Current-source alternatives increase design flexibility

An op amp's feedback loop is an excellent constant-current circuit. But if your requirements call for a ground-referenced load, high speed or high efficiency, consider several other approaches.

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If traditional feedback-loop-based methods of current control aren't adequate for your needs, investigate some alternative approaches to designing constant-current sources. The circuits described here can prove useful in a variety of applications requiring current rather than voltage control—resistance-temperature-detector (RTD) and thermistor excitation, ramp generation and deflection-yoke modulation, for example.

Traditional method exhibits shortcomings

The most commonly used current source—the one most frequently encountered in op-amp cookbooks—is the feedback loop of an operational amplifier (**Fig 1**). Although the amplifier's voltage gain varies with R_{FB}, the current in the feedback loop remains fixed, assuming a fixed E_{IN} and R_{REF}. Thus, the op amp, viewed from the feedback resistor, is a constant-current source. The amplifier inputs accommodate offset and scaling.

In general, this simple op-amp-based circuit provides good results. You can increase current or voltage compliance by adding an output stage, and precision greater than 0.01% is easy to achieve. However, the approach also has limitations. The most serious is that the current-driven load isn't referred to ground. Although the amplifier junction is at 0V, it's forced there by feedback and remains sensitive to noise and lead capacitance. Thus, because remote transducers and test fixtures are often driven with respect to ground, feedback-loop designs often exhibit problems.

Providing a grounded load

The clever circuit shown in **Fig 2**, devised in 1959 by B Howland at MIT, solves this ground-reference

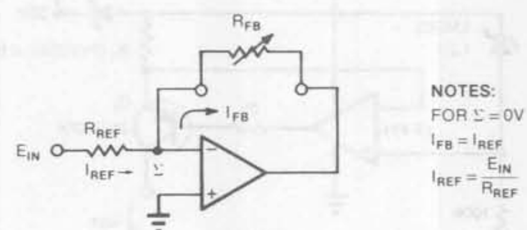


Fig 1—A feedback-loop-based current source *produces excellent results but isn't useful in applications requiring a ground-referenced load.*

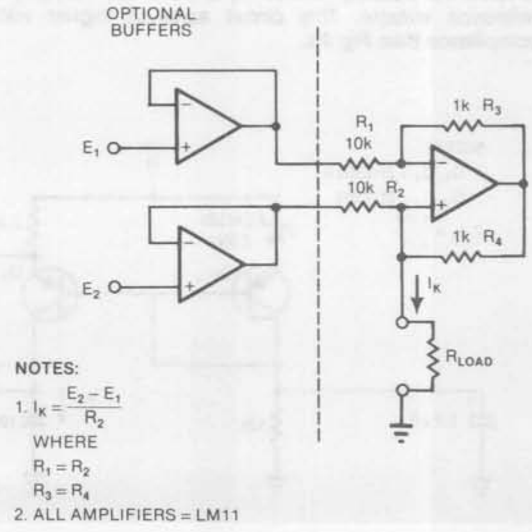


Fig 2—A Howland current-source circuit *supplies a grounded load and has differential inputs.*

problem. This single-amplifier circuit is a true instrumentation-grade current source: It supplies a grounded load and has fully differential inputs. You can delete the input followers if you don't need high input impedance.

Because positive feedback makes the circuit's output impedance appear infinite, understanding circuit operation isn't easy. To start, assume E_1 is 0V, E_2 is some positive value and the load is a short circuit. The configuration is then the well-known inverting amplifier. Because the input E_1 is at 0V, the output is also 0V, and input current E_2/R_2 is the only current flowing into the now-shorted load.

As the current-driven load's resistance increases, the voltage across the load also increases. This increasing voltage at the op amp's noninverting input forces the voltage at the inverting input to rise. As a result, the negative-feedback network causes the op-amp output to rise above the inverting-terminal potential; the op amp supplies the additional current to the load that's no longer supplied from E_2. In other words, as the load value increases, less and less current gets taken from E_2, with the op amp taking up the slack.

For precision results, this circuit demands an op amp with good common-mode rejection; in dc operation, an LM11 provides 0.01% precision without too much difficulty. *(Ed Note: A future article will examine the Howland circuit in greater detail.)*

Increasing voltage compliance

Another way to achieve grounded-load operation involves the circuit shown in **Fig 3**. Here, the op amp forces the voltage across R_1 to equal the LM385 voltage

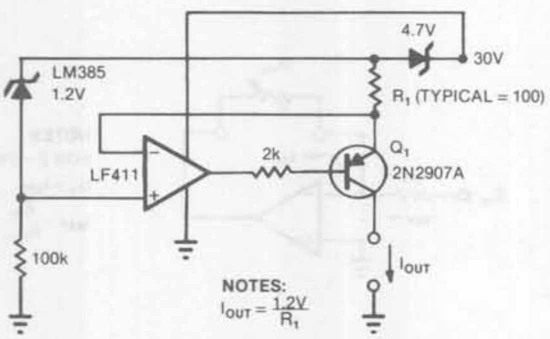


Fig 3—Another way to achieve grounded-load isolation *is to force the potential across R_1 to equal the LM385's 1.2V reference voltage. This circuit achieves higher voltage compliance than* **Fig 2**'s.

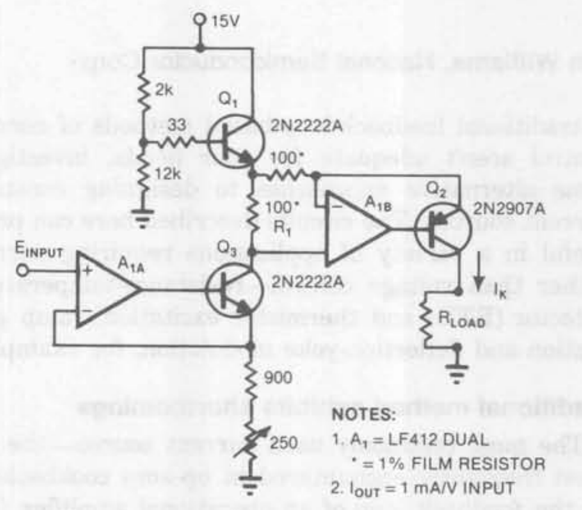


Fig 4—Achieve voltage control *by forcing the voltage drop across R_2 to equal the drop across R_1.*

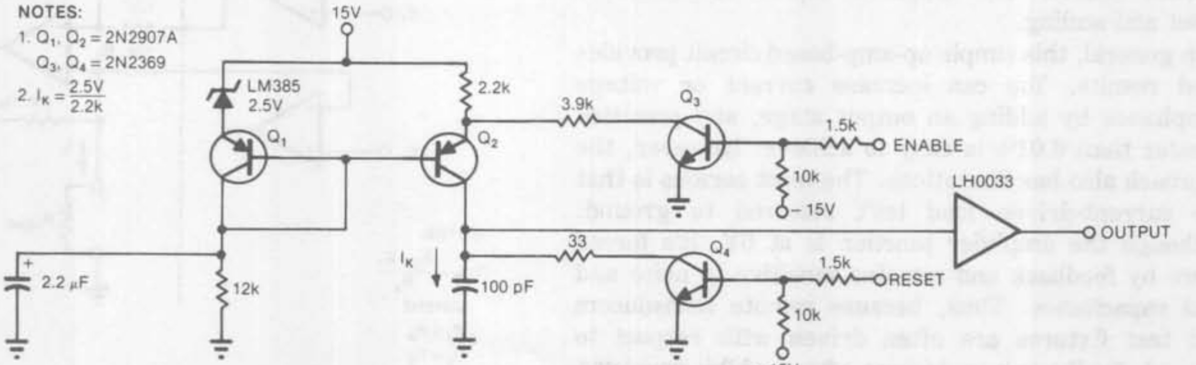


Fig 5—High-speed operation *results when you abandon feedback techniques. Obtain ramp-and-pedestal operation by gating the charging current to the loop's capacitor.*

reference's 1.2V potential, regardless of transistor Q_1's load. The 4.7V zener diode ensures that the op amp's inputs are within its common-mode range. The circuit's output current measures

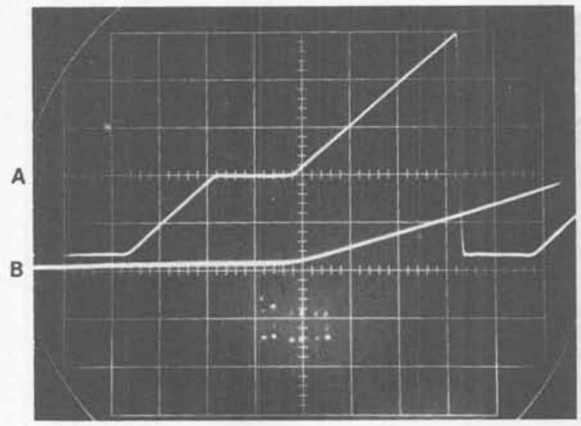
$$I=1.2V/R_1.$$

This circuit's advantage compared with the Howland design is its greater voltage compliance. That is, it exhibits a greater ability to maintain current in high-resistance loads. (In an ideal current source, the voltage goes to infinity when you increase the load because the source tries to maintain constant current. In **Fig** 3's circuit, the voltage output rises with increasing load resistance to a maximum value of 24V; beyond this voltage-compliance value, the output source can no longer increase the resistor's voltage, and it clips.)

Voltage-controlled source sports high impedance

If you need a voltage-controlled ground-referenced current source, consider **Fig** 4's design. This circuit features high input impedance and noninverting operation. A_{1A} and Q_3 act as a voltage follower, producing an input-voltage-controlled drop across R_1. A_{1B} and Q_2 then force this drop to appear across R_2; Q_2's collector supplies the output current. Q_1 acts as a voltage regulator, reducing the supply voltage to 12V so that A_{1A} and A_{1B} operate within their common-mode range.

The 250Ω potentiometer provides trimming, resulting in an input/output relationship of 1 mA/V. To set the scale factor, apply 10V to the input and adjust the potentiometer for 10-mA output. You can alter the scale factor by changing R_2.



TRACE	VERTICAL	HORIZONTAL
A	2V/DIV	500 nSEC/DIV
B	0.2V/DIV	50 nSEC/DIV

Fig 6—The ramp-and-pedestal operation *of* **Fig 5**'*s circuit shows sharp transitions, with no ripple.*

Abandon feedback for high speed

In addition to lacking the ability to operate with a grounded load, feedback-loop-based circuits can't achieve accurate high-speed operation without using

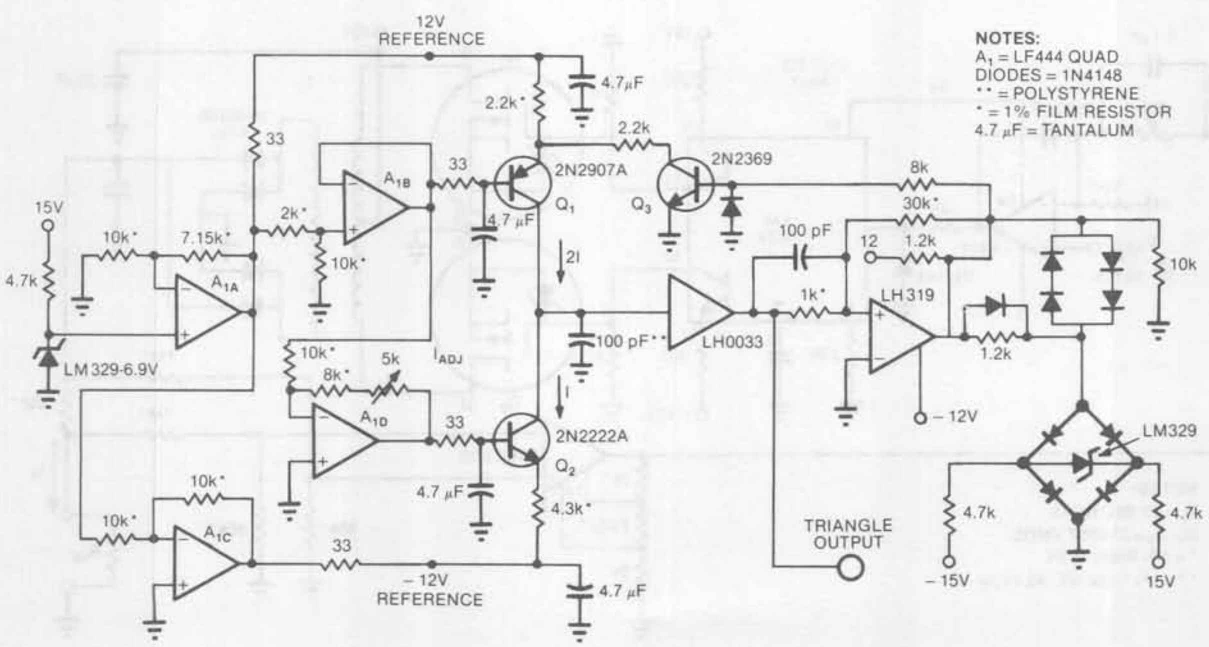
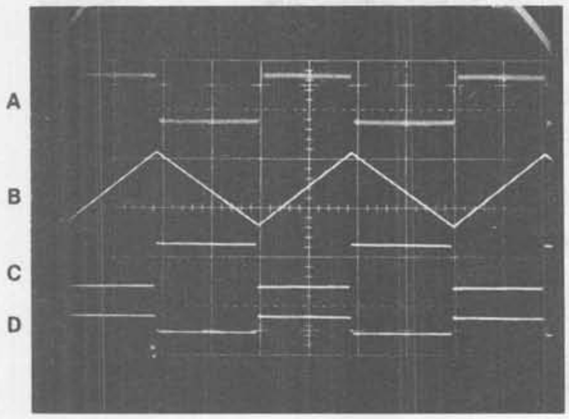


Fig 7—A bipolar current source *generates a highly linear triangular wave. It functions by alternatively charging and discharging a capacitor with positive and negative currents.*

Abandon feedback for high-speed operation



TRACE	VERTICAL	HORIZONTAL
A	2 mA/DIV	200 nSEC/DIV
B	2V/DIV	200 nSEC/DIV
C	20V/DIV	200 nSEC/DIV
D	10V/DIV	200 nSEC/DIV

Fig 8—Performance to several megahertz *characterizes Fig 7's circuit.*

elaborate and expensive op amps. That is, the ac dynamics of maintaining accurate feedback place limitations on loop-based current sources. Fortunately, several high-speed alternatives are available.

In **Fig 5,** for example, the Q_1/Q_2 transistor current source supplies a gateable current to the 100-pF capacitor to produce a very-high-speed voltage ramp. (Q_2 is the actual current source, with Q_1 furnishing V_{BE} compensation.) The LH0033 buffer provides a low-impedance output; the LM385 reference fixes the current, which you can vary by changing the value of Q_2's emitter resistor.

Q_3 gates the current source by reverse-biasing Q_2. This procedure allows you to obtain the high-speed ramp-and-pedestal operation shown in **Fig 6**'s trace A—a common requirement in nuclear- and particle-research instrumentation. Because the design has no feedback loop, operation is quick and clean, even at high speed. **Fig 6**'s trace B shows an expanded version of the center section of trace A. Here, the pedestal begins to ramp as the source is gated ON. The transition is sharp, with no discontinuities.

Another high-speed current source appears in **Fig 7.** Here, alternately charging a capacitor with positive and negative current sources generates a high-linearity 1.5-MHz triangle wave—a capability that op-amp based circuits can't achieve. The positive current source Q_1 supplies a current of value 2I to the 100-pF capacitor, while Q_2 sinks I. The resulting charging current is I, and the capacitor charges linearly. **Fig 8**'s trace A shows the charging current, while trace B depicts the voltage across the capacitor.

When the capacitor voltage ramps sufficiently high, the LM319 comparator changes state (trace C), turning transistor Q_3 ON. This action back-biases Q_1 (trace D),

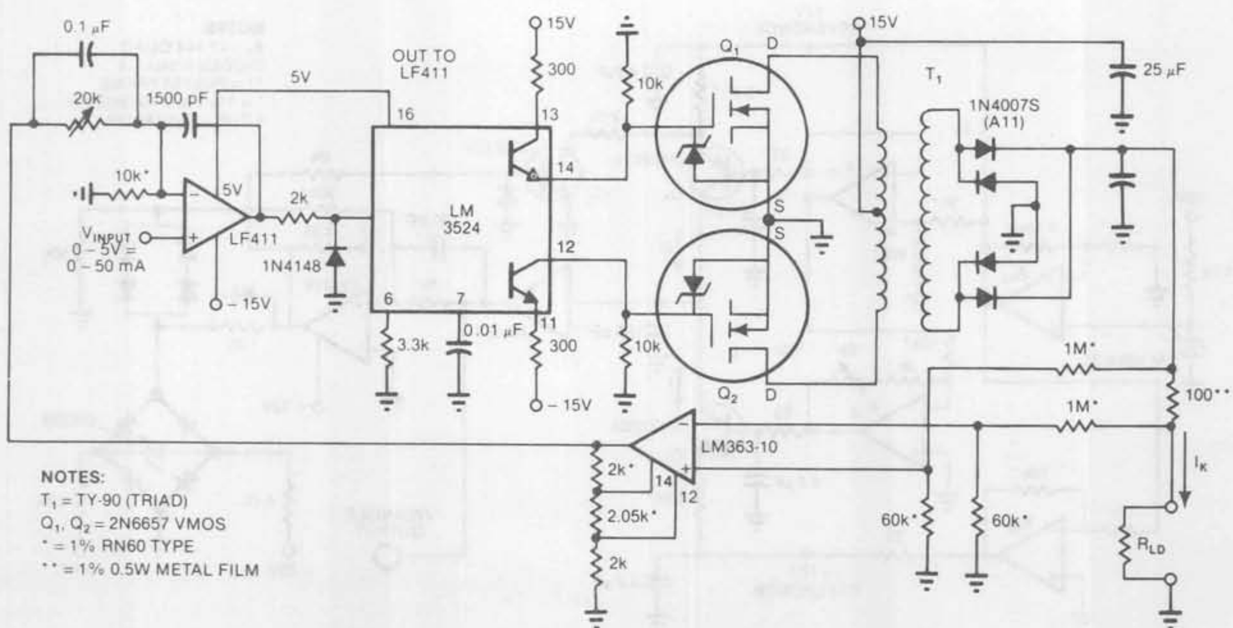


Fig 9—A switching converter *provides 0 to 50 mA into a load, with a compliance of 200V.*

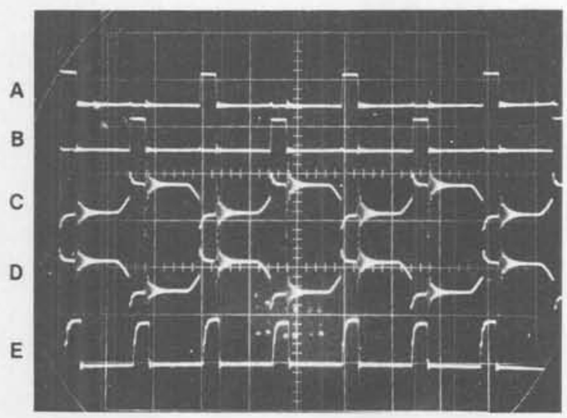
shutting off the 2I current flow. From this point on, the capacitor discharges at a rate proportional to I until the LM319 changes state again, reinitiating the cycle.

The zener bridge and associated diodes ensure a stable, bipolar comparator trip point, while the 100-pF comparator input capacitor compensates for propagation delay. The LH0033 unloads this capacitor, and the quad op amp sets the bias points for the current sources, using the LM329 as the master reference. A_{1A} and A_{1C} generate $\pm$12V for the Q_1 and Q_2 emitters, while A_{1B} and A_{1D} bias the transistors' bases. The 33Ω/4.7-μF combinations furnish decoupling, and the $\pm$12V emitter voltage also biases the comparator's output stage.

You can vary the triangle-wave frequency by driving A_{1B} directly, changing the current sources' base bias. With a good ground plane and a low-capacitance wiring technique, the current sources can generate good triangle waveforms out to several megahertz. To adjust the circuit, trim the I_{ADJ} potentiometer until the triangle waveform is symmetrical. This action essentially adjusts the I/2I ratio and also corrects for propagation-delay-induced errors.

Use a switched-mode source for efficiency

Some current-source applications require high current or high compliance voltage, and in these cases, efficiency suffers. The source shown in **Fig 9**, however, operates in switched mode to achieve low losses.



TRACE	VERTICAL	HORIZONTAL
A	20V/DIV	20 μSEC/DIV
B	20V/DIV	20 μSEC/DIV
C	20V/DIV	20 μSEC/DIV
D	20V/DIV	20 μSEC/DIV
E	2A/DIV	20 μSEC/DIV

Fig 10—Because the pulse drive of Fig 9's switching converter *is not a square wave, the waveforms appear distorted. But the current in the transformer primary is clean and distortion free.*

This current source provides 0 to 50 mA into a load with a compliance limit of 200V. The LF411 receives the control-voltage input and biases the LM3524 pulse-width modulator. The complementary LM3524 outputs (**Fig 10,** traces A and B) drive the VMOS transistors at 30 kHz. The toroidal transformer provides a voltage step-up when excited by these VMOS transistors (drain waveforms appear in traces C and D). Because the pulse drive is not a square wave, the drain-voltage waveforms appear distorted. But the current in the transformer primary is clean and orderly (trace E). The transformer output gets rectified and filtered to produce the current output.

The LM363 divides down the voltage across the 100Ω shunt resistor to a usable level; it also transforms the voltage to single-ended form. The LM363 is trimmed to

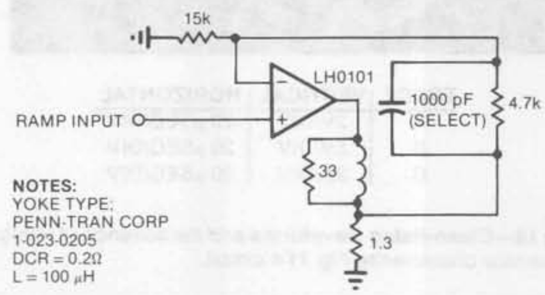


Fig 11—A deflection-yoke driver *achieves precision current drive, avoiding display distortion.*

a gain of 30; its output returns to the LF411, completing a loop that forces the pulse-width modulator to run at whatever duty cycle is required to keep the current through the 100Ω shunt constant, regardless of loading conditions. Although the pulsed transformer can develop a 200V output, it's loop-limited to produce only the voltage required to satisfy the circuit's current output. The result? High efficiency.

The VMOS devices permit high-speed operation while requiring little drive. The LF411 gets driven from the LM3524's internal 5V regulator, ensuring that the LM3524 input can't be overdriven during startup or transients. The capacitors at the op amp ensure loop stability, and the 20-kΩ potentiometer trims the circuit's 100-mA/V scale factor.

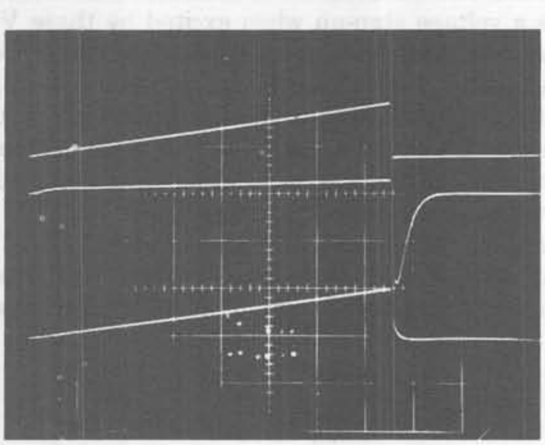
Deflection yokes require current drive

As a final example of a constant-current source, consider the circuit shown in **Fig 11.** It provides a carefully controlled current drive—useful in a precision display's deflection yoke, whose magnetic field is proportional to the current through it.

The LH0101 power op amp provides a current-controlled drive to the yoke at a scale factor of 1V/A.

Obtain high efficiency with a switching converter

The 33Ω resistor furnishes yoke damping; without it, a high inductive flyback voltage would be produced at a step discontinuity. The 1000-pF capacitor trims the circuit. For a ramp input (**Fig 12,** trace A), the yoke input current (trace C) rises cleanly with no ripple or discontinuities. When the ramp resets, the inductor current falls to zero, and the op-amp output (trace B) must swing sharply negative to compensate for the inductive flyback. Because damping is optimized, the yoke-current sweep reset is clean and doesn't cause display distortion. **EDN**



TRACE	VERTICAL	HORIZONTAL
A	2V/DIV	20 μSEC/DIV
B	5V/DIV	20 μSEC/DIV
C	2A/DIV	20 μSEC/DIV

Fig 12—Clean-rising waveforms *and the absence of unruly dynamics characterize* ***Fig 11****'s circuit.*

Author's biography

Jim Williams was applications manager in National Semiconductor's Linear Applications Group (Santa Clara, CA), specializing in analog-circuit and instrumentation development, when this article was written. Before joining the firm, he served as a consultant at Arthur D Little Inc and directed the Instrumentation Development Lab at the Massachusetts Institute of Technology. A former student of psychology at Wayne State University, Jim enjoys tennis, art and collecting antique scientific instruments in his spare time.