques and fast Fourier transforms
Scrambling and unscrambling coded transmissions
Generation of arbitrary signals and transfer functions

Digital methods, especially with microprocessors, can provide a powerful set of tools for dealing with analog functions and the transfer functions that operate on them in the time and frequency domains, as we have suggested in Chapter 5.

The key that unlocks the door is the A/D converter, which "freezes" a sample of the waveform and makes possible permanent storage without degradation. Thereafter, digital shift registers, binary rate-multipliers, memories, comparators, microprocessors, and control logic can perform a variety of operations entirely in digital format.

Except for errors due to the discrete (in time and amplitude) nature of the sampled signal, and approximations or roundoff errors in computation (where necessary or permitted), there is no loss of information, even though the signal be stored, multiplied, integrated, added, subtracted, correlated, or otherwise man(or machine-)ipulated. It can of course be returned to the analog domain, via D/A conversion, and subjected to further processing there, while its attributes are still retained in Memory.

The circuits and ideas that appear here, all variations on the basic theme of the shift register delay line, represent promising areas of application, but they are not necessarily new or original. Their pupose is to unleash the reader's curiosity and creativity, in the field broadly encompassed by the title of this section. We've tried to avoid, except where necessary, mathematical particularities (and the controversies they sometimes engender).

### *SHIFT-REGISTER DELAY LINE*

The basic tool for performing many interesting functions is the shift-register delay line, mentioned briefly in Chapter 4, and shown here again for further discussion.

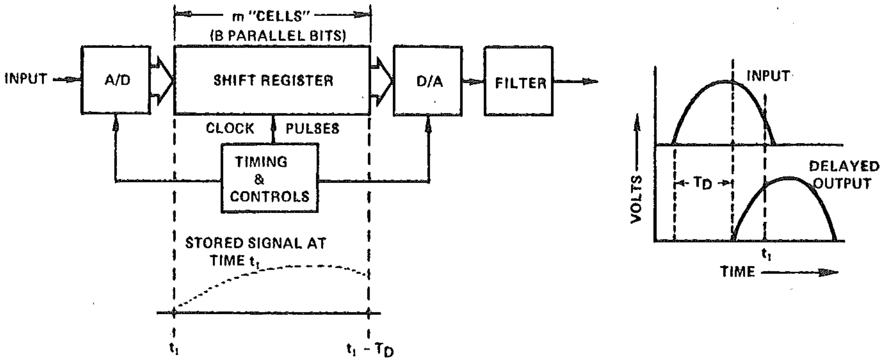


*Figure 2. Parallel shift-register delay line.*

Suppose the analog signal is a one-shot occurrence, of which *m* samples have been taken, that the clock has stopped, and the conversions have ceased. The signal is now stored in the delay line in digital form, and it will remain there until it is advanced or cleared or the power has been turned off. A number of interesting things may be done with the stored signal:

*Read out into memory*

The stored signal can be read out, a word at a time, and stored in memory, while the line awaits another transient (Figure 3).

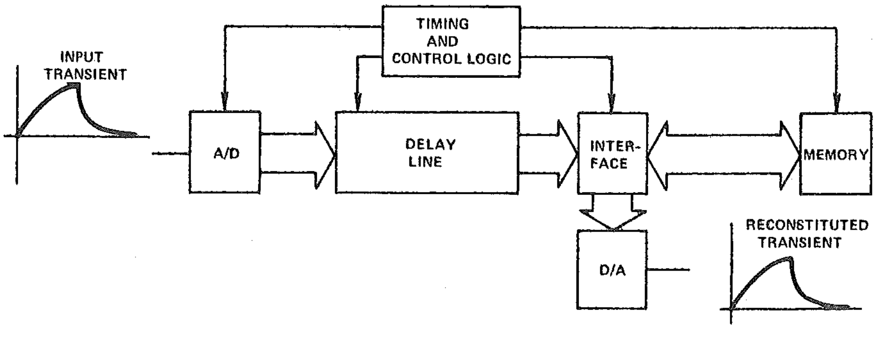


*Figure 3. Transient recorder.*

*Read out as an analog signal*

The signal can be read out and converted to an analog signal, each sample in turn, but at a rate arbitrarily determined by the choice of clock frequency. For example, the transient may have been quite rapid, but it is desired to plot it out on a chart recorder. Or, it may have been fed into the line slowly (perhaps even manually as an arbitrary waveform), to be used as a shaped stimulus for an analog process, and is to be discharged at high speed.

*Recirculate*

If the output end of the line is fed back to the input, it becomes a recirculating delay line (Figure 4). The stored signal will then appear at the end of the line repetitively, allowing the transient to be displayed on an ordinary oscilloscope. By loading, or "charging", with an arbitrary input signal (either analog or digital), then providing rapid recirculation and D/A conversion, it is possible to create an extremely wide range of arbitrary repetitive analog waveforms, of controllable repetition rate and amplitude.

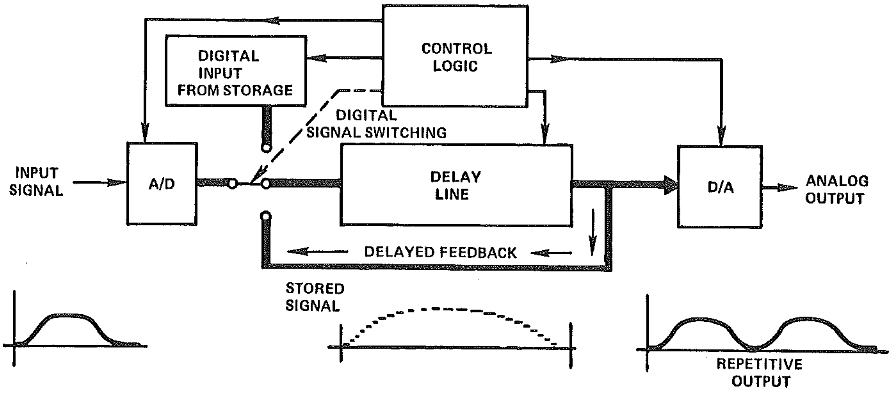


*Figure 4. Recirculating delay line.*

*Perform waveform averaging by addition*

If the same message is sent repeatedly but arrives at the converter accompanied by (and perhaps "buried in") noise, it can be recovered by summing all the versions of the message: the coherent portions will add directly with the number of items summed, while the rms noise will tend to be "averaged out" and will increase only as the square-root of the number of items. For example, with 100 repetitions, the signal will be increased in relation to noise by a factor of 10. This can be accomplished with a delay line by summing each sample increment of the newest message with the sum of the corresponding samples of previous messages, accumulated in the delay line (Figure 5). Thus, when the second message arrives, its first sample is summed with the already-stored sum of the two previous first samples. Since the original messages are presumably identical, while the noise varies randomly, each iteration adds 1 unit of original signal to each sample, while the noise components tend to be averaged out.

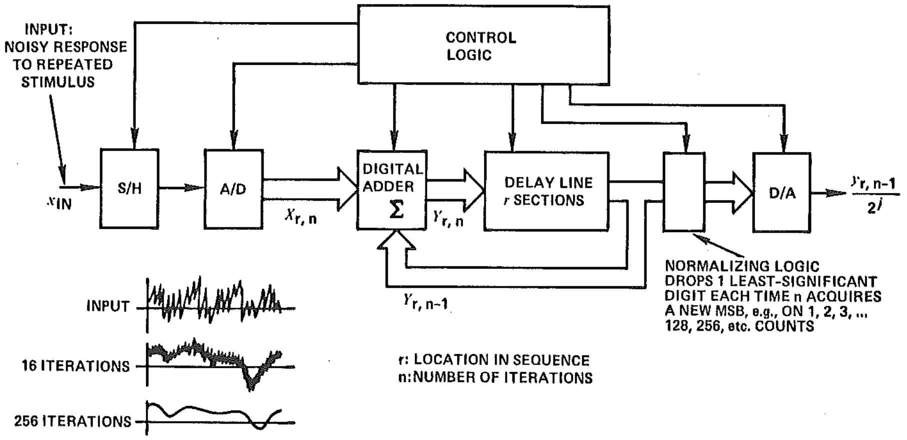


*Figure 5. Waveform averaging by addition – basic scheme.*

In practice, computing the simple sum

$$Y_{r,n} = Y_{r,n-1} + X_{r,n}$$

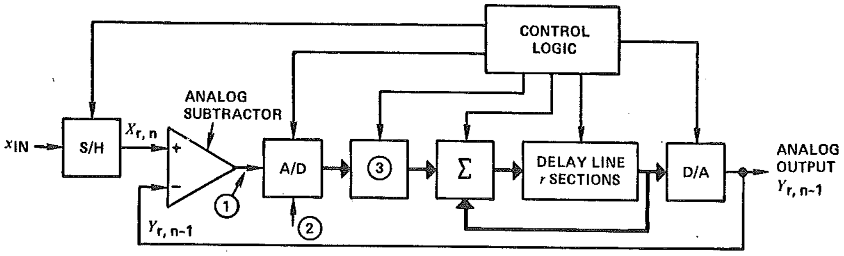
where

$Y_{r,n}$ = output of the $n$th sample at the $r$th position
$X_{r,n}$ = input of the $n$th sample at the $r$th position

leads to an "open-ended" output amplitude, which is expensive to implement digitally and difficult to display on an oscilloscope during summation. It is a better idea to consider normalizing the output, i.e., dividing it by *n*, so that its average value tends to be constant. Since dividing digitally is not especially desirable, except for integral powers of 2, we may consider several alternatives based on the error-correcting relationship

$$Y_{r,n} = Y_{r,n-1} + \frac{X_{r,n} - Y_{r,n-1}}{n}$$

The first thing to observe is that as *n* becomes large, $Y_{r,n}$ and $Y_{r,n-1}$ are very nearly equal, and each additional increment causes little change, because it is divided by *n*. The second thing to note is that, since both terms of the difference can occur in analog form (the input and the last value of output), the difference could be taken before conversion, substituting an op amp for a digital subtractor (Figure 6). Finally, one might observe that division by *n* could be performed either as an analog function (counter and DAC supplying reference voltage proportional to *n* to the ADC), or as a digital approximation using only integral powers of 2, obtained by shifting the ADC output code one bit toward the right (dropping the last bit), as each increasingly-significant bit of *n* appears on a counter.



①,②,③ NORMALIZING SCHEMES:

① ANALOG DIVISION BY E = K*n* BEFORE CONVERSION

② RATIOMETRIC CONVERSION, $E_{REF}$ = K*n*, USING COUNTER AND DAC.

③ SIMPLIFIED DIGITAL DIVISION BY USING $2^{-j}$ AS AN APPROXIMATION FOR 1/*n* AND SIMPLY SHIFTING DOWNWARD AT *n* = 1, 2, 4, 8, ... 256, 512 ...

*Figure 6. Waveform averaging by addition using normalized variables.*

*Time Compression by Sampling*

In Figure 7, a shift register is advanced at a high frequency, $f_c$, for example 513kHz. The converter is digitizing a slowly-varying signal at a rate $f_s$. Suppose that the shift register has 512 steps, and that at a given instant, the 512th sample appears at the output and is fed back to the input. On the next step, starting the *m*th iteration, the converter output, $X_{1,m}$, is fed into the line to replace the output $X_{1,m-1}$. The line then advances for 512

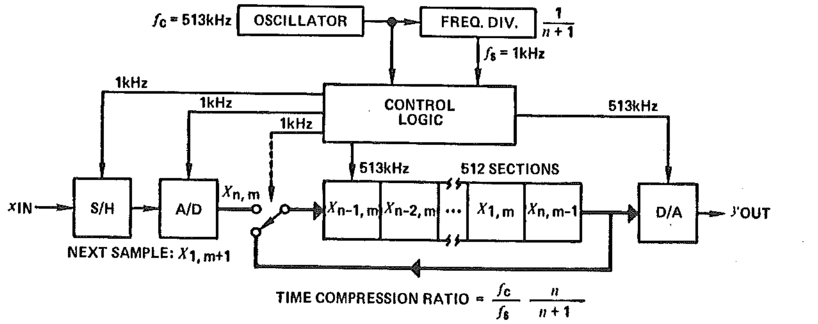


*Figure 7. Time compression by sampling. On next count, $X_{n,m}$ is introduced into the line to replace $X_{n,m-1}$. At n+1 additional counts, $X_{1,m+1}$ is introduced to replace $X_{1,m}$.*

steps. On the 512th step, the input is once again $X_{1,m}$, and $X_{2,m-1}$ appears at the end of the line, while $X_{2,m}$ is ready at the converter output. On the 513th step, the converter output is fed into the line to replace $X_{2,m-1}$. $X_{1,m}$ and $X_{2,m}$ are now indexed down the line, and on the 513th step, $X_{3,m}$ replaces $X_{3,m-1}$. By the time 512 conversions have occured, in real time, the sampled signal (including new and previous values) has circulated 513 times, thus providing a 512-fold-speeded-up version of the (1.96Hz) analog input waveform at the output of the D/A converter, at the equivalent of 1ms per sample.

If each cycle of the analog waveform is identical to the adjacent ones, and if the clock is synchronized to the analog signal, the output of the DAC, plotted on an oscilloscope screen, swept at 1kHz, will appear to stand still, plotting the low-frequency input, but *with no flicker.* Changes of the input signal, from iteration to iteration, will appear as progressively-appearing changes to the stationary pattern.

Since the compression ratio depends on the time required for each 511 samples, it is proportional to the clock frequency, which can be locked in at any convenient value. A typical application for time compression is in real-time spectrum analyzers.

*Real-Time Correlation*

For an input function, f(t), the output of the delay line over a complete circulation (in compressed time) is a set of values of $f(t - \tau_i)$. If the successive values are multiplied by the sampled value of another waveform, g(t), which, with f(t), is updated after each circulation, and if each individual product is averaged with its synchronous counterparts from previous circulations, the output of the averager will represent a sample-by-sample cross-correlation of *f* and *g* at a real-time rate, delayed by the product of the sampling period and the number of samples circulated (Figure 8).

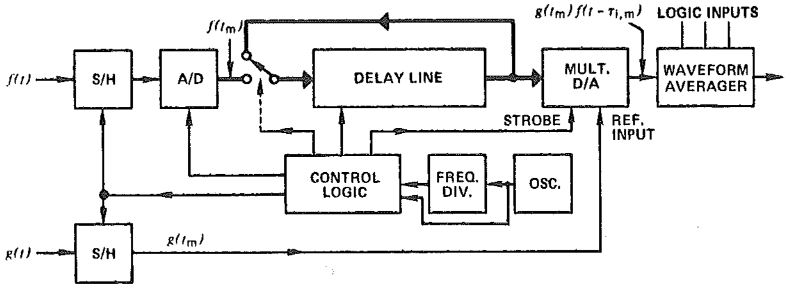


*Figure 8. Real-time correlation using delay line.*

*Incremental Delay Line as a Filter*

If the delay line consists of a number of sections, and the outputs at these taps are converted to analog form, and summed, with arbitrary coefficients, it is possible to synthesize arbitrary time-domain responses to steps, pulses, or other waveforms. Since the output bears a linear* relationship to the input, the resulting transfer function may provide amplitude and phase responses to other signal forms (over limited ranges of frequency) that can be expressed by transform integrals but are otherwise formally considered "unrealizable." In this case, the output is a function of the input only (Figure 9a).

*Recursive Filtering*

When the output is a function of input only, the number of possible responses is limited, because the output will settle within a finite time after the input has ceased to vary. However, by making the output a function of both output and input, a more-general (and more interesting) set of responses becomes possible.

Recursion may be achieved by feeding back from the output to each tap point (after it has made its contribution); but this requires an A/D converter for each tap. A more economical scheme uses a second tapped delay line, fed back (in sections – if desired) to the output summing amplifier, thus requiring only D/A converters for each tap point (Figure 9b)

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*i.e., if the input is doubled, the corresponding output will be doubled.

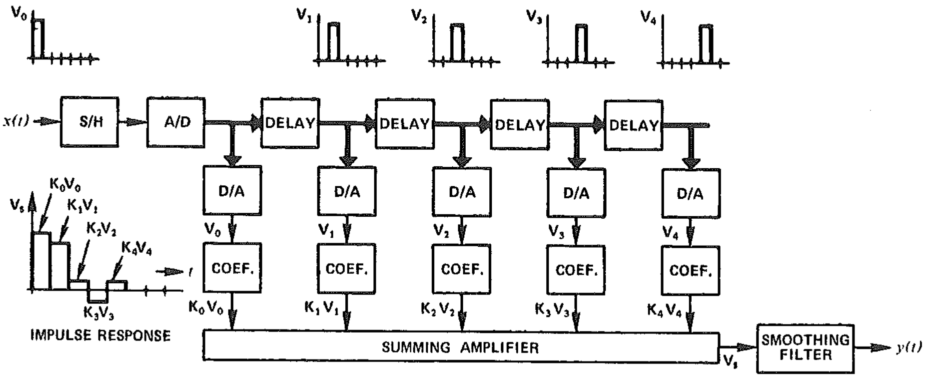

*Figure 9a. Delay line as a filter with programmable real-time response. (Small number of sections shown for clarity).*

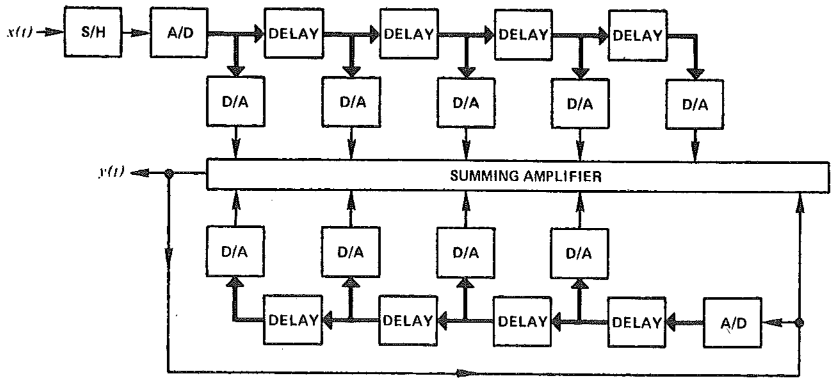

*Figure 9b. Delay line in recursive filtering. Coefficients (not shown) can be applied manually or digitally (multiplying DAC's).*

## *CONCLUSION*

Though it has been limited in scope, we hope that this section has provided the reader with an awareness of the power of digital techniques in signal processing, just through the use of delay-line storage. There are many more hard-wired processing tricks available, such as the use of binary rate-multipliers for digital frequency modulation of digital signals, counters for converting from frequencies to discrete digital values, and voltage-to-frequency converters for analog modulation of digital signals.

The growing availability of digital components of high complexity (FFT processors), increasing speed, and low cost (microcomputers), plus the possibility of overall control of the processing by CPU's and stored commands, makes the outlook for analog waveform synthesis and processing by digital techniques extremely bright, whatever the source: speech, music, noise, gas chromatographs, electroencephalograms, mechanical vibrations, to mention just a few.

## C. CATHODE-RAY-TUBE DISPLAYS

In the industrial and scientific world, the close association of computer and cathode-ray tube provides an unparalleled method for speedy access to stored and real-time data. It simultaneously affords the opportunity for interactive dialogue with the computer for the purpose of actually controlling what the computer does. The recent growth of electron-beam recording (on film negative) poses a serious challenge to the centuries-old tradition of typesetting, while the ability to use computer power to adapt data to the needs of the human operator prior to presentation makes the computer-CRT display a powerful combination indeed.

While systems do exist for the sole purpose of display, the more general application of displays is in connection with data-acquisition systems and systems involving computers. Such systems may be either purely digital in nature (e.g., business systems with punched-card inputs), or they may involve A/D and D/A converters in maintaining input and output contacts with the "real world." Whatever the display's purpose, or the source of the data, many cathode ray displays involve the use of D/A converters for generating sweeps, characters, and vectors, for positioning and intensification, relying on their inherent linearity, reproducibility, and controllability by entirely digital sources of command.

Since we are concerned here primarily with display systems that employ converters – with particular emphasis on the way they are used and the factors of importance in selecting and using them – the number of systems chosen will be limited and system description brief.

In general, a cathode-ray display system consists of a display processor and the display chassis. The processor usually holds the information to be presented for update, the instructions for presenting it, the signals needed to activate the display elements, and the digital-to-analog processing hardware, and may include a *refresh memory*. The display chassis itself contains power supplies, CRT, circuitry for beam positioning intensification, nonlinearity correction, and focus.

Representative display techniques include:

TV raster (picture and graphic displays)
Stored-character display, e.g., Monoscope (alphanumerics)
Dot-matrix (alphanumerics)
Cursive: stroke and vector generators (alphanumerics and graphics)
Rotating (PPI)

In addition, electron-beam recording (EBR) is a high-precision technique allied to the TV raster, but capable of considerably greater resolution, because it records on film, without regard for screen persistence or "flicker" problems, and can thus afford considerably greater time-per-frame.[1]

## *BASIC SYSTEM*

Figure 10 shows the generalized system outline for an installation capable of accepting, processing, storing, and displaying information on a CRT screen. A purely clerical system would not normally involve sensors and A/D interface systems, but might on the other hand, involve other forms of peripheral data input. An air traffic control system, based on radar data, is an example of current usage of CRT displays for interactive handling and presentation of complex information.

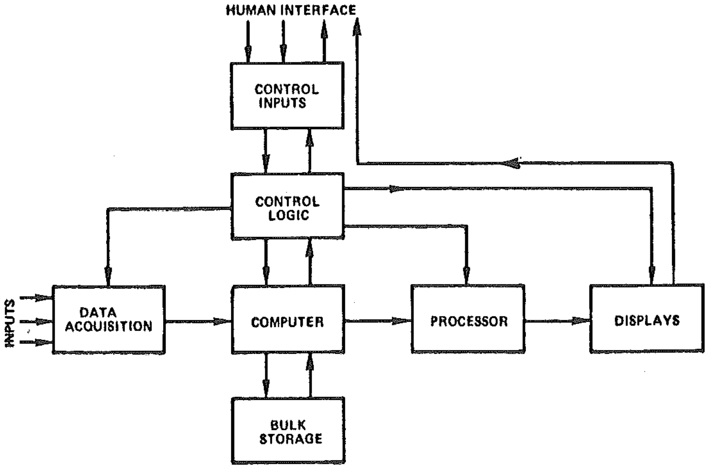

*Figure 10. Display system outline.*

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[1] *Analog Dialogue*, Vol. 6, No. 1, p. 14 "EBR uses 16-Bit DAC"

Further ingredients of the generalized display system are quite straightforward. The manual controls provide human interface, enabling the operator to call for a specific picture (or portion of a picture), to enter new information into the system, to command new modes of operation, and to initiate different data-processing and display functions. Bulk storage forms part of the data-processing capability; further auxiliary storage is often required, in the absence of storage-type CR tubes, for display refreshing at high speed to avoid annoying flicker. Control logic interfaces between computer data and the various peripheral devices, including displays, memories, communications links, the human operator, data-acquisition circuits, etc.

## *USES OF D/A CONVERTERS IN DISPLAYS*

### *Raster Displays*

In Chapter 4, a counter-driven D/A converter was suggested as a sawtooth sweep generator. When used for displays, this scheme can provide highly-repeatable, controllable, and linear sweeps of arbitrary resolution and accuracy.

Rasters conventionally are generated by a fast horizontal scan, that is swept vertically at a slower rate that will allow a given number of lines to be generated during the period for a frame. Intensity modulation during each horizontal scan provides the pictorial information. The picture resolution is expressed in terms of the number of discernible data points per line multiplied by the number of lines. The minimum frame period is the time allowed for the horizontal scan-plus-retrace (i.e. time for 1 line) multiplied by the number of lines, plus vertical retrace time.

D/A converters are well-suited to vertical sweeps, for a number of reasons:

- Timing, controlled by a clock and logic, is quite precise and uniform.
- Lines are horizontal (analog sweeps have slight tilt).
- Line-spacing-uniformity depends on linearity, while maximum number of lines depends on DAC resolution. DAC's having 10-bit resolution (1024 lines) and 12-bit linearity (0.0125% linearity error) are readily available. In electron-beam recording, a 16-bit DAC provides 4096 lines with less than 5% spacing error.
- DAC switching transients are blanked because they occur during the horizontal retrace interval.

For horizontal sweeps, the requirements on DAC's are more severe, and analog sweeps are likely to win the cost tradeoff, in most applications. For example, to resolve 500 points per line, at 500 lines per frame, at a 30Hz frame rate, requires that each digital horizontal step settle well within 100ns, and that there be no "glitches." (Even if the display is blanked between horizontal steps, large glitches at major carriers can cause deflection-amplifier transients, which distort the pattern.) While this is feasible (e.g., DAC-10DF), cost is increasing rapidly with resolution.

Raster displays using either analog or internally-synchronized digital sweeps have the weakness that the whole picture must be updated at once: specific portions cannot be singled out for local refreshing. For this reason, plus the low cost of video hardware (if it can be successfully adapted to the use at hand), a major application of raster displays is in multiple or remote monitoring, where no interaction is needed.

However, if it is necessary to update the display in local spots only, or to interact with it (for example, in editing), a form of display that allows access to specific portions of the tube face must be used.

### *Dot-Matrix Displays*

Another name for a display in which each point to be brightened has a definite address is the highly-descriptive one: dot-matrix. While it can take the form of a raster display with both sweeps digital, the speed limitations and memory requirements make a variation of it more useful, especially for alphanumerics: the stored-character dot-matrix.

Each character might be represented by a matrix of points, e.g., 4 X 7, with each point that is defined as part of the character intensified, by either a "mini-raster" scan or a character trace. The X and Y coordinates of each point are located at addresses in two ROM's; in character tracing, the point is addressed by a word consisting of a format code for the character (e.g., ASCII) and a number from a counter indicating the order of the point in the writing sequence.

In a typical system using this presentation (Figure 11), two DAC's with outputs that are summed are used for each axis. One set of DAC's, producing sweeps in raster format, locates the index point (i.e., position) of the character. The second set produces a sequential set of outputs that rapidly move the spot from one point to the next, until the character has been traced out.

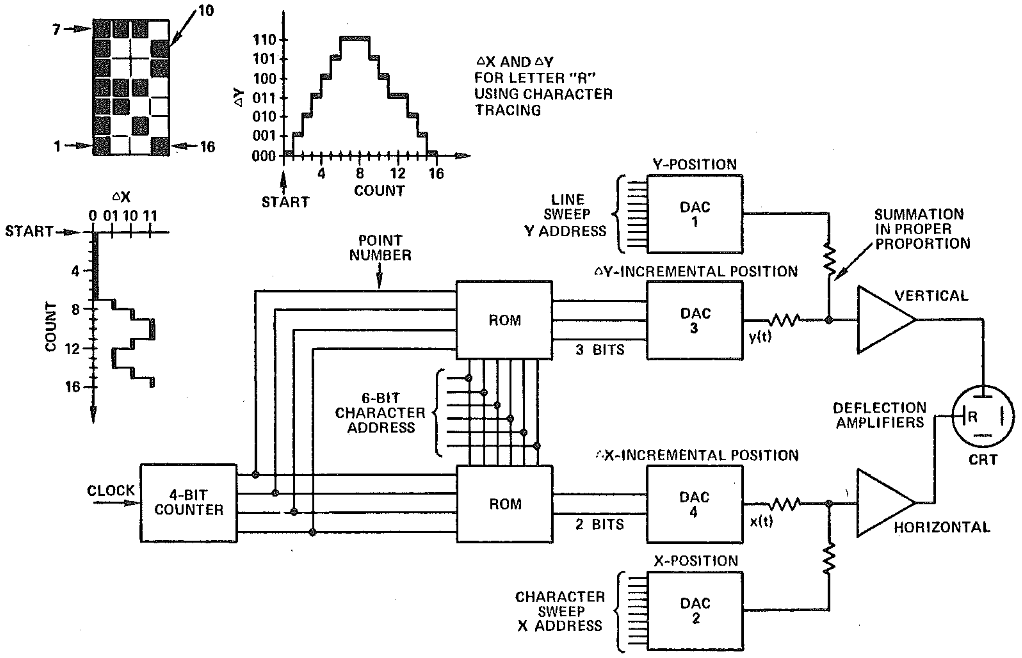


*Figure 11. Dot matrix display scheme.*

An important advantage of this scheme is that low-resolution (but high linearity) DAC's can be used to locate each character, in the same way that a typewriter indexes across a page, character by character, and down the page, line by line. Glitches are no problem because the trace is blanked in transit. The DAC's that produce the characters need only have fast response, with very modest resolution and accuracy. And the refresh memory needs to store only the character codes, rather than all points for each character.

For a purely alphanumeric display, type "point size" and "leading" could be determined by manual gain controls of the respective DAC's, to the degree allowed by the logic determining the character count per line and the amount of information to be presented in each frame.

Information can be updated incrementally by addressing specific display locations, and grossly by either displaying new frames, or by a "scrolling" or "waterfall" (in reverse) scheme in which data is advanced vertically. Old data disappears at the top as new data appears at the bottom.

Of course, the "typewriter" presentation need not be used at all. For example, in a display that combines graphics and alphanumerics, the X and Y DAC's may be set at the appropriate arbitrary address for each character of a caption, which is then supplied via the ROM. Captions may also be read along vertical lines if axes are interchanged. Although 2 and 3 bits served to display the character adequately in the example, the D/A converter may have many more bits available for handling other forms of additive input. It is important to note, though, that the accuracy and resolution of the positioning DAC must be such that its errors are less than the relatively-weighted value (taking differing scaling into account) of the least-significant bits of DAC's whose outputs are summed. Otherwise, overlapping or uneven spacing may result.

### *GRAPHIC DISPLAYS*

The general objective in graphic displays is to provide a flickerless presentation of numerical, line-drawing, or pictorial information, with the possibility of editing, changing, storing, or isolating any element of it. If the drawing is synthesized by definable and reproducible computer operations, then any number of schemes may be used for the actual control and interaction, ranging from keyboards to "light pens."

The general problem is to start with the spot at a given point (which may be any point arrived at in the course of plotting the display, or it may be a point that has been recalled for replotting), and proceed by a straight-line increment to another point, using a programmed analog technique. (For better control of spot position, it could be done digitally by closely-spaced dots, perhaps employing a binary rate-multiplier, but, on the other hand, it may be highly desirable to reduce the amount of memory or digital manipulation involved.) It is important to avoid variations of intensity caused by velocity modulation, by either maintaining constant writing speed or by compensating for variable writing speed by appropriate intensity modulation (the former is preferable if it can be accomplished simply).

#### *Delay-Line Integrator*

In Figure 12, a single high-resolution converter is used for each coordinate. The outputs of the converters are incremented in small, equal steps of X or Y, whichever is the greater in magnitude. Between the converter output and the deflection amplifier is a "delay-line integrator," essentially a fast analog delay line tailored for step response that has a fixed delay time, and is linear with time from the initial value to the final value. It will then hold the final value until the input changes. Because the maximum input steps are equal, the delay line will maintain a constant maximum writing rate in the X or Y direction (until the other variable becomes greater). Since the larger of the two variables has been chosen, the largest possible vector change (occurring in the case where they are equal) is 1.4 times as great. The range from 1 to 1.4 is sufficiently small that only a few values (if any) of intensity-modulation voltage will be needed to provide adequate correction for changes in writing speed.

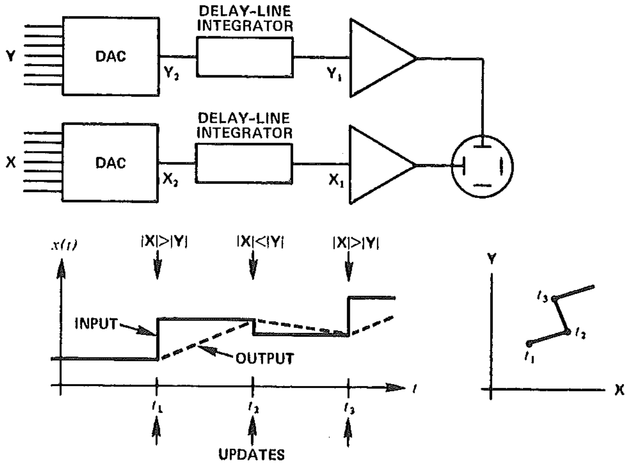


*Figure 12. Delay-line integrator. DAC outputs have just switched to new values, $X_2$, $Y_2$. Delay line outputs $X_1$, $Y_1$ will change to new values linearly.*

### *Vectors and Segments*

An obvious way of obtaining a given rate of change of voltage is to feed a constant into an integrator: the rate of change of output is proportional to the input. Thus, starting with an intial position $X_0$, $Y_0$, furnished by a DAC pair, there is added to it the output of a pair of integrators, the inputs of which are slope update outputs from another DAC pair with inputs from the refresh memory. The slope update signals may change during the configuration of a character, or they may allow long uninterrupted straight sweeps. The two major difficulties with this approach are that the integrator must be reset to eliminate drift, and there is no easy way to maintain constant trace brightness.

Another approach uses ramps instead of integrators. In the (perhaps unwieldy) circuit of Figure 13, there are two out-of-phase triangular waves, two high-accuracy DAC's for initial positioning, and four multiplying D/A converters supplying the coordinates of the points to be connected.

Starting from an initial point, determined by the X and Y position DAC's, the rates of change of X and Y are determined by multiplying the digital input values by the ramps and summing the out-of-phase values in the output amplifier, e.g., $(X_2 - X_1)$ and $(Y_2 - Y_1)$ for the positive slope of the synchronous ramp.

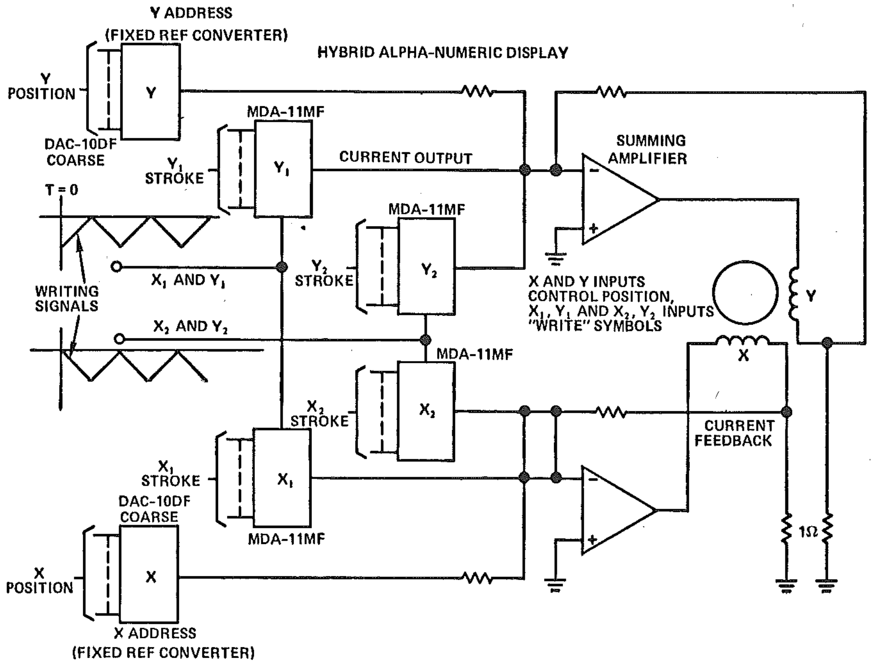


*Figure 13. Display system combines fixed-reference converters for coarse positioning, plus multiplying converters for applying "writing" analog signals to the deflection circuits. Method uses common analog triangular waveform for synthesizing all alpha-numeric symbols, instead of using a unique analog waveform for each symbol.*

When updating occurs, the ramp at the same time changes slope, and the old value, i.e., $X_1$,$Y_1$ is replaced by $X_3$,$Y_3$. The new rates of changes are thus determined by $-(X_2 - X_3)$ and $-(Y_2 - Y_3)$, or $X_3 - X_2$ and $Y_3 - Y_2$. Thus, each new incremental slope is determined by the difference between the new input and the previous input, always in the proper sense.

Unlike the integrator, resetting is not necessary; however, the values of X and Y should be refreshed from time to time, since the net change depends on the ramp amplitude, and tolerances build up. Also, it is necessary for the computer to determine the vector change and modulate the intensity appropriately.

There are many other schemes that could be conceived of, and a number have been described in the literature. In some recent schemes, binary rate-multipliers are used for direct digital multiplication to supplant multiplying DAC's.

In the large majority of display schemes, either a fixed-reference or a multiplying D/A converter is a key element, determining to a large extent the accuracy, linearity (except for geometrical sources of nonlinearity) and sharpness (lack of transients and flicker) of the display. The elements of DAC performance that are often necessary in other applications are *crucial* in displays because of the high visibility of defective performance. A few of these elements are:

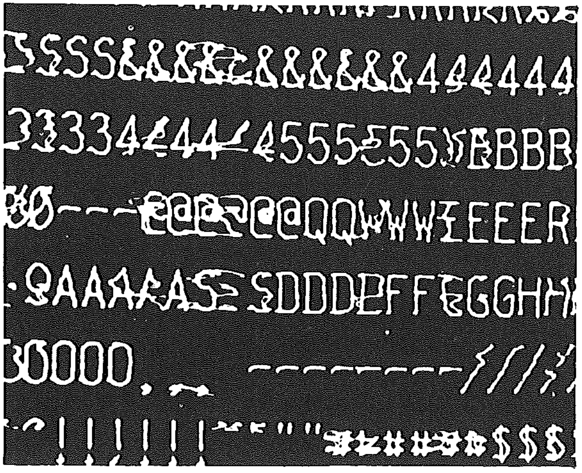
*Differential Linearity and Linearity*

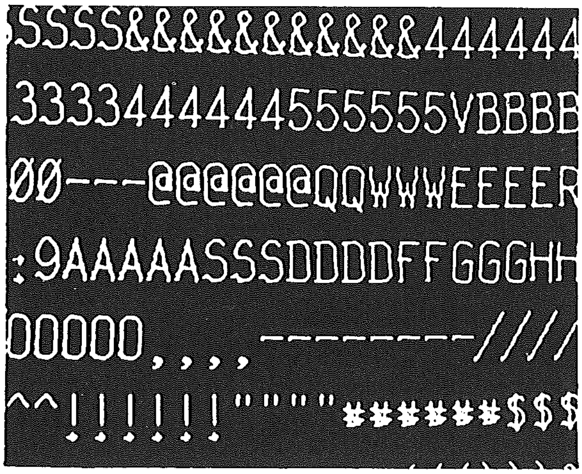
If differential linearity is poor, gaps, banding, and irregular line- or dot-spacing will result. Straight lines develop wobbles. If linearity is poor, it may not be especially bothersome in alphanumeric displays, but graphics become distored. If linearity is poor in electron-beam recording for aerial photography, maps pieced together to make larger maps may suffer discontinuities at the edges.

*Speed and Dynamics*

Slow settling will result in unevenness in spot locations, a loss of "sharpness" in transitions. Because of the mathematics of filling space, compromises must be made between flicker, resolution, and dynamics. Glitches cause raggedness in patterns where sweeps go through major carries, and poor tracking at corners in graphic displays. Speed variations resulting from transients superimposed on linear tracks result in intensity variations due to velocity modulation of the image. Fast DAC transients that are not of themselves important (because the brief interval in which they occur can be blanked out) are rendered more important by the dynamics of the deflection system, which involves amplified energy levels and higher inertias, and can result in hundredfold prolongation of the transient interval, as well as ringing and overshoots.

The photographs show the effect of "glitches" on a typical display. About 5% of the picture area is shown. (Courtesy of The Foxboro Company, Foxboro, Mass.)





## D. COMMERCE, INDUSTRY, AND ELSEWHERE

The reader who has arrived at this point (after presumably reading all of the material in Part One) has been exposed to a large variety of circuit configurations and application suggestions. It would not have been difficult for him to have noticed that some of the configurations looked more-or-less alike, though offered from somewhat different viewpoints.

In this section, he will not find anything especially different, from the circuit point of view, but he may find it of interest as a microcosmic glimpse of the applications of conversion devices in the workaday world. We will show here just a few applications, with the descriptive emphasis more on what they *accomplish,* rather than on how their circuits go together.

At the end of this chapter will be found a brief appendix, listing a large number of randomly-aggregated present and possible uses for conversion and the associated analog-digital technology. This list, in no sense complete, and in no wise organized in any rational way, might represent the result of a quick scan of one or two current magazines, and the recesses of one's mind. It will not impress anyone now working in the field. However, for the reader who is unaccustomed to the power of computational techniques, it may be an excellent point of departure for the development of ideas as to how they might help in his own field.

Because A/D and D/A converters were originally developed as computer interfacing devices, used primarily for getting data into and out of digital computers, the casual observer still tends to associate them with computer application alone. In reality, as Chapter 5 has demonstrated, both A/D and D/A converters have followed the operational amplifier out of the computer laboratory and into the industrial world-at-large.

Digital communications is increasingly employed for its noise immunity. Likewise, digital methods are used in testing, controlling, and measuring, owing to their ease of application, and the simplicity with which digital data can be manipulated, stored, processed, addressed, distributed, scaled, and otherwise handled.

One result is an interesting variety of applications for A/D and D/A converters, in which the unit has a life of its own, quite independent of a computer, as a component of a piece of equipment designed for a purpose.

### *AUTOMATIC SCALE ZEROING*

The use of a D/A converter to reset zero in a weighing machine (Figure 14) is typical of a large number of uses for the D/A converter as a long-term sample-hold device, as mentioned in Chapter 5.

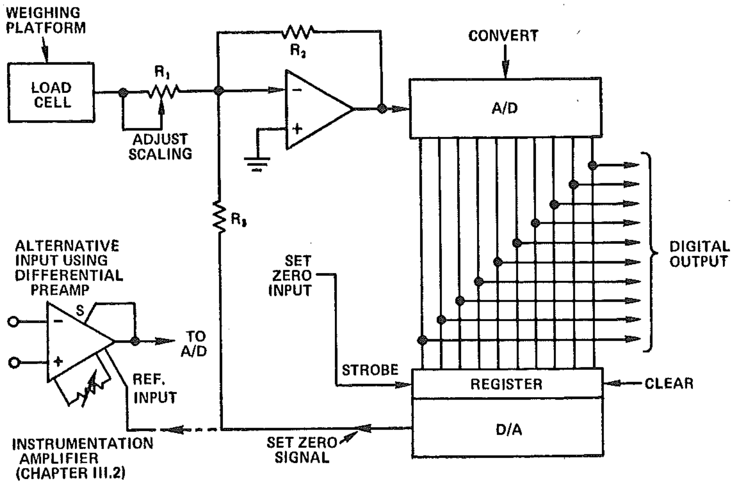


*Figure 14. Weighing device with automatic "push-button" tare weight compensation.*

The purpose of the arrangement is to measure the container (or "tare") weight and feed it back to the summing point of an operational amplifier, to produce a null reading, so that when the container is filled, only the weight of the contents is read out.

The procedure is simple: The empty container is placed on the scale, with the D/A output at zero. The voltage representing the container's weight is converted to digital form by the A/D converter. Then the A/D output is strobed into the D/A converter, producing an output that is equal, but of opposite polarity, to the input, thus zeroing the summing-amplifier output. When the load is applied, another conversion is performed (but does not affect the D/A output), and the weight of the load alone is read out.

The amplifier can be so scaled that the converter (which may be part of a DPM) reads out in engineering units of weight, or some function of weight, such as cost. If the A/D converter is a BCD type, the D/A converter should be similarly coded. If the input range of the A/D converter is similar to the output range of the D/A, $R_2 = R_3$, with $R_1$ setting the overall gain relationship. If an instrumentation amplifier is used, the DAC adjusts its reference.

The same basic idea is applicable to any situation for which push-button zeroing is desirable, usually when sophisticated equipment is being operated by untrained personnel, or when time is of the essence, as in production-line operations.

## *LOW-NOISE COMMUNICATIONS*

Digital techniques for voice and data transmission[1] are widely used by the common carriers, NASA, the military, railroads, and many more. The purpose is to gain increased immunity to noise and to preserve the fidelity of the transmitted information in the presence of nonlinearities, analog crosstalk, etc.

Low noise communication is possible when a voice signal is converted to digital form before transmission. Analog signals pick up noise, and, though amplified in "repeater" stations along the way, tend to become progressively degraded. But if digital transmission is used, the signal can be restored by reshaping or regenerating the pulses. At the receiving end, a D/A converter reconstructs the original voice signal.

Figure 15 is a simplified diagram of such a system. The analog signal is sampled at regular intervals, converted to digital form in the A/D converter, and transmitted serially, along with the clock pulses. At the receiving end, the signals are assembled in a shift register, kept in step by the clock pulses, and converted back to the original audio signal with the D/A converter.

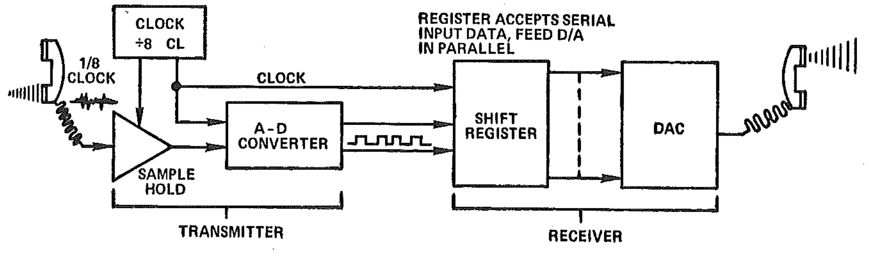


*Figure 15. Digital voice communications.*

The clock frequency is divided by 8 before being applied to the sample-hold. The A/D converter thus sends one serial 8-bit word for each time the sample-hold circuit is strobed. The shift register at the receiving end assembles the words of eight bits each.

The sampling rate should be at least twice the bandwidth. Thus for 5kHz bandwidth, a 10kHz sampling rate is required. The converters thus should operate on 0.1ms cycle times.

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[1] This topic and the following one (among others) were described in *Electronics*, October 26, 1970 "Purring D/A Converters to Work. . ." and are still of timely interest.

## *MUSIC DISTRIBUTION SYSTEMS*

Music-distribution systems in commercial aircraft (e.g., the Boeing 747) utilize digital techniques to conserve wiring and economize on weight. As an alternative to piping eight analog channels to each seat, in parallel (with all the wiring involved, as well as the possibilities of crosstalk), the music channels are multiplexed, distributed digitally on one pair of wires, and decoded at the seat.

In Figure 16, the analog music channels are multiplexed into the sample-hold circuit. The A/D converter sends out serial words corresponding to each of the eight channels in sequence. A 3-bit address code is added to the 8 bit of analog information, and the complete word is wired to every seat in the plane. At each seat, an address decoder is linked with the channel-selector switch, and the D/A converter operates only on the digital word corresponding to the selected channel.

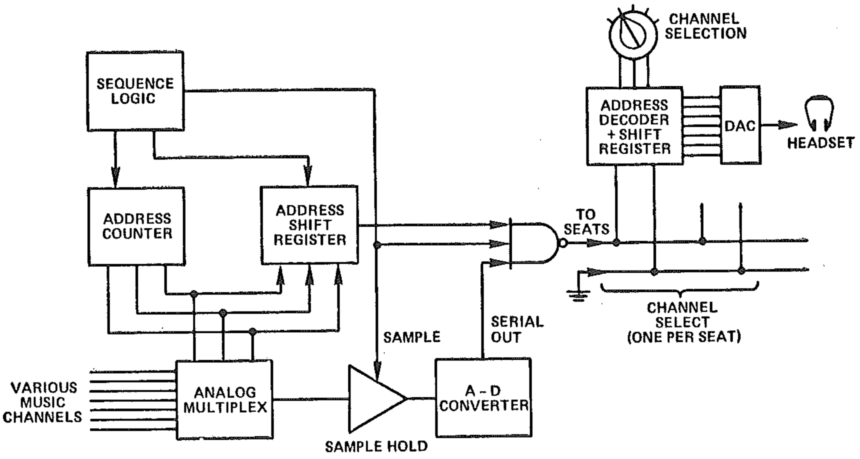

*Figure 16. Aircraft music distribution.*

As in the previous application, absolute accuracy in the D/A converters is unimportant – all that counts for good sound reproduction is linearity. It's also interesting to note that only 6 bits are required for reasonably satisfactory music reproduction (6 X 6 = 36dB). ("It's a nice place to visit, but I wouldn't want to live there.")

## *POWER RECTIFIER MONITORING*

Availability of low-cost digital computers and peripheral equipment has opened up a new field in the real-time monitoring of high-power systems, and detecting incipient danger signals in time to protect against (really) catastrophic failure. One can foresee application of the principle to large turbines, generators, engines, pumps, and machine tools, and other equipment where continuous monitoring and comparison of oil pressure, bearing temperature, mechanical stresses, etc., can prevent destruction of expensive (perhaps irreplaceable) equipment and even save human lives.

Digital protection is well-suited to systems that must operate constantly and consistently, but it is perhaps even more advantageous for systems that operate over wide ranges of temperature, pressure, altitude, speed, or must be started and stopped frequently.

The concept of digital protection is exemplified very effectively by a 128-megawatt power-rectifier system used at the Lawrence Radiation Laboratory, Berkeley, California,[2] for magnet-field control in the Bevatron particle accelerator (Figure 17).

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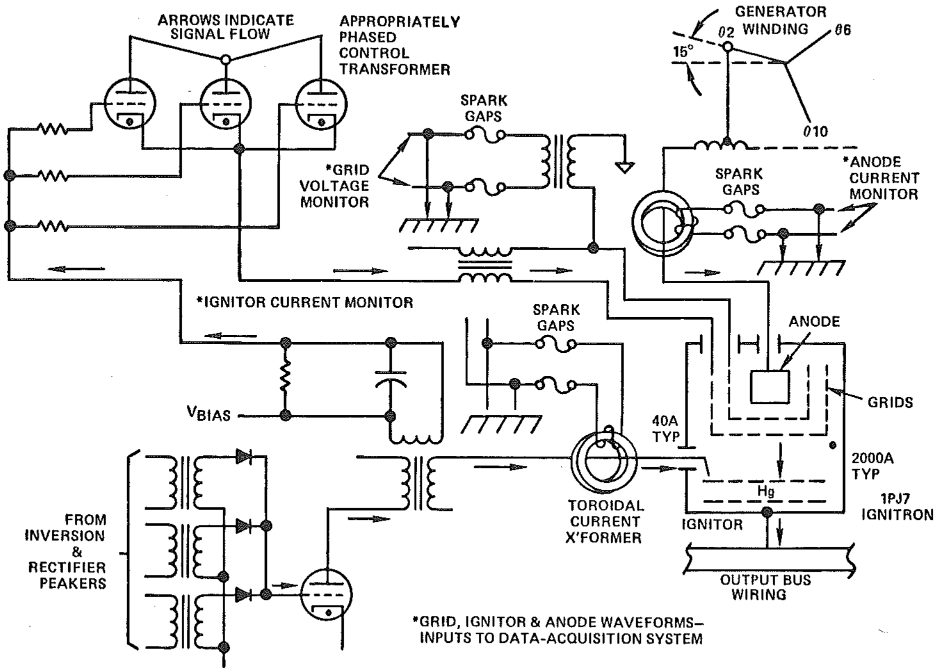
[2] *Analog Dialogue,* Vol. 5, No. 3, "Protecting a 1/8 Gigawatt Power Supply (8kVA at 16kV) or How Do You Make a 2000A Fuse?"



*GRID, IGNITOR & ANODE WAVEFORMS– INPUTS TO DATA-ACQUISITION SYSTEM

*Figure 17a. Ignitron monitoring system.*

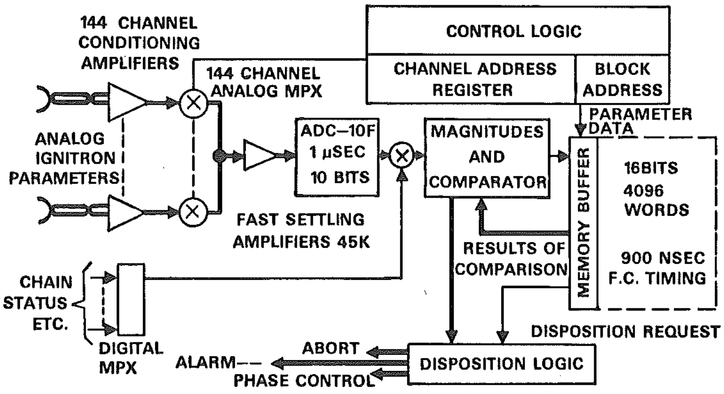


*Figure 17b. Data acquisition system.*

*Figure 17. Bevatron data-acquisition system.*

The rectifier system is based on 48 mercury Ignitrons (high-power rectifiers), operating in parallel pairs, each of which handles an anode current of 2000 amperes. Output dc power is controlled SCR-fashion by adjusting the time, within each cycle of the 12-phase 60Hz excitation power, at which the individual ignitrons conduct. Firing control is accomplished by varying the phase of the drive pulses applied to each ignitron's grid. Faulty firing can obviously create havoc within the system, by simply causing one ignitron in a pair to conduct prematurely – or not at all – so that current is unequally distributed between ignitron pairs.

A fast data-acquisition system samples such waveforms as grid voltage, ignitor current, and anode current, for each tube, at a large number of intervals during each cycle and compares them with stored threshold values (perhaps obtained by processing earlier data). Any significant disparities are noted, analyzed, and appropriate action is automatically initiated, ranging from minor adjustments, to a "flag," to shutdown.

Since such anomalies can signal incipient breakdowns, this scheme can prevent the very expensive consequences of loosing large amounts of power under fault conditions, even for very short times. The method also allows observation of aging and so can effect parts replacement at appropriate, rather than arbitrary, intervals. It also provides rather obvious means of feedback of life data to parts manufacturers, who can use the information for product reliability improvement. (It's much harder to diagnose the source of failure by investigation of a hardened puddle of metal and glass, or after an explosion of suddenly-vaporized coolant.)

Although most readers of this book are unlikely to be designers of control systems for Bevatrons, a little thought will show that the monitoring principles applied in this case may prove useful elsewhere for minimizing risks of failure, and for failure analysis, in any system where catastrophic failure should be unthinkable.

# APPENDIX TO CHAPTER SIX

A random, incomplete, disorderly, and possibly presumptuous *(but, hopefully, thought-provoking)* list of present and likely areas where A/D and D/A conversion may help.

Accumulated life information
Actuators, displays, indicators
Aircraft hydraulic system testing
Air traffic control system
Angular rate, linear force, swept frequency, programmed temperature, forced vibrations, etc., generated electronically
Architectural work
Automated production processes
Automatic pushbutton zeroing by nontechnical personnel
Automatic scale zeroing
Automatic test system

Bins, putting things into
Blood, automatic chemical testing
Blood pressure monitoring in intensive care

Calibration curves
Chart-recorder overrange
Chemical plants & complexes
"Chirp" radar
Communications signals
Complete testing from several-hundred tests/min
Constant-speed alternator
Continuous blending
Controllers

Depth of cut
Digitally-controlled aircraft simulator
Digital control of steel mills
Digital speech & music transmission, multiplexed
Doppler radar, ignoring returns from stationary objects

Electrical substation
Electronic weighing
Electrochemical analyzer
Electrochemical baths
Emitted energy from bombarded target
Energy level, momentum, light intensity

Factory electrical power demand peaks
Firmware
Flow meter
Fluidic devices
Food processing operations
Foundry operations
Frequency synthesizer

Gas chromatographs
Generate ideas for rectifier improvements
Grading apples
Graphics design

Hangar and airfield testing of aircraft
High-voltage power supplies
High-power systems (real-time monitoring)
Histograms

IC semiconductor test equipment
Industrial, aeronautic, or scientific
Infrared optical pyrometers
Infra-red techniques
Instrument servos

Lasers and optoelectronics
Level indicators
Load cell

Machine shops
Maintenance scheduling
Mass spectrometers
Materials testing
Mechanical handling
Mechanical servos

Metal fabrication
Metal-removing speed
Metalworking
Monitoring oil pressure, bearing temperature, mechanical stress
Motor drive
MPX music distribution systems for passengers in 747's

Nuclear accelerators
Null balance
Numerically-controlled machine tools
N/C positioner

Oceanography
Ocean technology
On-line chemical process

Pharmaceutical plants
Plating plants
Pollution monitoring
Power-rectifier monitoring
Precision 3-phase output (synchronous motor speed control)
Pressure gages
Pressure regulators
Pressure, temperature, seismic, sonar, radar, and other transducers
Printing and graphics
Programmable power supplies
Protects against breakdown
Pulp and paper mills
Pulse-height analysis

Radar or fire-control system
Radar plan-position & moving-target indicators
Real-time process control
Relay testing
Remote or unattended monitoring
RF measurements

Seismographic experimentation
Ship's turbine, widely-differing speeds, temperature, pressure, humidity, shaft speed, torque
Signal processing in radar and sonar systems
Simulator's altimeter
Solenoid valves
Sonar returns
Spectral analysis
Speed control
Steel industry
Steel rolling mill
Stress signals
Sulfur dioxide monitors
Supersonic air blasts
Synchro-resolver

Tachometer signals
Tanks, boilers, vats, pipelines, bearings, oil burners (temperature sensing)
Tare weight compensation
Textile mills
Thermal ovens
Tone generator
Tracked air-cushion vehicle
Training simulators
Turbines, generators, engines, pumps, machine tools
Typesetting

Utility Substation

Valves and Actuators

Weather charts
Weather stations
Weighing machines
Wind tunnel

X-ray dosage