analog dialogue

A forum for the exchange of circuit technology: Analog and Digital, Monolithic and Discrete

VERSATILE ANALOG-to-MICROCOMPUTER INTERFACE

(Page 3)

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High-Performance Analog Multiplier

CMOS Converters as I/O Devices

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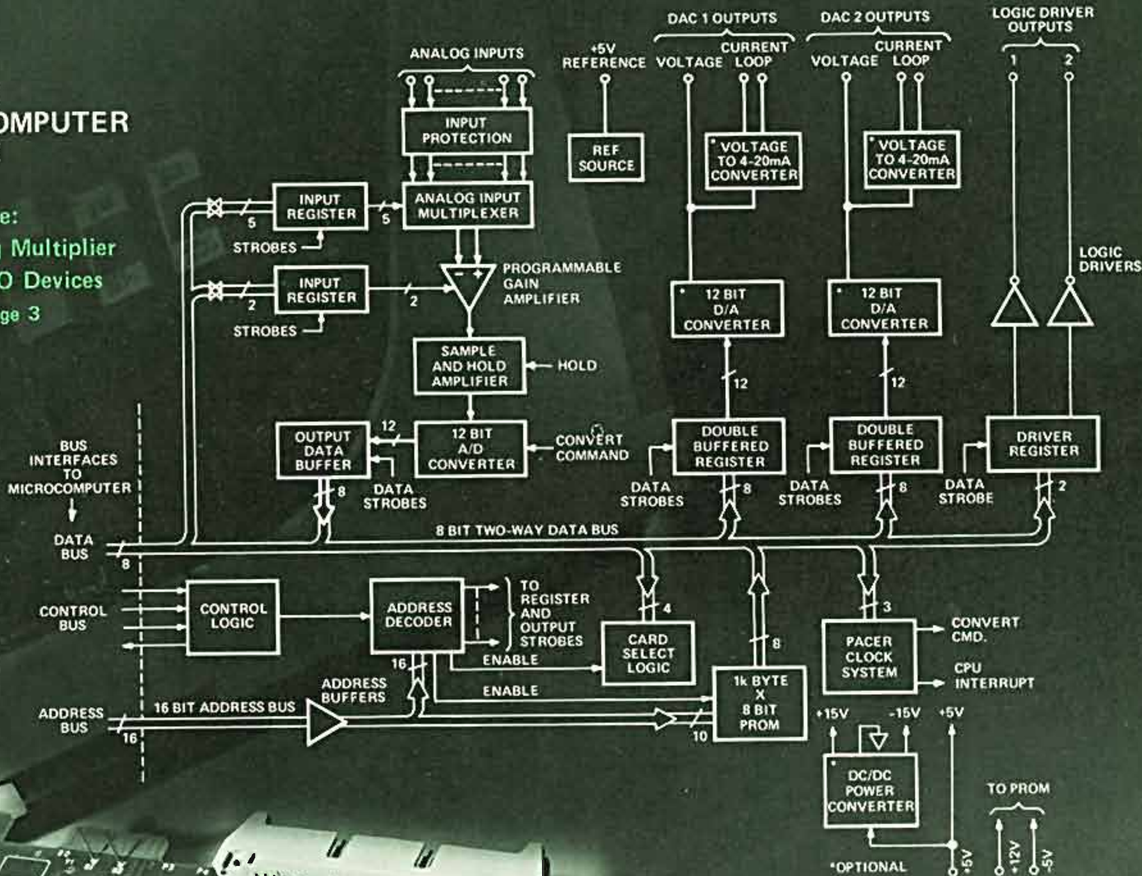

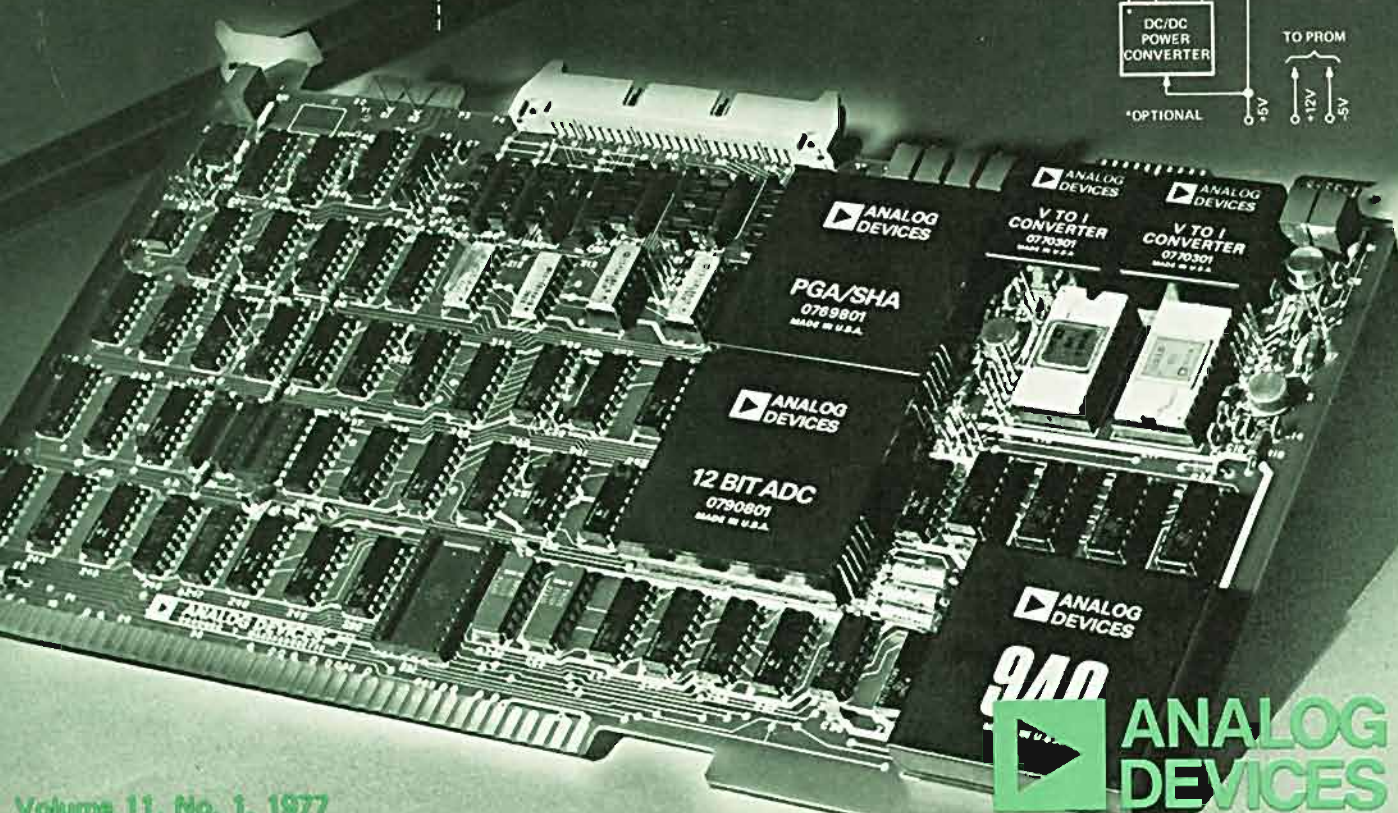

Volume 11, No. 1, 1977

ANALOG DEVICES

Editor's Notes

ANALOG-to-DIGITAL CONVERSION

The theme of 1976 might well have been "Born Again," a phenomenon comprising everything from the opening of the tercentenary to the characterization of presidential candidates. An unheralded (and somewhat unsettling) rebirth, of little importance (except to its subject) also occurred. The circumstances may be of interest:

There is a vanishing breed of scientists and technologists who, whatever their pursuits, are united in a tenacious belief that there is considerable merit to analog approaches to computational and transformational manipulations of real-world (analog) data. The Environment has not favored this breed. Its numbers have been perenially decimated as it has been driven from one ecological nook to another, its ranks increasingly thinned by converts seeking solace in digital definitude.

Those with long memories can recall the glories of the room-sized general-purpose analog computer, the retreat to the (then) low-cost desktop computer, the fallible bastion of the special-purpose multi-op-amp kluge, and more-recently, the struggle to retain collections of low-cost, precise functional IC's and modules. They dream of triumphs but awaken to the nightmare of the incredible shrinking computer, the telescoping of complexity and cost, the burgeoning ubiquity of the nanosecond. They hoped for the coming of a messiah-on-a-chip; instead they face the microcomputer-on-a-chip.

And yet they survive. Those who were steadfast even prosper, because analog is the "real world", and this small coterie of specialists is the bearer of the arcana of instrumentation and measurement. But this is an uneasy prosperity; outside the busy workshop, there lurks the shadow of things to come – and its name is The Direct Digital Transducer (on a chip).

The crux of this present chronicle is the train of apostasy: the first doubts about the cost-effectiveness of the general-purpose analog computer, the retreat to analog computation's (less glamorous) role in signal conditioning, the discovery that at the end of the analog circuit there often stood a converter, the learning about logic and the ease of implementing it with TTL chips, the pensioning-off of the trusty slide rule that had been one's faithful companion for decades (while embracing a scientific pocket-calculator), the increasing fascination with software, and finally, the revelatory thrill of hands-on discourse with a sub-$1000 microcomputer.

But betrayal of principle engenders guilt. In what form will Banquo's ghost, or the Commendatore's statue, or the handwriting on the wall materialize to the analog apostate? Is there to be an analog Hereafter in which punishment consists of eternal calibration of drifting multipliers, continual 600V shocks from vacuum-tube circuitry, a 4096 x 4096 patchboard with one wire missing, an unscaleable problem with excessive dynamic range, a calendar watch with randomly failing segments to mark the passage of eternity? One shudders at the prospect!

Dan Sheingold

THE AUTHORS

Barrie Gilbert (page 6) received a "best paper" award at the 1974 IEEE International Solid State Circuits Conference for a paper on the AD534's design. A consultant to Analog Devices, his photo and a brief biography appear in *Dialogue 9-1*.

Dave Kress (page 10) is Product Marketing Specialist at Analog Devices Semiconductor. His photo and a brief biography appeared in the last issue (10-1).

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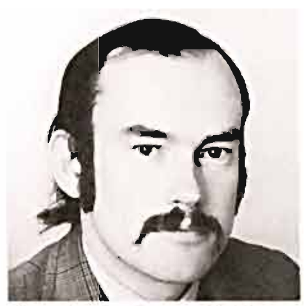
Ivar Wold (page 13) is Director of Systems Development for ADI's Instruments and Systems Group. A native of Norway and long-time resident in England, he obtained a B.Sc. in Aero-and Astronautics from the University of Southampton, with "first-class honors." Following graduate work, he has developed complex digital measuring instruments and a real-time multi-terminal banking computer. At Analog Devices, he has designed devices ranging from IC converters to panel meters, and systems ranging from SERDEX to a new advanced measurement and control system to be introduced in these pages shortly.



Russell Smith (page 17) is Manager of Wormald International Sensory Aids Limited, a company formed in 1976 with the objective of developing and manufacturing electronic aids for the handicapped. He holds a Ph.D. degree in E.E. from the University of Canterbury, Christchurch, N.Z., and his research activities have been in the field of sonar systems, both in the air and underwater. He headed the design team which developed the SONICGUIDE.

analog dialogue

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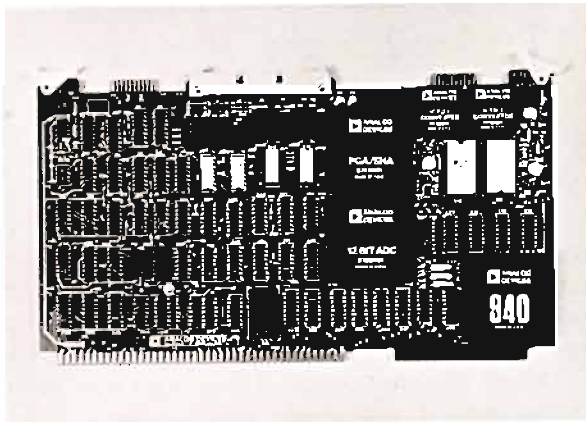
VERSATILE ANALOG-TO-MICROCOMPUTER INTERFACE

RTI-1200 Interfaces Analog Inputs/Outputs to Intel SBC-80/10 Cards are Physically, Electrically, and Software-Compatible

by Jim Fishbeck

The RTI-1200 "Real-Time Interface" is a complete analog input/output subsystem that greatly simplifies the interfacing of analog signals to microcomputers. Though designed expressly to be plug-in compatible with the Intel SBC-80/10 Single-Board Computer, it can readily be used with other 8080-based microcomputers. The RTI-1200 appears to the computer as a block of memory locations, a direct benefit of memory-mapped I/O – a technique that offers some powerful advantages in simplifying (and increasing the versatility of) the software associated with handling analog input and output quantities. The RTI-1200 is a near-optimum answer to the need for an easy, cost-effective way to get analog signal information into and out of microprocessors and microcomputers. Its panoply of available functions is shown on the cover of this Journal.*



ORIGINS OF THE PROBLEM

It was commonly thought in the past that a converter is the key link between the analog and digital worlds. In truth, in the measurement and control of real-world phenomena, the converter is only a portion of the link, as Figure 1 shows. The digital output of a conventional a/d converter is usually not in a form that can be directly connected to a microprocessor or microcomputer.† Some type of digital-to-digital interfacing is generally required to allow a converter to communicate with a microcomputer or a microprocessor. Similarly, at the analog end, transducer-output signals (and the like) may require some kind of analog signal conditioning to make them suitable for connection to the input of an a/d converter.

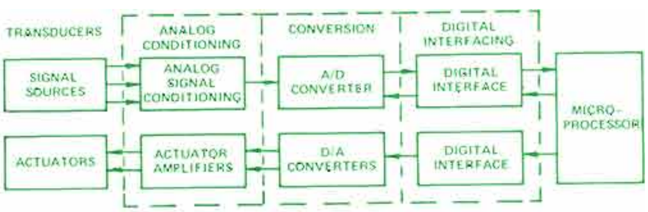


Figure 1. Interfacing with the real world.

At the μC's distribution end, a conventional d/a converter's digital inputs are generally not configured in such a way that they can be directly connected to a μP. And the analog output signal from a d/a converter may have to be processed further before it can be fed to an analog input device like a servo motor or a recorder.

The problem, then, is not merely one of converting an analog signal into digital form (or vice versa); it typically involves the entire data-acquisition process: analog signal-conditioning, a/d and d/a conversion, digital-to-digital interfacing, and signal transmission in analog and/or digital form.

*Use the reply card for technical information on the RTI-1200.
†For a discussion of converters that are less conventional, see pages 12-15.

THE DIGITAL-TO-DIGITAL PROBLEM

There are two techniques commonly used to interface a/d and d/a converters with nearby μP's and μC's. The conventional approach, sometimes known as *isolated*, or *accumulator* I/O (I/O: Input/Output), involves the connection of an I/O device, whether a/d or d/a converter or some other device, to a microprocessor through an I/O structure that is separate from the structure used for access to memory. Figure 2 shows how I/O devices are connected to a microprocessor, using this scheme: An 8-bit address sent out on the I/O bus selects a particular I/O port, and data is exchanged between the I/O device and the μP via the standard 8-bit data bus. An *I/O read* pulse brings data into the μP from an external I/O device, and an *I/O write* pulse transfers data *to* the device. Though not shown here, all data-transfer operations must go through the microprocessor's accumulator.

(continued on the next page)

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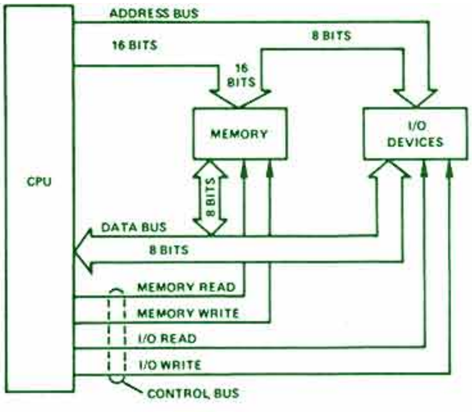


Figure 2. Accumulator or Isolated I/O vs. memory-mapped I/O.

The other technique, based on making the I/O device appear as a series of memory location, is commonly called "memory-mapped I/O". In the system of Figure 2, I/O devices interfaced as memory would in fact simply be part of the block marked MEMORY. All data and commands sent to a device would be executed as instructions that write into memory, and all data and status information retrieved from an I/O device would be accomplished with *memory read* instructions.

Memory-mapped I/O (inherent in the RTI-1200) provides two powerful advantages. First, it allows the use of all memory-reference instructions, such as *load, store, increment, move,* etc. (With conventional I/O, *accumulator in* and *accumulator out* are the only instructions that can be used.) Second, I/O devices, such as analog input/output subsystems, when treated as memory, can be used with many different types of microprocessors and microcomputers. The reason is that most µP's and µC's handle memory in pretty-much the same way, while they can be expected to differ from one another in the way they handle I/O peripherals. An example of memory-mapped I/O software is shown on page 5.

THE ANALOG INTERFACING PROBLEM

Connecting analog signal sources to a/d converter inputs —and analog outputs to analog actuators—frequencly involves more than simply hooking up the input of one device to the output of another, even if multiplexing, selection logic, sample-hold, and programmed gains are included. For example, in many applications it would be highly desirable (often mandatory) to have the input to the converter or multiplexer overvoltage-protected, so that unexpectedly large signals do not damage the system. It might also be desirable to be able to have different analog gains available on different channels, or to be able to input and/or output the 4-20mA current-loop signals frequently used in process and industrial control systems. All of these concerns indicate that considerable thought must be given to how to get analog signals into or out of an interfacing subsystem.

THE SOLUTION MUST BE COST-EFFECTIVE

We've shown that the design of an instrument or system that involves the interface between real-world (analog) data and a microprocessor involves much more than a converter. While a design engineer (or team) may have adequate background and experience to deal with all these issues, a product that is specifically designed to solve the most-often-recurring interface problems can save time and money, and allow high-powered technical talent to accomplish much more in the areas of highest payoff.

If a suitable analog-to-microcomputer interface product can be bought, it is possible to plug in the hardware and start running sample programs very quickly. This frees the designer for the tasks really requiring attention: the aspects of the hardware design that are unique to the application, and –the real time-eater–system software development. Saving the time eaten by the analog-interface problem allows the designer to get equipment into operation sooner (and, in the case of an OEM, to get the product into the marketplace faster). In short, buying–rather than building–an analog interface makes sense for the same reasons it makes sense to buy a microcomputer on a card rather than to buy and assembly a collection of chips.

THE SOLUTION IS THE RTI-1200

The whole purpose of the RTI-1200 is to make it as easy as possible to get high-precision (12-bit) analog signals in and out of 8080-based microcomputers–the Intel SBC-80/10, in particular. In pursuit of that goal, a large number of extraordinarily useful features have been deliberately designed into the RTI-1200.

DATA ACQUISITION

Data acquisition is the RTI-1200's basic function. As the block diagram on the cover shows, an analog-input multiplexer, a programmable-gain amplifier, a sample-hold amplifier, and a 12-bit a/d converter are all inherent. The standard RTI-1200 offers either 16 single-ended or 8 differential-input channels, and an *on-board* expansion option doubles those numbers. All of the analog inputs are fully protected against continuous overloads of up to ±28V, and protection beyond that level is provided by fusing-resistors in series with the inputs.

The user can configure the inputs for full-scale ranges of 0 to +10V, ±5V, or ±10V. The programmable-gain amplifier has *software-selectable* gains of 1,2,4, or 8V/V, which expands the effective dynamic range to 15 bits and provides a corresponding increase in input sensitivity. For example, in the 0 to +10V input configuration, full-scale input is 1.25V at a gain of 8V/V, with 12-bit resolution. The ability to change gain via software allows the user to program *different gains for different input channels,* or to write software subroutines that implement automatic gain ranging (described in detail in the User's Manual). Since the RTI-1200 does not tie up the central processing unit (CPU) while a converison is being made, system throughput rates can be enhanced by pursuing other tasks while the a/d converter is performing a conversion.

ANALOG VOLTAGE OUTPUTS

The RTI-1200 has provisions for two optional on-board 12-bit d/a converters, which are software-controlled via double-buffered registers. They can be used to drive analog input devices, such as recorders, servo drivers, or controllers. Both d/a converters can be set by the user to any of 5 output ranges.

4-20mA INPUT/OUTPUT

Eight of the analog input channels can accept user-supplied shunt resistors to allow them to accept 4-20mA current-loop signals directly. One or both of the output channels can be equipped with optional 4-20mA current-loop output. This ability to deal with 4-20mA current-loop signals at both input and output makes the RTI-1200 well-suited for applications in industrial and process control, where such loops are common.

MEMORY-MAPPED INTERFACE

One of the RTI-1200's most-important features is the way it interfaces to a microcomputer. It appears as a block of memory locations, using the memory-mapped I/O technique; all of the 8080's memory-reference instructions can be used in communicating with the RTI-1200. For example, one of the memory locations used by the RTI-1200 contains the address of the analog-input channel selected by the multiplexer. Stepping from one channel to the next can be accomplished with a single instruction that increments or decrements the contents of a memory location.

A diagram of the RTI-1200's location in memory space is shown in Figure 3. It occupies a 1k (1024-location) block, located at any of 14 positions selected by the user. The functions relating to the operation of the RTI-1200 are located in the top 16 locations; the remaining 1008 locations are reserved for use by a 1k programmable read-only memory (PROM) that a user may furnish (and plug in on-board). Such a PROM can be used simply to expand the computer's memory space independently of the RTI-1200's functions. More frequently, it can be used to store subroutines related to the RTI-1200 (transducer linearizing, for example). This can be especially advantageous if more than one RTI-1200 is to be used with a single microcomputer.

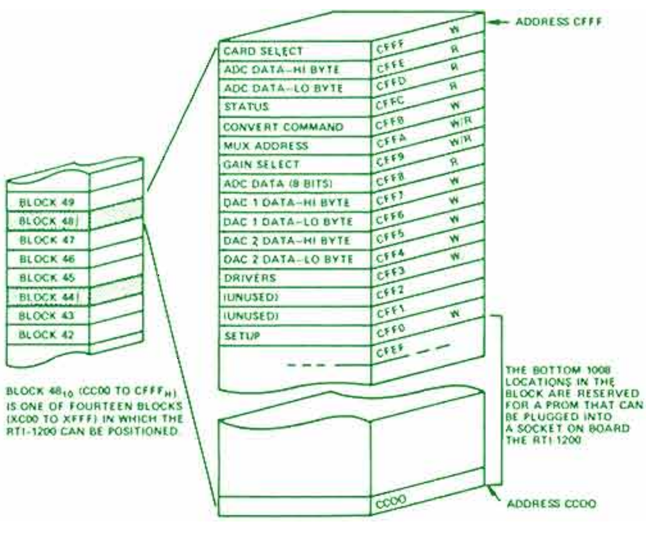


Figure 3. An expanded view of block occupied by the RTI-1200.

As an illustration of the simplifications afforded by the RTI-1200 in the conception and writing of software, here is the entire (8080 assembly language) program for acquiring a single reading from a single channel:

```
        MVI   A,07H
        STA   MUXADR     ; SELECT CHANNEL 07H
        STA   CNVCMD     ; ISSUE CONVERT COMMAND
LOOP:   LDA   STATUS
        RLC
        JNC   LOOP       ; CHECK EOC BIT
        LHLD  ADCLO      : READ DATA
        HLT
```

This program selects the desired channel (07), issues a *convert* command, determines when the data is ready, and reads the data. At its conclusion, 12-bit data from the converter will be present in a two-byte register-pair. This program assumes only that the desired gain has previously been selected (i.e., the desired data stored in the GAIN SELECT byte), and that the proper setup data had been written into the SETUP byte. In this case, the correct setup byte would be "00H" (00, hexadecimal), which means that the pacers are turned off, and an end-of-conversion will not trigger an interrupt.

REAL-TIME PACER CLOCKS

Since most applications that require analog signal-interfacing also require reference to real time, the RTI-1200 is equipped with a versatile real-time pacer-clock system. Two clocks are provided; either of them can be used to trigger evenly spaced a/d conversions or to signal CPU interrupts for use in establishing a system's real-time clock. One clock is a wide-range-adjustable R-C type, the other provides high-accuracy timing with a user-supplied crystal. The pacer system can be shut off if not needed.

MORE FEATURES

Two software-controlled open-collector *logic-driver outputs* are available for general-purpose system-control functions, such as providing pen-lift commands to an X-Y recorder. A 5V *precision reference* is available externally for use in calibration and testing. A *card-select* feature ("horizontal" memory mapping) is available; it permits as many as 16 RTI-1200's to share a single 1k block of memory locations–the desired card is selected from among the others by its own user-programmed *select* code. Finally, the RTI-1200 can be ordered with a dc-to-dc power converter; if ±15V power is not readily available, this option allows the RTI-1200 to be powered solely from the same +5V source that powers the microcomputer.

Not the least of the salient features is the *User's Guide*, shipped with each unit. This manual contains extensive hints on writing software for the RTI-1200 and includes a number of sample program segments. It is available separately for $5.00.*

To sum it all up, the numerous features of the RTI-1200, including its versatility, make the interfacing of analog signals to a microcomputer a pleasurable task instead of a confusing chore. The user can simply plug the RTI-1200 into a card cage containing an Intel SBC-80/10, connect his analog signal-inputs and -outputs, and begin writing software. The basic unit contains all of the above features, except for the optional plug-in output DAC's, 4-20mA current-loop generators, dc-to-dc converter, and input-channel expansion MUX. The price of the RTI-1200 depends on which one of the 24 convenient factory-tested plug-in option combinations is chosen, it ranges from $629 to $979 (1–9).

▶▶▶

THE AUTHOR

Jim Fishbeck is Marketing Manager, Systems, for ADI's Instruments and Systems Group. Jim's photo and a brief biography appear in *Analog Dialogue* 9-1.

*Send check for $5 per copy (or your Master Charge numbers and expiration date) to Analog Devices, Inc., P.O. Box 796, Norwood Ma 02062; ask for the *RTI-1200 User's Guide*.

ACCURATE, LOW-COST, EASY-TO-USE IC MULTIPLIER

The AD534 Has Differential Inputs, Many Potential Applications Laser-Trimmed on the Wafer to Accuracy Within 0.25% (AD534L)

by Barrie Gilbert

The Analog Devices AD534* is a monolithic laser-trimmed multiplier having accuracy specifications conventionally associated with discrete modules. The AD534L guarantees an *overall* error of less than 0.25% of full scale, while the AD534J is within 1.0%. These accuracies are for operation at ±15V and 25°C; while these are not as "tight" as the specs of some discrete circuits under the same operating conditions, many of the specifications regarding supply-sensitivity, temperature-sensitivity, and long-term stability are in fact better, making accurate operation feasible over worse environmental conditions than was previously possible. For example, the AD534J, as a multiplier, typically maintains less than 1.5% error *over the specified temperature range and ±1V variation of the power supplies.*

In addition to this, the AD534 has lower noise and better linearity than any other monolithic multiplier presently available, and offers greater flexibility of use, which results from having *all* its inputs (X,Y, and Z) in differential form. Many complex algebraic functions can be synthesized with a single AD534, rather than in combination with other active elements, as was previously necessary, and, like earlier circuits, it may also be used as a Divider, Squarer, or Square-Rooter, (MDSSR), with added advantages, such as choice of input/output polarity in all modes.

Like all Analog Devices monolithic multipliers, the AD534 uses the highly-successful "linearized transconductance" or translinear principle[1], introduced by the author in 1968. The improved performance is due largely to the extreme care given to the design of the layout of the chip, which includes special thin-film resistor geometries designed to exhibit low post-trim drifts. A new active-feedback scheme is incorporated to achieve very low nonlinearities[2], particularly on the Y input, for which they are typically below 0.01%. Active laser-trimming on the wafer reduces initial parametric errors (*Analog Dialogue* 9-3) and eliminates the need for external trims.

The purpose of this article is to serve as a brief introduction to the device and to suggest a few of the applications that go well beyond the basic algebraic properties of conventional MDSSR's.

Figure 1 shows the overall scheme of the AD534, with its differential, high-impedance inputs. In most applications, the output voltage is fed back to one or more sets of inputs, and it is usually safe to describe its operation in terms of the balance: $(X_1 - X_2)(Y_1 - Y_2) = E_S(Z_1 - Z_2)$, where the variables all represent terminal voltages and E_S is a scale constant. Figure 2 shows the application as a simple multiplier, and Figure 3 shows the AD534 applied as a divider.

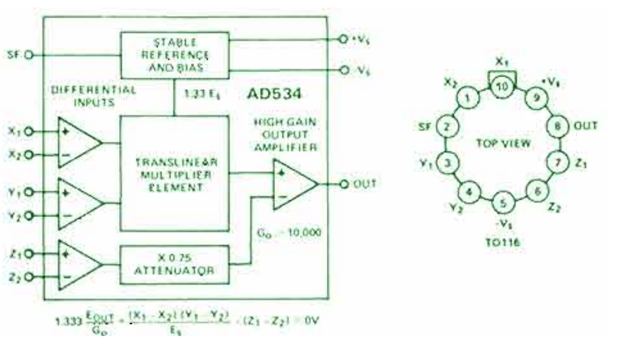


Figure 1. Functional block diagram and TO116 pin configuration of the AD534. The scale factor, E_S, is pre-trimmed to 10V.

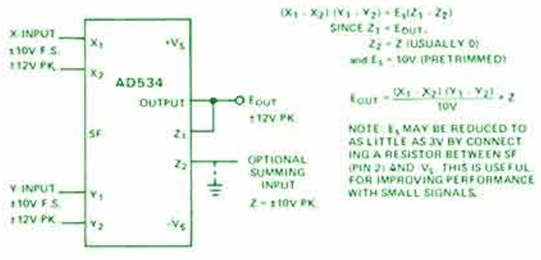


Figure 2. Basic multiplier connection. Overall gain can be achieved by attenuating the feedback from E_{OUT} to Z_1.

Though the most common and widely-used of applications, these are just a beginning. On the next few pages, we show a dozen applications that hint at the possibilities of the AD534, imaginatively applied. They are but a small sampling. The basic assumption—that the above equation is exact—should of course be modified by consultation of the specifications, weighing each parameter with respect to the specific application. However, as with operational amplifiers, the concept of an ideal device removes many barriers to creative design; the AD534 brings this concept a step nearer to actuality. Price of the "commercial" J/K/L versions are: $16/$24/$36, and the "military" S/T: $45/$60 (100+).

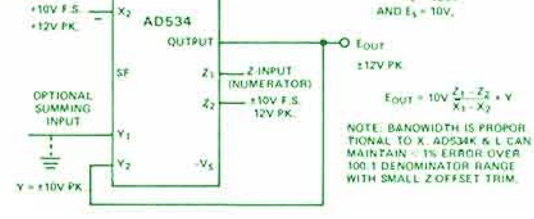


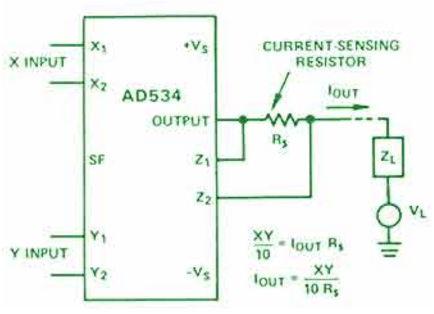
Figure 3. Basic divider connection.

*Use the reply card to request a data sheet on the AD534.

[1] Gilbert, B., "A Precise Four-Quadrant Multiplier with Subnanosecond Response", IEEE Journal of Solid-State Circuits, pp. 365–373, December, 1968.

[2] Gilbert, B., "A High-Performance Monolithic Multiplier Using Active Feedback", IEEE Journal of Solid-State Circuits, pp. 364–373, December, 1974.

OUTPUT-TO-CURRENT CONVERSION



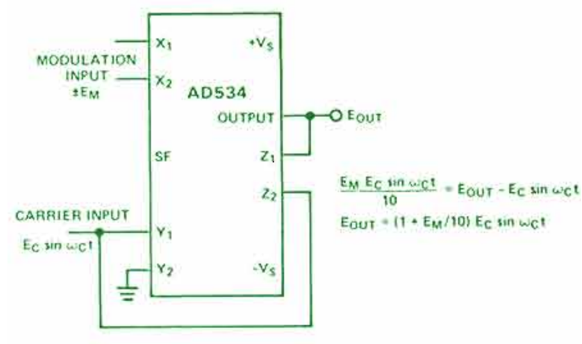
Occasionally, it is preferable to generate a current, rather than a voltage, output into the load. The availability of differential inputs allows this to be accomplished in any of the four basic modes. The illustration shows the appropriate connection for the multiplier mode.

If the output is to be integrated, Z_L can be a simple high-quality capacitor, unloaded by an op amp connected as a high-impedance follower. Note that, if desired, one side of a *reset* switch can be grounded.

The compliance constraint for this configuration, where V_L is an arbitrary common-mode potential, is

$$|V_L + I_{OUT}(Z_L + R_S)| \leqslant 12V$$

LINEAR (AM) AMPLITUDE MODULATOR



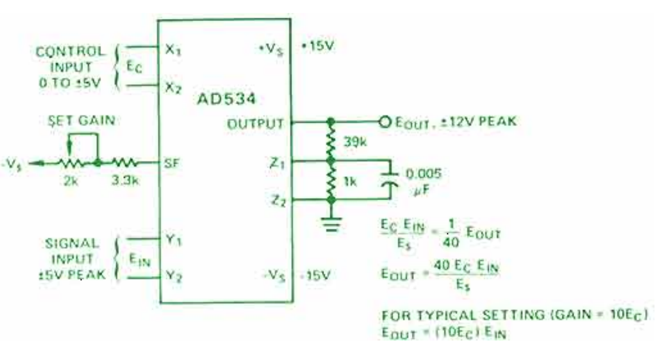
This is a very simple amplitude modulator. It makes use of the Z_2 terminal to add the carrier directly to the output, thus by-passing the multiplier for zero modulation-input. It has the advantage of allowing operation from a differential modulation input.

With Z_2 grounded, the circuit becomes a balanced modulator:

$$E_{OUT} = \frac{E_M E_C}{10} \sin \omega_C t$$

For overall signal amplification, attenuate the feedback to Z_1, or use resistance between SF and $-V_s$. To operate from a single supply, bias Y_2 to $V_s/2$ (bias Z_2 to $V_s/2$ for the balanced modulator on a single supply).

VOLTAGE-CONTROLLED AMPLIFIER

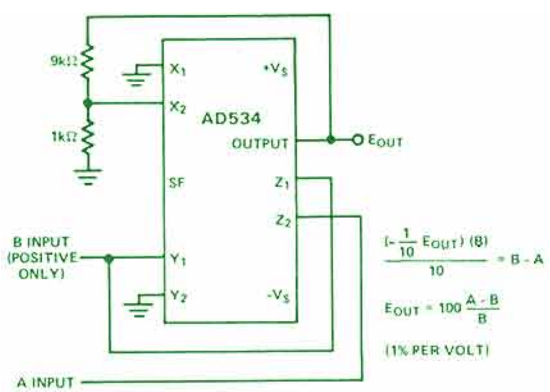


In this application, a constant or varying signal applied to the X input, E_C, controls the gain for a constant or variable signal applied to the Y input, E_{IN}. The inputs could be interchanged, but, as noted elsewhere, the Y input has the better linearity.

For this circuit, the "set gain" potentiometer is typically adjusted to provide a calibration for gain of X 10 per-volt-of-E_C.

Bandwidth is dc to 30kHz, independent of gain. The wideband noise (10Hz to 30kHz) is 3mV rms, typically, corresponding to full-scale signal-to-noise of 70dB. Noise, referred to the signal input (E_C = ±5V) is 60µV rms, typically.

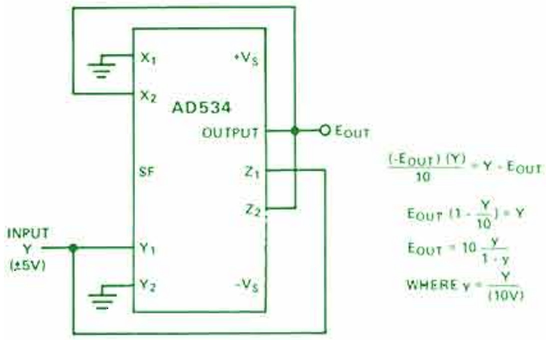
Δ% RATIO COMPUTER



The percentage-deviation function is of practical value for many applications in measurement, testing, and control. For example, the output of this circuit might be applied to a pair of biased comparators to stimulate particular actions or displays depending on whether the gain of a circuit under test were within limits, or deviating by a preset amount in either direction.

The indicated scale factor, 1%/V, is convenient and easily demonstrates the principle. However, other sensitivities, from 10%/V to 0.1%/V, as required by the application, can be obtained by altering the feedback attenuation ratio, from 1 to 1/100. Gain or attenuation is easily applied to the A signal externally for calibration to the normalized form.

BRIDGE-LINEARIZING FUNCTION



If one arm of a Wheatstone Bridge varies from its nominal value by a factor, (1 + 2x), the voltage or current output of the bridge will be (with appropriate polarities):

$$y \approx \frac{x}{1 + x}$$

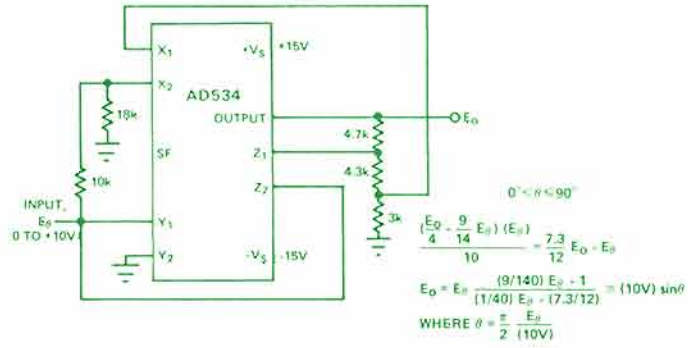
Linear response requires very small x and, usually, preamplification. The circuit shown here enables large-deviation bridges to be used without losing linearity.

This circuit computes the inverse of the bridge function, i.e.,

$$x \approx \frac{y}{1 - y}$$

Depending on which arm of the bridge varies, it may be necessary to reverse the polarity of the z connections.

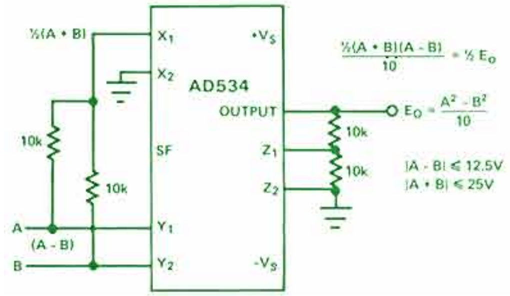
APPROXIMATION FOR SIN θ



The AD534 is remarkably easy to use in the implementation of the approximation formulas described in Chapter 2-1 of the *Nonlinear Circuits Handbook*. Many of these involve implicit loops to generate the function and previously required several additional op amps for the addition and subtraction of the various terms. This circuit is an example of what can be done with external resistors only. For θ between 0° and 90°, the approximation maintains a theoretical accuracy to within 0.5% of full-scale; 0.75% is practical with AD534L and 0.1% resistors.

Resistances are "preferred values" in the 5% resistor list, but since they determine vital constants, close-tolerance components must be used. In the practical evaluation, 0.1% resistances were used.

DIFFERENCE OF SQUARES

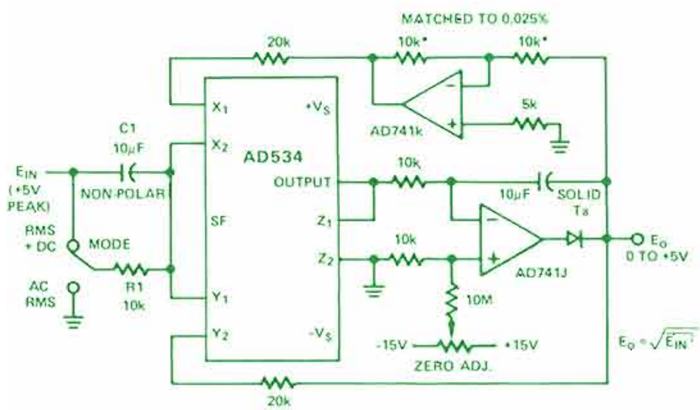


A single AD534 can be used to compute the difference of the squares of two input signals. The function may be useful in vector computations, and in weighting the difference of two magnitudes to emphasize the greater nonlinearly. The two matched sets of resistors could be those in the AD1805 precision-resistor quad. A slight variation of this circuit can also be used for absolute-value computation: let A be the input, let B be connected to E_O, through a diode which conducts when E_O is positive, and let both Z terminals be grounded. Since the balance equation becomes: $A^2 - B^2 = 0$, the output, B, must be equal to the absolute value of A.

Another variation of this scheme is used in the adjacent rms-computing circuit.

If $|A - B| > 12.5$V, Inputs Y1 and Y2 may be attenuated and the feedback attenuation increased in the same proportion (also suggested by G. Woollvin, Cossor Electronics, Ltd.).

WIDEBAND, HIGH CREST RMS



The balance equation for this circuit is:

$$-(E_{IN} + E_O)(E_{IN} - E_O) = -10RC\frac{dE_O}{dt}$$

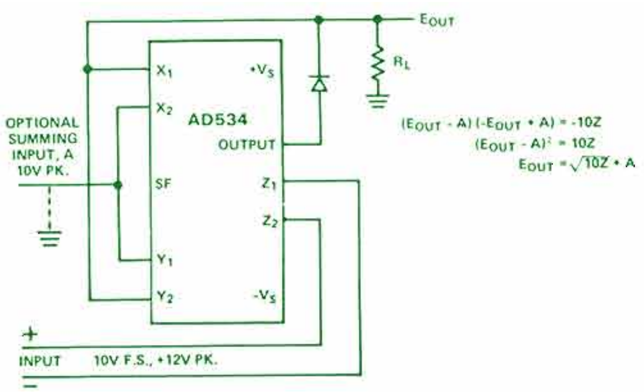
For steady-state values of E_O, the right-hand term is zero, the average value of E_{IN}^2 is equal to E_O^2, hence E_O measures the rms value of E_{IN}.

After calibration, error < 0.1% is maintained for frequencies up to 100kHz; it increases to 0.5% at 1MHz @ 4V rms. Crest factors up to 10 have little effect on accuracy.

To calibrate, with the mode switch at "RMS + DC", apply an input of (say) 1.00VDC. Adjust the zero until the output reads the same as the input. Check for inputs of ±5V.

See also *Electronics Letters*, (U.K.), Vol. 11, No. 8, p.181.

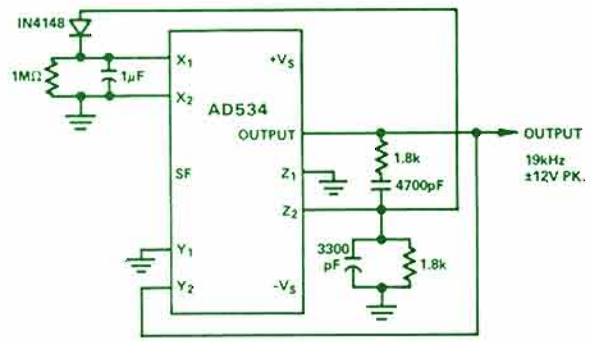
SQUARE ROOTER



This illustration shows the connection of the AD534 for square-rooting, with differential inputs. The diode prevents a latching condition – common to this configuration – which would occur if the input momentarily changed polarity. As shown, the output is always positive; it may be changed to a negative output by reversing the diode polarity and interchanging the X inputs. Since the signal input is differential, all combinations of input and output polarities can be realized.

If the output circuit does not provide a resistive load to ground, one should be connected to maintain diode conduction. For critical applications, the Z offset can be adjusted for greater accuracy below 1V.

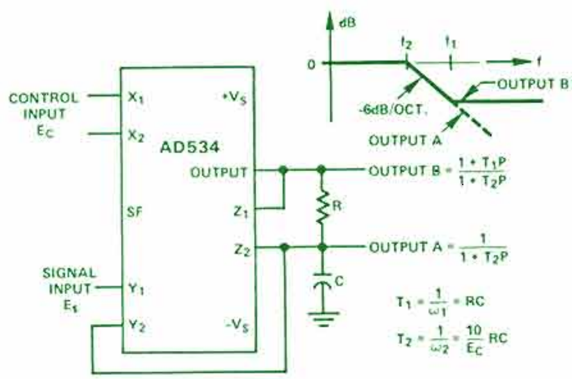
STABILIZED WIEN-BRIDGE OSCILLATOR



In this application, the AD534 is used as a variable-gain amplifier for the feedback signal from the output to the Y input, via the Wien bridge. The peak-rectifier & filter combination applies sufficient voltage to the X (denominator) input to maintain a stable oscillation-amplitude (with about 0.2% ripple). At startup, since X is small (divider mode), the gain is high, and the oscillation builds up rapidly.

This is but one of several possible schemes, involving no external active elements. Its forte is simplicity, rather than high performance; nevertheless, the amplitude is not greatly affected by supply and temperature variations, about 0.003dB per volt, and 0.005dB per °C.

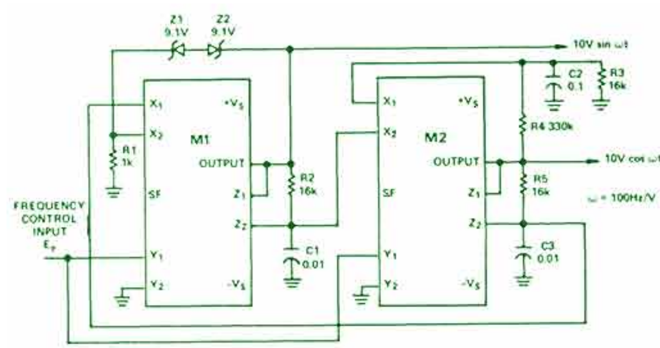
VOLTAGE-CONTROLLED LOW-PASS FILTER



The voltage at Output A, which should be unloaded by a follower, responds as though E_S were applied directly to the RC filter, but the filter's break frequency were proportional to E_C (i.e., $f_2 = E_C/(20\pi RC)$). The frequency response has a break at f_2 and a 6dB/octave rolloff. The voltage at Output B has the same response, up to f_1 ($f_1 = 1/(2\pi RC)$), then levels off at a constant attenuation of $f_2/f_1 = E_C/10$.

For example, if R = 8kΩ, C = 0.002μF, Output A has a pole at 100Hz to 10kHz, for E_C ranging from 100mV to 10V. Output B has an additional zero at 10kHz and can be loaded. The circuit can be converted to high-pass by interchanging C and R.

VOLTAGE-CONTROLLED 2-PHASE OSCILLATOR



This circuit, like the circuits shown on pp. 78–81 of the *Nonlinear Circuits Handbook*, employs two multipliers for integration-with-controllable-time-constants in a feedback loop. R2 and R5 will be recognized in the AD534 voltage-to-current configuration shown at the top of page 7; the currents are integrated in C1 and C3, and the voltages they develop are connected at high impedance in proper polarity to the X inputs of the "next" AD534. The frequency-control input, E_y, varies the integrator gains, with a sensitivity of 100Hz/V, and frequency error typically less than 0.1% of full scale from 0.1V to 10V (10Hz to 1kHz).

C2 (proportional to C1 and C3), R3, R4 provide regenerative damping to start and maintain oscillation. Z1 and Z2 stabilize the amplitude at low distortion by degenerative damping above ±10V.

HIGHEST-PERFORMANCE 10-BIT IC DAC
AD561 is Fast, Accurate, Stable, and Low Cost
Laser-Trim-on-Wafer and Buried Zener are Keys

by Dave Kress

The AD561* is a 10-bit single-chip digital-to-analog converter in a 16-pin ceramic DIP; it contains its own high-stability voltage reference. In response to a positive-true TTL or CMOS parallel digital input, it produces a high-compliance (-2V to +10V) 0 to 2mA current output. Completely self-contained are the reference, R-2R thin-film-on-silicon ladder network, current-steering switches, and the application resistors needed for generating high-precision ±5V and 0 to +10V outputs, when used with an output buffer amplifier. The AD561 has the best guaranteed accuracy at 25°C (¼LSB *max*–K,T) and the tightest tempco (30ppm/°C *max*) among known 10-bit IC d/a converters, and it is the *only* such IC to be guaranteed monotonic over the operating temperature range (0°C to 70°C–J,K; -55°C to +125°C–S,T). As a further bonus, full-scale settling time to within ½LSB is *250ns*.

Not only is the AD561 the most-accurate and stable in its class–it is also one of the *least-expensive* 10-bit d/a converters available! The "J" version costs less than $10 in 100's.

PROCESS LIMITATIONS

Until now, an appropriate IC with the right combination of accuracy and cost has not been available to system designers who need true 10-bit (0.1%) device accuracy.† The various options heretofore available–none of them attractive–ran the gamut from the compromises inherent in untrimmed, low-priced 10-bit converters to adequate (but expensive) 10-bit hybrids to overdesign by the use of 12-bit converters (to be sure of adequate 10-bit performance at the extremes of temperature). Semiconductor manufacturers have consistently found that it is well-nigh impossible to obtain substantial yields of IC's containing a resistive ladder network, with matching and tracking properties adequate for a 0.1% device, by the use of the photolithographic process alone (and low yield = high cost).

The key to overcoming these linearity limitations, using today's technology, is to laser-trim the resistor networks *and* the reference tempco *at the wafer stage*, a process developed as a cost-effective manufacturing tool at Analog Devices Semiconductor.[1] The thin-film R-2R ladder network is trimmed by a high-resolution laser-trimming system to provide conversion linearity of the order of 0.01%. These devices, which have been trimmed at the wafer stage, are then assembled, sealed, and burned-in, after which they are graded into ¼LSB(K & T) and ½LSB(J & S) categories. This system adds the benefits of high yield to the already traditionally low IC-manufacturing costs.

BURIED REFERENCE DIODE

The key to the AD561's overall gain accuracy is the stable reference. "Zener" reference diodes are easy to make on an IC chip: just use the reverse-breakdown voltage of a base-emitter junction. This technique is widely used. Unfortunately, such diodes are noisy and unstable, because the breakdown occurs at the surface of the die, where shifts of the breakdown point, caused by variations of stress produced by charged oxide impurities, especially mobile ions, can significantly affect stability. Long-term shifts of up to a few percent are not uncommon, a phenomenon hardly compatible with overall 0.1% device performance.

For the AD561, a deep-diffusion technique is used to "bury" its reference diode; the breakdown, occurring well below the surface, is characterized by considerably less noise and by long-term instability of only a few ppm/year. For the complete d/a converter, stability is typically within 50-100ppm/year. Stability of the reference with temperature is optimized by laser-trimming of the reference-compensation circuitry for near-zero overall drift. Combined with the close tracking of the metal-film (Si-Cr) resistors, this results in low initial calibration errors, high linearity, and low dirft with temperature.

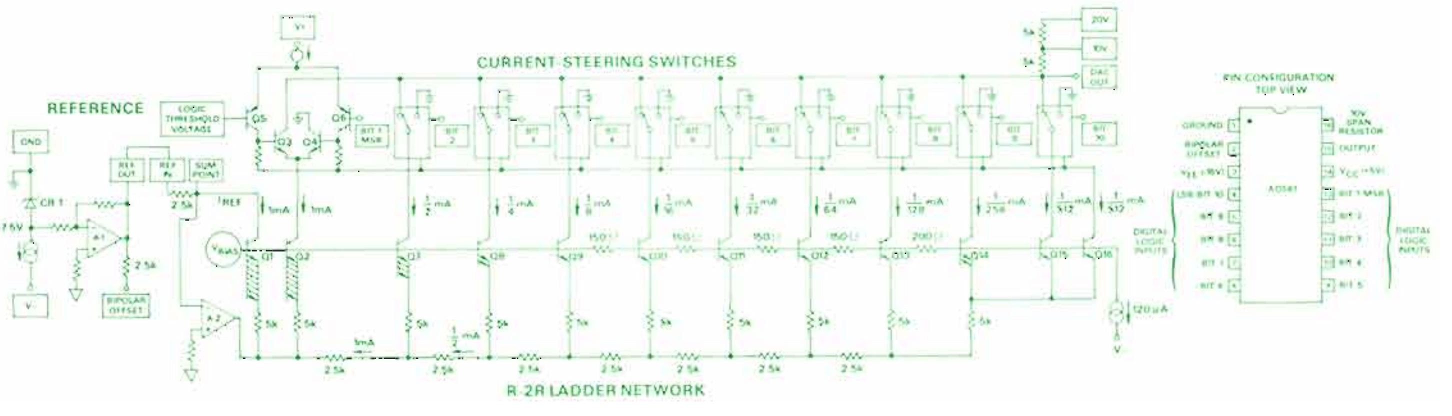


Figure 1. AD561 D/A converter: schematic and connection diagrams.

*For technical data on the AD561, use the reply card.

†For example, in an industrial measurement and control system, where transducer errors may be typically 0.5% to 1%, the AD561's performance combination may be needed to avoid the introduction of significant additional error and further degradation of system accuracy.

[1] *Analog Dialogue* 9–3, 1975

DESIGN

Figure 1 shows the complete (simplified) circuit of the AD561. The buried-reference-diode circuitry develops -7.5V, which is scaled by an inverting amplifier, Al, to +2.5V. This voltage level permits the AD561 to operate well with positive supply voltages as low as 4.5V. The reference voltage produces an input current to inverting amplifier, A2; the 1mA current (I_{REF}) is duplicated by the control transistor, Q1, which enforces the necessary voltage between the base line and one end of the R-2R ladder. Since Q2 is identical to Q1, and its base-emitter circuit operates under exactly the same conditions, its collector current (the MSB) is also equal to I_{REF}. The state of the digital input determines whether the collector current is added to the output current via Q3 or is harmlessly shunted to ground via Q4 by the Craven-cell current-steering switch[2].

A set of binary-weighted currents, produced via an R-2R ladder network, are stabilized and switched by familiar techniques[3] (with a few new wrinkles, explained on the data sheet). 5kΩ resistors provide the full-range scaling§, and a 2.5kΩ resistor, connected to the 2.5V reference, provides bipolar offset current.

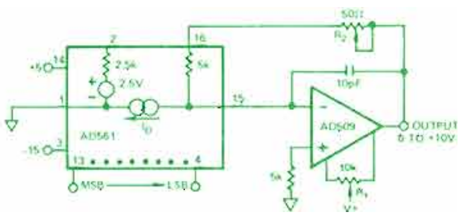


Figure 2. Connecting the AD561 for buffered 0V to +10V output. The adjustment pot may be replaced by a fixed 25Ω resistor for 10mV typical output error.

APPLICATION FEATURES AND CIRCUITS

In Figures 2 and 3, the AD561 is shown connected for operation in the unipolar (0 to +10V) and bipolar (±5V) output modes. The internal 5kΩ and 2.5kΩ resistors are pretrimmed and typically provide scale-factor and bipolar-offset accuracy to within 0.1% (0.5% *max*), with external 25Ω and 10Ω fixed resistors added in series. For higher absolute accuracy, variable resistances of 50Ω and 20Ω full-scale are used instead to calibrate the gain and bipolar offset.

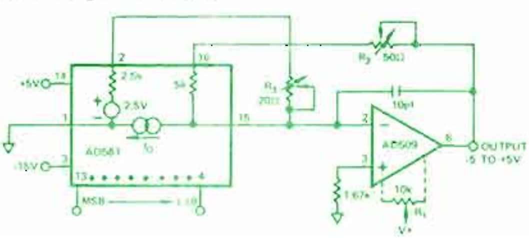


Figure 3. Connections for buffered ±5V output. Adjustment pots may be replaced by mid-range resistances with 10mV typical error.

Compliance Range. The AD561 has the widest-known compliance-voltage range available for a 10-bit IC DAC; the output is guaranteed to swing from -2V to +10V at 2mA full-scale output. The specified output impedance of (typically) 40MΩ means that a 12-volt swing through the compliance range will result in an output-current change of only 0.3μA (0.15LSB). This permits the AD561 to produce a voltage output without the use of an op amp. A resistor to ground will produce a voltage output; the parallel load resistance should be less than 1kΩ in order to stay within the -2V limit. Bipolar connections are also easily accomplished, and a 0V to +10V range can be achieved by connecting the resistor to a precision 10V supply, as Figure 4 shows.

Digital Threshold. The threshold for digital input is automatically set as a function of the positive supply level. For TTL/DTL or 5V CMOS, a 5V value of V_{CC} gives a 1.4V threshold and guarantees the input limits. The thresholds for V_{CC} = 10V and V_{CC} = 15V are 5V and 7.5V, which provides suitable limits for the respective logic families. Since the logic inputs are high-impedance, even unbuffered CMOS can be used without difficulty.

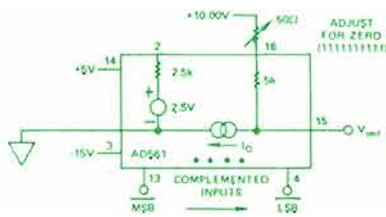
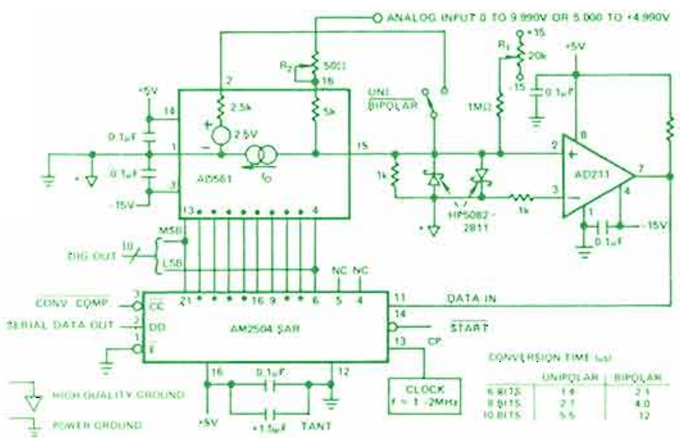


Figure 4. AD561 connected for unbuffered 0V to +10V output, with 5kΩ output impedance. For this application, data inputs are negative true. Typical applications call for light load, e.g., with high-impedance devices or in null-seeking.

Fast Settling. The high-speed Craven-cell output switches and critically damped control amplifier produce fast-settling performance. Worst-case settling time to within 0.05%F.S. (½LSB), for all-bits-off to all-bits-on is less than 250ns; the lower-order



	UNIPOLAR	BIPOLAR
6 BITS	1.4	2.1
8 BITS	2.1	4.0
10 BITS	5.5	12

Figure 5. Fast 10-bit A/D converter. Its implementation is discussed on the AD561 data sheet.

bits settle individually in less the 200ns. When the AD561 is used with the AD509‡ high-speed op amp, the output can be made to settle in less than 600ns. This kind of high-speed performance is useful for constructing a fast a/d converter, such as the one shown in Figure 5.

[2] *Analog Dialogue* 8–2, 1974, U.S. Patent 3,961,326
[3] *Analog-Digital Conversion Handbook*, D.H. Sheingold, ed., Analog Devices, Inc., P.O. Box 796, Norwood MA 02062, $3.95

§Standard output range is ±5V or 0 to +10V. Also available on the chip for optional bonding are: ±10V, 0 to +20V; ±2.5V, 0 to +5V.

‡Use the reply card to obtain an AD509 data sheet.

STABLE, LINEAR V/f CONVERTERS

458 Family (100kHz) & 460 Family (1MHz)

Linear to 0.01% Max, Tempco to 5ppm/°C Max

Our voltage/frequency converter line continues to grow as we introduce two new families of high-accuracy, low-drift V/f's. The 458J/K/L 100kHz VFC's* and the 460J/K/L 1MHz* series are pin-compatible with several popular competitive models but offer better performance specs at lower cost.

Guaranteed maximum nonlinearity is 0.01% for the 458's and 0.015% for the 460's, over the entire signal range from 100μV to 11V. Both types are graded according to *max* tempco: the 458J/K/L drift at 20/10/5ppm/°C *max*, and the 460J/K/L have *max* tempco's of 50/25/15 over the 0° to 70°C temperature range. No external components or adjustments are required to achieve rated performance.

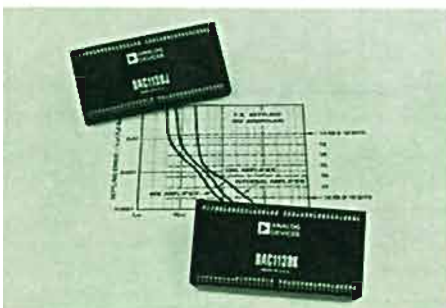
Typical applications for VFC's with high performance include a/d conversion with better-than-16-bit resolution, long-term precision integrators, analog isolation in the presence of high common-mode voltage, two-wire high-noise-immunity digital transmission, and 4+-digit DVM's.

Both types have versatile differential front-ends, permitting input ranges of 0 to +11V or 0 to -11V. Current inputs of 0 to 1mA (458) or 0 to 0.5mA (460) can also be handled. Prices (1-9) are $72/$84/$99 for 458J/K/L, $90/$110/$135 for 460J/K/L. ▶▶▶

*For technical data, use the reply card.

18-BIT (!) DAC1138K

4ppm Resolution, Linear to Within ½LSB



An industry first, the DAC1138K* is a complete self-contained modular d/a converter that has 18-bit resolution, compatible accuracy, and settling time (current mode) of 10μs to within ½LSB, for a full-scale step input. Inputs are TTL-compatible, and output can be configured by the user for either current (2mA full scale) or voltage (±10V, ±5V, +10V, +5V F.S.) modes.

Normally furnished as a 2" x 4" x 0.4" (51 x 102 x 10.2mm) module, it is also available in a card-mounted assembly, which permits the user to select from an assortment of input codes and output amplifiers, depending on the needs of the application.

Examples: an external model 44K output amplifier will provide much faster settling than the internal AD510L; an input register permits TTL data to be latched in.

The DAC1138K is capable of delivering the kind of accuracy required for a broad range of instrumentation applications. Its 4ppm resolution is useful in data-distribution systems, high-resolution CRT displays, automatic semiconductor testing, typesetting, frequency synthesis, and reactor control. The DAC1138J can be used for applications calling for "a bit more" than 16-bit converters, or "a bit less" than the DAC1138K (at a substantial cost saving). Both versions are pin-compatible with the popular DAC-16QM. Prices (basic unit, 1-9) are $750(J), $950(K). ▶▶▶

*For a data sheet, use the reply card.

TRUE-RMS DPM

Also Reads dB

3½ Digits, Line-Powered

The AD2033* is a 3½-digit line-powered digital panel meter that measures dc and ac input signals. It uses a 0.5"(13mm)-high light-emitting-diode display. The meter obtains the true-rms value of an ac, dc, or ac + dc input, and displays it either directly or as a log ratio (dB format).

The meter is direct-coupled, making it possible to read the rms value of a fluctuating dc of either polarity or of ac signals having a dc component. An external capacitor can be used when measuring ac components only, e.g., power-supply ripple. Bipolar dc measurements are also possible.

Since accuracy of measurement is essentially independent of the shape of the input waveform, the 2033 will handle steady-state trains of square pulses, triangular pulses, SCR-chopped sinewaves, and pure sine waves, with high accuracy and no recalibration to handle specific waveforms.

Log-ratio (dB) readings can be made with respect to internal or external references, from +5mV to +5V, including the standard 1mW in 600Ω used in audio measurements—for example in noise-meters.

Five separate full-scale rms input ranges are provided: 0.1999V, 1.999V, 19.99V, 199.9V, and 600V for true-rms readout; 0.5V, 5V, 50V, 500V, and 600V for readout in dB. The floating opto-isolated analog input withstands common-mode voltages up to 300V rms; it facilitates both differential voltage measurements and current measurements using off-ground resistors.

The AD2033 is packaged in the case used for line-powered DPM's and has a U.S.-industry-standard panel cutout. Price (1-9 units) is $325.

*For a data sheet, use the reply card. ▶▶▶

CMOS CONVERTERS AS I/O DEVICES

Memory-Managed I/O Architectures Using ADI Microprocessor-Compatible IC Converters

by Ivar Wold

Elsewhere in this issue, you have read about a complete analog-to-microcomputer I/O interface, the RTI-1200. We have described its ability to interface as memory and have mentioned its "card-select" feature, which permits a number of such devices to occupy the same block of memory interchangeably when addressed (Figure 1). These features, "vertical" and "horizontal" memory-managed (or memory-mapped) I/O, as mentioned, offer significant advantages and are becoming well-recognized in the industry.

The many inherent features of the RTI-1200, including its clean analog design, thorough software documentation, on-board PROM capability, and total compatibility with the Intel SBC-80/10 microcomputer, establish its architecture as the definitive general-purpose data-acquisition-system interface for systems involving 8080-type microprocessors. We expect it to gain widespread acceptance—as a system building block to accompany the SBC-80/10—among busy system-designers who value their time above all else.

Despite its flexibility, however, there is a price paid in some applications: some users might find that they need only a few of its features, others might have wished for a different architecture (for example, a converter-per-channel), yet others must save money on parts cost and, in any event, "would rather-do-it-myself."

The good news, as evidenced in these pages[1,2,3] on several recent occasions, is that low-cost IC converters, readily available from Analog Device, can be used with little external circuitry to provide conversion and interfacing to microcomputers. They can provide memory-managed I/O with but little external logic. We shall discuss the devices and the principles involved in interfacing them to microprocessors. Since the details of analog application circuitry and performance have been covered earlier and are available on data sheets, we shall confine this essay to their connections in the digital domain and software.

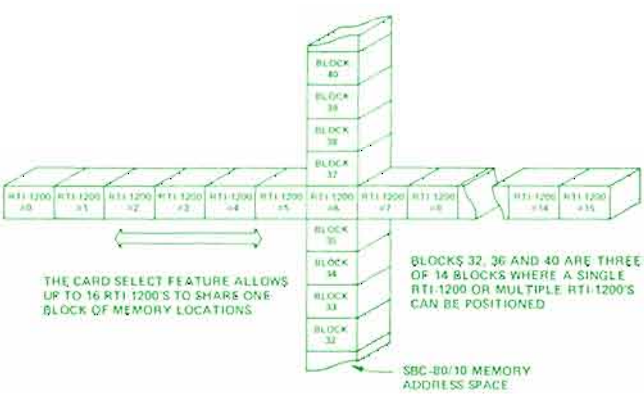


Figure 1. Vertical and horizontal memory-managed I/O as applied to the RTI-1200.

[1] *Analog Dialogue* 9-2, cover story (AD7570)
[2] *Analog Dialogue* 9-3, page 10 (AD7522)
[3] *Analog Dialogue* 10-1, cover story (AD7550)

The (first-generation) products to be discussed are:

- AD7522 10-bit multiplying d/a converter
- AD7550 13-bit 2's-complement quad-slop a/d converter
- AD7570 10-bit successive-approximation a/d converter

The digital data terminals of these devices employ 3-state logic and are byte-addressable. This means that no peripheral interface circuitry is required, and the digital lines can be connected directly to the bidirectional data-bus of an 8-bit microprocessor with clock speed compatible with the device *enable* time. The user provides only the address decoding appropriate to the application for the control and data-read/write functions.

WHAT IS A MICROPROCESSOR?

For our purposes, it is useful to consider that, like all stored-program digital computers, a microprocessor is basically a memory controller. Its primary function is to fetch instructions from memory, read data from memory, and write data back into memory (a satisfying internal game, but unfortunately, this cozy little world must communicate with the outside world, which consists of peripheral I/O devices —Teletypewriters, CRT terminals, and printers—for communicating with human beings, and converters for dealing with the transducers that measure and control real-world variables).

Figure 2 shows an idealized microprocessor, which will be used throughout this article to describe the interface techniques favored by the author (and in use for some time at Analog Devices). While most microprocessors provide special I/O signals and I/O instructions to deal with external devices, it is easy to conclude that it is simpler and more elegant to make these input/output devices and their associated registers appear to the microprocessor as memory locations. To review the advantages:

- Since different microprocessors communicate with memory in essentially the same way, it becomes simpler (for both user and vendor) for a company like Analog Devices to furnish memory-managed-I/O integrated circuits that will communicate with all available microprocessors.

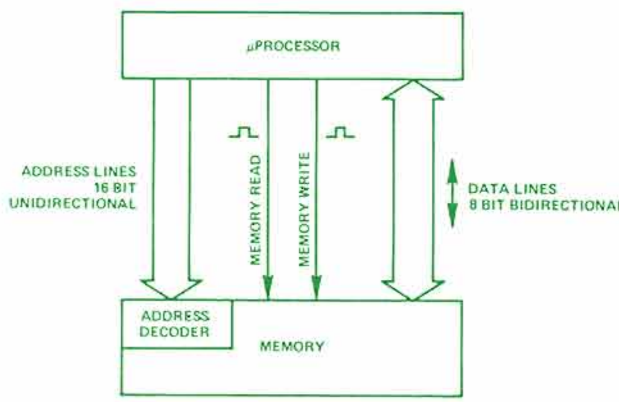


Figure 2. A micro-processor is a memory-controller.

•Most microprocessors offer a larger repertoire of memory-reference instructions than of I/O instructions, and , in particular, many processors–such as the 8080–provide a double-precision 16-bit memory load-and-store instruction, which becomes directly available for input/output control.

•A very-large number of input/output ports become available, with a much-wider range of choice over their disposition. Essentially the entire memory space is accessible to I/O devices.

•The use of memory ports for I/O permits the use of "horizontal" memory-managed I/O (*card select* in the RTI-1200). This technique allows the design of highly structured operating-system architectures, which can sidestep the difficulties posed by lack of relative- and index-addressing modes in the 8080. Horizontal memory-managed I/O is particularly applicable to general-purpose systems that must retain a high degree of flexibility of I/O device configuration, while the simpler vertical memory-managed I/O is adequate for special-purpose applications, where circuit configurations are fixed.

CMOS CONVERTER ARCHITECTURE

Several years ago, when we decided to design a range of microprocessor-compatible a/d and d/a converters, the first dilemma that faced the designers was the complete lack of standards for microprocessor interfaces. It would clearly be desirable to have integrated circuits that were compatible with all the µP's in the marketplace–with 4-bit, 8-bit, and even 16-bit processors. Also, it would be useful to have IC's that would fit easily into higher-level system structures, such as operating systems. Given the advantages of memory-managed I/O, we decided to adopt that concept as a standard approach to be used in present and future IC converter families designed for direct microprocessor interfacing.

The devices to be discussed here are unique in that, while they offer the ability to communicate on an 8-bit data bus, they can also be applied conventionally in the full-parallel mode.

A good example of the approach is the AD7522* 10-bit (4-quadrant multiplying) digital-to-analog converter (Figure 3). A

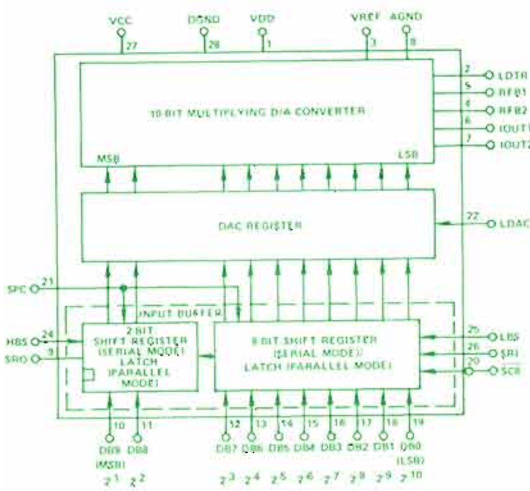


Figure 3. AD7522–double buffered multiplying digital to analog converter. Relevant control inputs are: HBS–High-Byte Strobe, LBS–Low-Byte Strobe, LDAC–Load DAC.

*For technical data on any of the products mentioned here, use the reply card.

§These specs appear on all data sheets issued since January, 1976.

double-buffered converter, it has two sets of input registers. The first set consists of an 8-bit register and a two-bit register; they can be separately loaded. The outputs of these two registers can be strobed in parallel into the DAC register for full-parallel monotonic update of 10-bit analog-output data (500ns§ access time for LDAC, HBS, LBS).

INTERFACING THE AD7522 D/A CONVERTER

It is easy to see that it is a simple matter for a microprocessor to first load the 8 least-significant bits into the 8-bit register, then load the two most-significant bits into the 2-bit register, and finally, to strobe 10-bit data into the output register, for the d/a converter. Note that the DAC register can also accept data in the form of a stream of 10 serial bits–and shift them out as well as in.

Figure 4 shows how the AD7522 is connected into an 8-bit data bus. The bus is wired directly to the 8 least-significant bits;

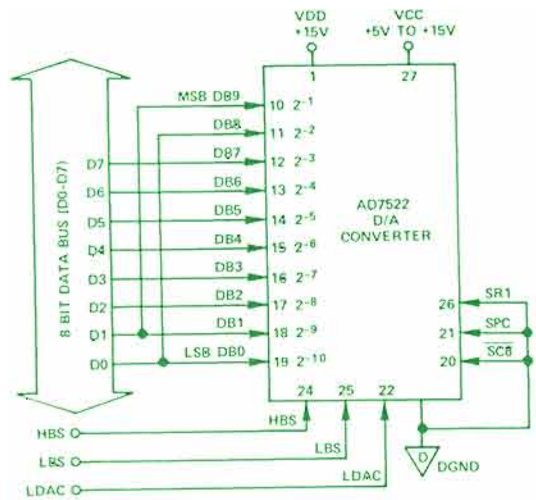


Figure 4. AD7522 – Connection for 2 byte operation.

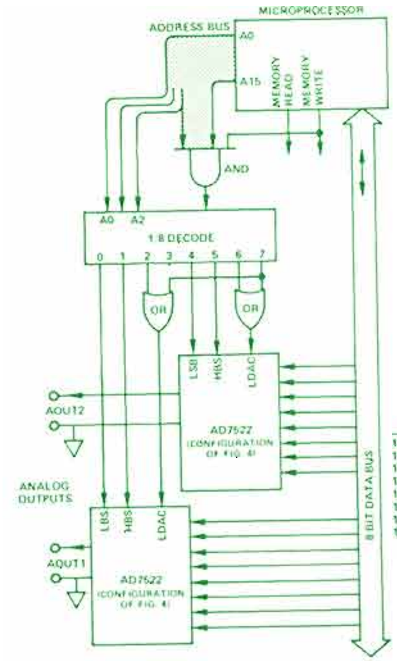
and the two most-significant bits of the converter are wired to the two least-significant bits of the bus.†

Figure 5 shows two AD7522's (configured as in Figure 4), interfaced to our "ideal" microprocessor. Since the AD7522 was designed as a compromise for both parallel and byte-serial operation, the external address-decoding logic is necessary as shown. Nevertheless, the interface is extremely simple and can allow either simultaneous or non-simultaneous update of the two d/a converters. The *or* gates allow a single memory address to update the output registers of both d/a converters simultaneously. It is worth noting that many µP's (the 8080 included) incorporate 16-bit data instructions, which would allow the processor to output the data to both converters with a single *memory write* instruction.

†The reason for this is that most µP's use formats that are "right-justified" for ready interpretation as integers, i.e., the LSB (Data-Bit 0) of a one- or two-byte n-bit word corresponds to an integer with a weight of 1; the MSB has a designation of n-1 and a weight of 2^{n-1}. Converter-users, on the other hand, are accustomed to a left-justified fractional format: the LSB (Bit n) has a weight of 2^{-n}, and the MSB (Bit 1) always has a weight of 2^{-1}. The difference in format, for a 10-bit word, can be seen in this comparison:

µP: | XXXXXX10 | 11101011 | vs. | 10111010 | 11XXXXXX |

(For better or for worse,) the devices discussed here are formatted for ease-of-use with popular µP's rather for either historical continuity or highest analog accuracy in the single-byte 8-bit mode.



ADDRESS	FUNCTION
177770_8, $FFF8_H$	OUTPUT LOW BYTE DAC 1
177771_8, $FFF9_H$	OUTPUT HIGH BYTE DAC 1
177772_8, $FFFA_H$	STROBE DAC 1
177773_8, $FFFB_H$	– –
177774_8, $FFFC_H$	OUTPUT LOW BYTE DAC 2
177775_8, $FFFD_H$	OUTPUT HIGH BYTE DAC 2
177776_8, $FFFE_H$	STROBE DAC 2
177777_8, $FFFF_H$	STROBE DAC 1 AND DAC 2 (SIMULTANEOUS UPDATE).

Figure 5. Interfacing multiple AD7522's to a microprocessor.

INTERFACING A/D CONVERTERS

The AD7550 is a high-precision essentially self-contained (except for the reference) 13-bit integrating a/d converter capable of maintaining zero-and gain-stability better than 1ppm/°C (Figure 6). The AD7570 is a 10-bit successive-approximations a/d converter that is essentially complete with an external comparator and reference. We will use the AD7550 as the context for our ADC interfacing example; the AD7570 is somewhat similar, but has 650ns *enable* time.

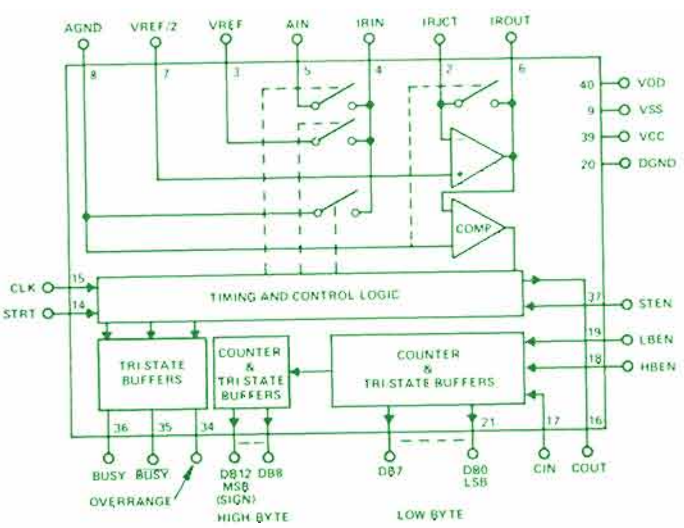


Figure 6. AD7550—13 bit analog-digital converter. Relevant control inputs are STRT—Start Conversion, STEN—Status Enable, LBEN—Low-Byte Enable, HBEN—High-Byte Enable; Relevant control outputs are BUSY, $\overline{\text{BUSY}}$—Status of conversion. Reference, voltage divider, and integrating RC are external.

Figure 7 shows how the AD7550 may be connected to an 8-bit data bus. The outputs of the AD7550 are arranged in three groups, each having 3-state outputs and independent *select* lines. The three groups are:

- Low 8 bits of the data word
- High 5 bits of the data word and the overrange bit
- The "status" bit (busy signal)

When wired as shown, each of the three groups can be selected and enabled (500ns access time, max) for transmission on the data bus. A fourth signal, START, is required to initiate conversion.

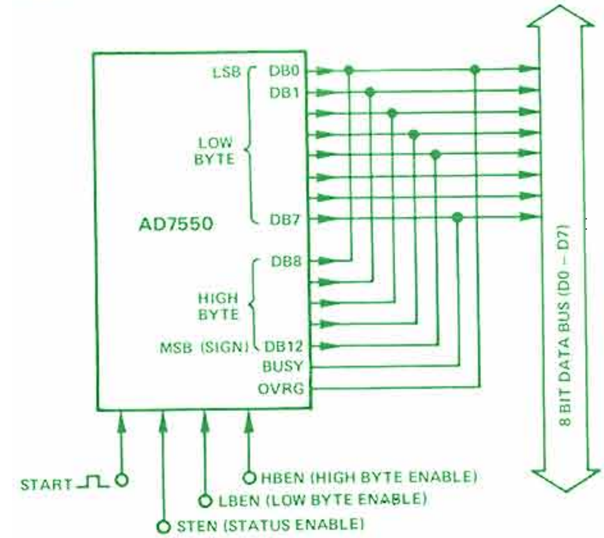
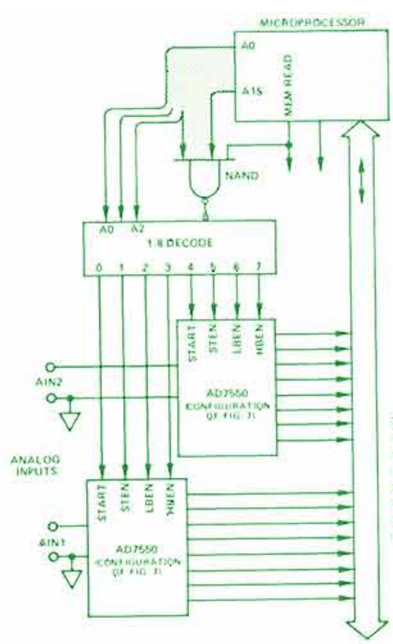


Figure 7. Interfacing the AD7550 to an 8 bit data path. Coding of AD7550 is 2's complement.

Figure 8 shows how two AD7550's, connected as described above, would interface to the "ideal" microprocessor. As in the case of the AD7522, since the AD7550 was also designed for conventional, full-parallel –as well as byte-serial– operation, a few external logic components are necessary. The resulting interface is nevertheless quite simple.

Figure 8 is similar to Figure 5, except that the circuit is wired to perform MEMORY READ operations. Note that one of the addresses for each AD7550 is decoded for the purpose of obtaining a *start* conversion command; the microprocessor must issue a dummy *read* command to start a conversion. Following



ADDRESS	FUNCTION
177770_8, $FFF8_H$	START CONVERSION ADC 1
177771_8, $FFF9_H$	READ STATUS ADC1
177772_8, $FFFA_H$	READ LOW BYTE ADC 1
177773_8, $FFFB_H$	READ HIGH BYTE ADC 1
177774_8, $FFFC_H$	START CONVERSION ADC 2
177775_8, $FFFD_H$	READ STATUS ADC 2
177776_8, $FFFE_H$	READ LOW BYTE ADC 2
177777_8, $FFFF_H$	READ HIGH BYTE ADC 2

Figure 8. Interfacing multiple AD7550's to a microprocessor.

the *start* command, the microprocessor can examine the status of conversion at will by reading data from the *status* addresses. When this datum indicates that the conversion process has been completed, a single 16-bit MEMORY READ instruction will provide the 13-bit digital value. If it is desired that the end of conversion produce an interrupt request, the *status* line could be wired to an interrupt request line and enable at the start of conversion.

This scheme can be extended to embrace any number of ADC's, or indeed, any, number of combinations of ADC's and DAC's for an analog in/out subsystem.

HORIZONTAL MEMORY-MAPPED I/O

Figure 9 shows an architecture for horizontal memory-mapped I/O. In this example, all devices are mapped into the upper 1024 (1k) memory locations. The *and*-gate G1 provides a *map* signal whenever the upper 1k of memory is addressed.

All devices contain a *select register* (SR), which is loaded with data whenever the highest (177777_8 or $FFFF_H$) memory location is addressed (detected by *and*-gate G2). To select one of the devices, the µP outputs a device number to location $FFFF_H$, which causes the SR's of all devices to be loaded with the device number. All devices compare this number to their own (different) device numbers, and the one which finds itself selected *enables* its device circuits (ROM, RAM, registers, etc.) to respond whenever the µP references the top 1k of memory.

Using this configuration, a given device-access routine or device parameter can be assigned a fixed entry location within the *map* area, directly analogous to the displacements within a device driver based on indexed addressing. So, clearly, this memory-mapped I/O configuration allows the structuring of a *device driver* for general-purpose µP-based data-acquisition systems, even for µP's which lack proper indexed-addressing modes.

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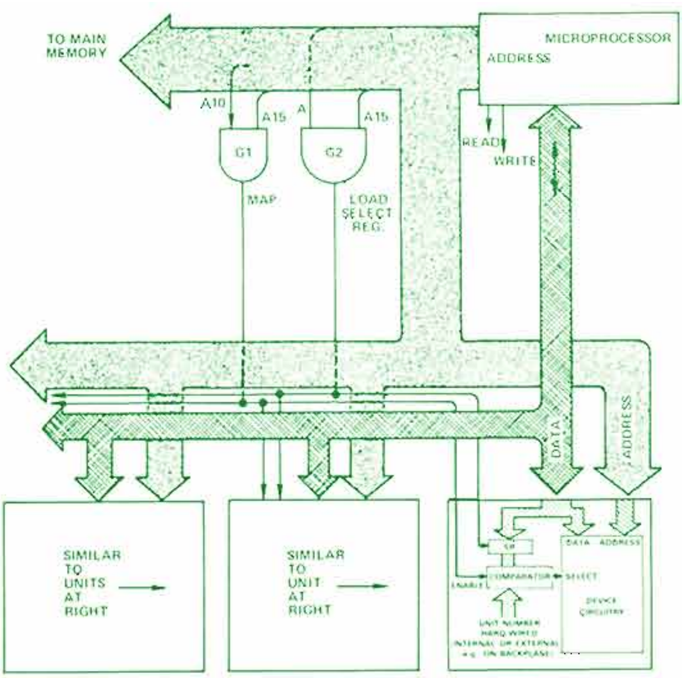

Figure 9. Horizontal Memory-Mapped I/O.

Application Brief

284J AS A CURRENT-LOOP RECEIVER

Isolated 4-20mA Analog Interfacing Low-Cost Protection from kV Spikes

by Jim Maxwell

The 284J Isolation Amplifier*, announced in the last issue of this Journal, provides a key to measuring analog quantities transmitted via 4-20mA current loops over substantial distances through harsh environments with reasonable accuracies and high common-mode rejection. Both the amplifier and the circuitry that its output serves are protected from kV-level common-mode transients.

Figure 1 shows a typical application of the 284J in such circuitry. A 37.5Ω resistor converts the 4-20mA current input from a remote loop to a 150-750mV differential voltage input, which the 284J amplifies, isolates, and translates to a 0 to +5V output level at local system ground.

Among the most-helpful characteristics of the 284J in this kind of measurement are the high common-mode rejection (110dB minimum at 60Hz with 5kΩ source unbalance) and the high common-mode rating (±2500 volts dc). The former means low noise pickup; the latter means excellent isolation and protection against large transients. The high common-mode rejection, permitting relatively low input voltage to be used (0.5V span, in this case), permits the use of a low current-metering resistance, which in turn results in low compliance-voltage loading on the current loop, and therefore permits insertion into existing loops without encountering overrange problems. The gain of 10 provides a substantial 5V output span, and the floating output permits biasing to a 0 to 5V range.

Earlier models 275J/K/L* could be used in this application (and would be necessary if linearity error as low as 0.05% were required), But, if 0.3% is adequate, considerable cost savings are available (284J: $59, 1-24; $41, 100+).

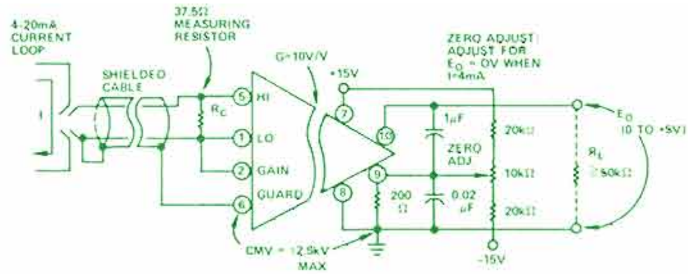

Figure 1. Isolated analog interface; 4 to 20mA is converted to 0 to +5V at the output, with up to ±2500V of isolation.

*For technical data on these products, use the reply card.

Application Note

SONICGUIDE™ HELPS BLIND AMBULATE FREELY

Ultrasonic Spectacles Use Programmable-Gain Multiplier(AD531)

by Dr. Russell P. Smith

Merv McCurdy, of Auckland, New Zealand, runs a successful poultry farm with the help of the SONICGUIDE

A mobility aid and environmental sensor for the blind, which was developed in New Zealand and extensively evaluated in the U.S.A.and other countries some years ago, is now in quantity production and is progressively being introduced in many countries around the world*. The ultrasonic device, known as the *Sonicguide,* is built into a spectacle frame and is connected to a pocket-sized electronics package via a lightweight cord.

The device radiates ultasound in front of its wearer to a distance of 4.5m or more. Any returned echoes are received by two miniature receiving transducers in the spectacle frame, producing audible signals and giving a blind person considerable information about the environment (s)he may be walking in. Figure 1 shows the spectacle frame and the electronics package.

Linear frequency-modulated ultrasonic transmission is used; audible signals are derived by modulating the received signals with the transmitting signal. By an appropriate choice of frequency-sweep rate, the difference frequency produced by the modulation falls into the audio range and may be amplified and coupled directly to the ear. As the range of an object increases, the difference frequency between the transmitted and received signals increases in proportion, due to the increasing round-trip delay of the echo. Thus, the blind person judges the *range* of a particular object by the *pitch* of the sound it produces.

Figure 1. The SONICGUIDE Consists of ultrasonic transmitting and receiving circuitry in a spectacle frame and an Auxiliary Package containing electronics and rechargeable battery.

There are two directional receiving transducers, splayed outwards to left and right; the return signals received by each are modulated separately. The resulting binaural signal presentation provides directional information. If the object (at a given range) is well around to the right, it will produce a considerably louder signal in the right ear than in the left; conversely, if the object is at the left, the left ear will receive a louder signal. The directional characteristics of the receiving transducers are chosen to provide a smooth variation of relative loudness for signals at the two ears as an object is moved around the wearer from left to right (or as he turns his head).

The Sonicguide is a miniaturized production version of an earlier developmental device, the Binaural Sensory Aid. The present design allows the user to fold the arms of the frame, detach the cable from the control box, and control the volume at the electronics package. These conveniences are made possible by incorporating the receiver electronics into thick-film microcircuits contained within the two side-arms of the spectacle frame. Only one-third as many wires now pass through the hinges of the frame and interconnect it with the control box. Figure 2 shows an encapsulated version of the custom thick-

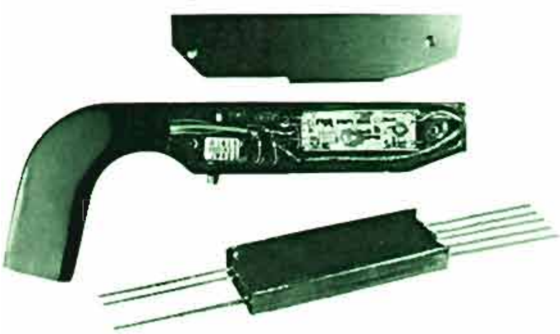

Figure 2. The Receiver circuit is encapsulated and fits in the spectacle frame, together with a trim pot and an earphone.

*The Sonicguide is manufactured by Wormald International Sensory Aids Limited, P.O. Box 19670, Christchurch, New Zealand. This company was established specifically to develop and manufacture aids for the handicapped. Agents for the U.S.A. and Canada are: Telesensory Systems, Inc., 1889 Page Mill Road, Palo Alto CA 94304; for the United Kingdom, Sensory Aid Systems, 113 Whitton Road, Twickenham, TW1 1BZ.

film microcircuit developed for the Aid and a partially encapsulated microcircuit mounted inside one of the side arms of the frame. Also visible in Figure 2 is an adjustment potentiometer and the miniature earphone which produces the audible signal; it is coupled into the ear by means of a small plastic tube.

The Sonicguide, in addition to presenting information about the spatial position of objects, also enables many objects to be recognized from the sound patterns they produce.

Initially, the principal application of the Sonicguide was as a mobility aid for blind adults. New application continue to be found, however: programs are currently underway in four countries involving young blind children, who can use the device to learn the features of their environment and also help to develop their natural hearing response. Promising research programs are also under way with partially sighted adults.

Figure 3 is a simplified schematic diagram of the receiver. Two Analog Devices integrated circuits (provided in chip form) embody the active functions of each receiver. The AD301A† boosts the ultrasonic signal from the preamp output by approximately 20dB before feeding it into the X input of the AD531J 4-quadrant programmable multiplier.† The amplified received signal multiplies an attenuated version of the carrier, producing a modulation which gives rise to the audible difference frequency.

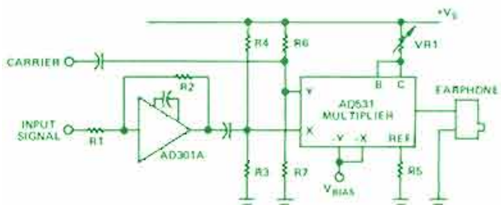

Figure 3. Simplified schematic diagram of the receiver.

The scale-factor of the multiplier can be programmed by setting adjustment potentiometer, VR1; it is possible to produce sufficient overall gain between the demodulator and the audio output to make further amplification unnecessary. The on-chip output amplifier of the AD531 is suitable for driving the low-impedance miniature earphone directly. System-gain adjustment, to compensate for variations in transducer and earphone sensitivity, is effected by trimming VR1 to adjust the quiescent current in the X-input differential transistor pair. Since the gain is taken at the multiplier input stage, rather than in a post-amplifier, noise tends to be minimized. In addition, the use of the (rechargeable) battery as the reference eliminates any noise contribution from the internal reference diode.

The use of a true 4-quadrant multiplier in this application makes it possible to control the gains of the two receiver circuits by simply varying the level of the carrier signal. This technique ties up only one wire in the 4-wire cable to provide volume variation for the two channels while achieving accurate gain-tracking over a 50dB volume range.

The offsets of the AD531, which give rise to signal- and carrier-feedthrough, are nulled by laser-trimming resistors R4 and R6 while the circuit is activated, and under test conditions. Signals are alternately fed into the X and Y inputs, while the output feedthrough voltage is monitored; the resistors are trimmed to within approximately 0.5% of the optimum value.

†Use the reply card for technical information on Analog Devices products. For information on chip availability, consult your local sales office.

Across the Editor's Desk

Bound (Limit) Circuits: NONLINEAR CIRCUITS HANDBOOK Erratum

Two sharp-eyed readers, Charles E. Glidden, of Intel Corporation, Santa Clara, California, and Charles A. Phaneuf, of Pratt & Whitney Aircraft Group, West Palm Beach, Florida, have called our attention to the fact that the circuit on page 24 of the *Nonlinear Circuits Handbook*[1] doesn't "play." The diodes associated with the second amplifier are reversed, the resistance labeled "4R" should be "2R". and the right-hand sides of all three elements of "equation" 20 should have minus signs. The correct rendering of the bound circuit, its defining equation, and the plot are given in Figure 1.

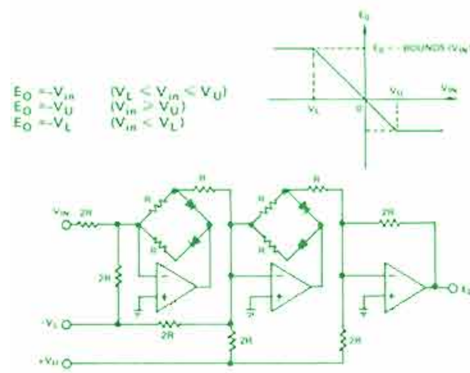

Figure 1. Corrected bound circuit. Note that output voltage has a sign inversion; note also that if V_L is a negative voltage, $-V_L$ is positive.

A similar function could be obtained with the circuit on page 25 by subtracting V_{IN} from the output, i.e., by connecting a resistor (2R) between V_{IN} and the summing junction of the output amplifier. The bounds, in that version, would not be inherently horizontal, but the zero-offset would not depend on resistance matching.

Finally, Mr. Phaneuf has suggested a 4-amplifier version with inherently positive polarity, using the differential inputs of the amplifiers (Figure 2). It should be noted, though, that either of the circuits mentioned above could also be non-inverting if the circuit were followed by a (fourth) inverting op amp.

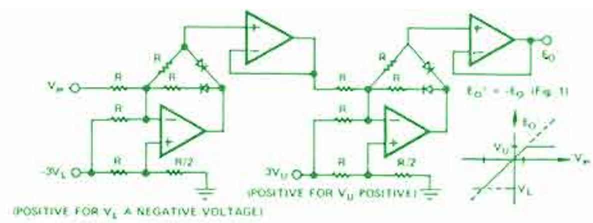

Figure 2. Alternative bounding scheme without overall sign inversion. Reference voltages of $-3V_L$ and $3V_U$ may be impractical if bounds approach full-scale input voltage.

[1] *Nonlinear Circuits Handbook*, D.H. Sheingold ed., 502 pp., xxxii, Analog Devices, Inc., P.O. Box 796, Norwood MA 02062, $5.95

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Miniaturization is aided by the purchase of the custom thick-film microcircuits from Newmarket Transistors. Ltd., in the United Kingdom, and the AD301A and AD531J chips from Analog Devices.

▶▶▶

Potpourri

An Eclectic Collection of Miscellaneous Items of Timely and Topical Interest. Further Information on Products Mentioned Here May Be Obtained Via the Reply Card.

NEW PRODUCTS . . . More on the 277J/K/A Isolation-Amplifier family, mentioned in the last issue: It has an uncommitted-op-amp front end, is usable in the inverting or non-inverting modes, provides adjustable gains to 1,000. Besides low max nonlinearity (0.025%) and drift (1μV/°C) -277K- the family withstands high isolation voltage (2,500V peak continuous, 3,500V rms, 1 minute) and has excellent common-mode rejection (120dB min @ 60Hz, 160dB min @ dc). To top it all off, floating auxiliary power outputs of up to ±15mA @ ±15V are provided for transducers and front-end buffers. Pricing is competitive, too (277J/K/A: $115/$145/$135, 1-9) . . . The SDC1700 synchro-to-digital converter is a 12-bit tracking family that contains its own transformers, yet it is housed in a low-profile (0.4", 10.2mm) package and has 50Hz to 2.6kHz capability. Besides the 12-bit resolution, accuracy to within 8.5' and tracking speed of 12,960°/s (400Hz) are available. A wide range of options is available, including the "universal version", SDC1700521, with a wide operating frequency range and the ability to be configured to work at high or low voltage levels. Pricing starts at $365 (1-9).

NEW LITERATURE . . . A new data sheet is available for the AD7550 monolithic 13-bit a/d converter. Completely revised, it provides new applications information, including an analysis of the factors affecting errors . . . A new data sheet is available for the AD7510DI switch family; these switches have now completely supplanted their non-DI forebears, at no increase in cost . . . Our new 32-page Short-Form Guide: Electronic Products for Precision Measurement and Control went into the mails recently. If you don't receive your copy soon, or need an extra for a colleague, use the reply card to request the "short-form catalog."

PRODUCT NOTES . . . In answer to a frequently asked question, the AD522 Instrumentation Amplifier will work in a socket wired for the popular AD521, but with these differences: (1) No R_S is necessary; use the AD522 gain equation to compute R_G. (2) The offset null pot for the AD522 must be wired to V_{S+} instead of V_{S-}; if no offset pot is used, no change is required . . . Underwriters Laboratories has listed certain versions of our standard power supplies in UL Guide QQFU2. The supplies so designated and their standard equivalents are: 1054 ← 920, 1055 ← 902-2, 1056 ← 904, 1057 ← 905, 1058 ← 903. For further information and prices, consult your local Analog Devices sales office.

OTHER NOTES . . . Data-sheet errata and clarifications . . . AD522: Pin 1 is identifiable by its juxtaposition with a square corner on the package, as well as by the conventional dot. On page 2, table 1, under "Specification", Gain Nonlinearity is ±0.002% max, and Offset Current Drift error is ±50nA/°C; the numbers in the other columns are correct . . . An errata-sheet/application-note for the AD2010 is available . . . An errata sheet for the 284J lists a single typo; on page 2, under "Input Voltage Ratings", the fifth line should read: "Max CMV, Inputs to Outputs".

IN THE LAST ISSUE . . . Vol. 10, No. 2 (1976) . . . Ultra-low-cost panel meter challenges analog meters (AD2026) . . . Versatile monolithic V/f or I/f converter (AD537) . . . Differential instrumentation amplifier is laser-trimmed (AD522) . . . Functional DPM for custom meter designs (AD2022) . . . Infra-low-power a/d and d/a converters use CMOS (ADC1121, DAC1122) . . . Protected analog switches are dielectrically isolated (AD7510DI family) . . . 12-bit data-acquisition system in a compact module (DAS1128) . . . dc/dc converters provide ±15V, ±12V, +5V from 5V or 28V (Models 940 through 946) . . . Small, low-cost isolation amplifier with super specs (284J) . . . Application Briefs, Potpourri, Editor's Notes, V/f converter comparison . . . Several errata: p.12, figure 2, connection to transistor base missing; p.7, AD537 Performance Characteristics, under "Current-to-Frequency Converter", 9th line should read: f = 100kHz nominal; for consolidated (and slightly differing) linearity specs, see the AD537 data sheet; p.8, upper figures, designation next to pin 6 should be 1mV/K.

The world's smallest complete Isolation Amplifier has

the world's smallest price.

We knew what you needed in isolation amplifiers. Smaller size, lower cost, better performance. So, we did it. We designed the Model 284J Isolation Amplifier to give you the kind of performance and versatility you need for a broad range of applications.

The 284J costs only $41 in 100s, yet delivers all the key parameters in a small (1.5" x 1.5" x 0.62"), self-contained module. It even includes isolated power supply outputs for input pre-amplifiers or calibration signals. And because it requires no external DC/DC converter, the 284J is the smallest and least expensive isolation amplifier available today.

The 284J's total noise referred to input is a mere 8μV p-p in a 100 Hz bandwidth. Add an adjustable gain of 1 to 10V/V, a CMV of 5000V pulse or 2500V continuous and a minimum CMR of 110dB. And you've got all you need for a myriad of applications where optimum measurement accuracy and safety are concerned.

We didn't stop there with the product line. Consider our higher performance, Model 277 Instrument Grade Isolation Amplifer. Its uncommitted op amp front end gives you extreme versatility. Its CMR of 160dB and its gain nonlinearity of less than 0.025% for a full 20V swing plus a drift of less than 1μV/°C give you exceptional performance. The 277's versatility and performance at a price of $115 (1-9) make it an excellent alternative in your most demanding instrumentation applications.

Then there's our Model 275 Industrial Grade Isolation Amplifier, $79 (1-9), that is gain programmable over a range of 1 to 100 by a single resistor with nonlinearity to less than 0.05%. And our Model 285 is like the 275 but features a low impedance op amp output. And our Models 279, 282 and 283 for multichannel applications.

We could go on and on about this line. But our free Analog Devices Isolation Amplifier Handbook says it all. Ask for a copy along with the data sheets on our new Isolation Amplifiers. Write Analog Devices, the real company in isolation amplifiers.

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