This 30-ppm scale proves that analog designs aren't dead yet

Electronics does not live by µP's alone. This analog instrument achieves 0.02% absolute accuracy, yet never needs adjustment.

James Williams, Massachusetts Institute of Technology

Body weight is a critical indicator in human nutritional studies. In fact, the ability to repeatedly resolve small weight changes is often the limiting factor in those investigations involving sweat losses and other metabolic functions. A very careful nutritional experiment conducted by the M.I.T. Clinical Research Center required an instrument that would repeatedly resolve 0.01 lb out of 300.00 lbs. F.S. That's 30 parts per million—about one doughnut bite in a 300-lb subject! Additionally, the instrument had to be portable, never require calibration or adjustment, and have an absolute accuracy within 0.02%.

Perhaps the most notable feature of the instrument is that, despite its ultra-high performance, its design used only readily available components and not one single custom item. By combining judicious component selection with careful engineering, a state-of-the-art instrument moved from conception to finished prototype in a very short time.

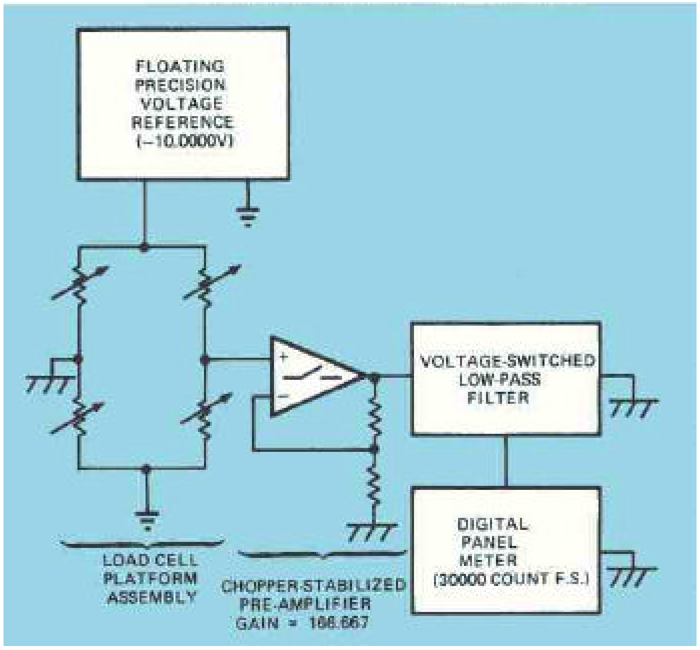


Fig. 1—Straightforward approach used in the scale can be seen from this block diagram. What can't be seen is the attention to detail required to obtain the outstanding performance.

Eliminate nonessential error sources

Basically, the metabolic scale combines precision strain gauges and low-drift electronics (**Fig. 1**). The 10x12x5-in. platform assembly contains four bonded strain gauges distributed symmetrically. Together with linearizing and offset-correcting resistors, these strain gauges form a bridge network. When a patient steps on the platform, the electronics amplifies and processes the bridge signals, producing a voltage linearly proportional to weight that is displayed on a DPM.

Ed Note: *True or false: Analog circuits continually need adjustment or must use custom components to achieve precision results? False! While it's true that analog designs have definite limitations—as indeed do digital ones—an inventive designer can overcome many obstacles and produce outstanding results. We hope that the following example of analog achievement will inspire designers to even greater triumphs.*

A precision voltage reference excites the strain gauge bridge. This supply derives its stability from an aged, current-trimmed, temperature-compensated zener diode. Because the reference supply is fully floated from system ground, the output of the load-cell bridge appears as a single-ended, rather than a differential signal. This factor is significant and deliberate, in that it eliminates all common-mode voltage error possibilities and allows the use of a high-stability chopper-stabilized amplifier as a pre-amplifier.

The pre-amplifier is required to boost the load-cell signal up to levels that can be easily processed. With 10V excitation the strain-gauge

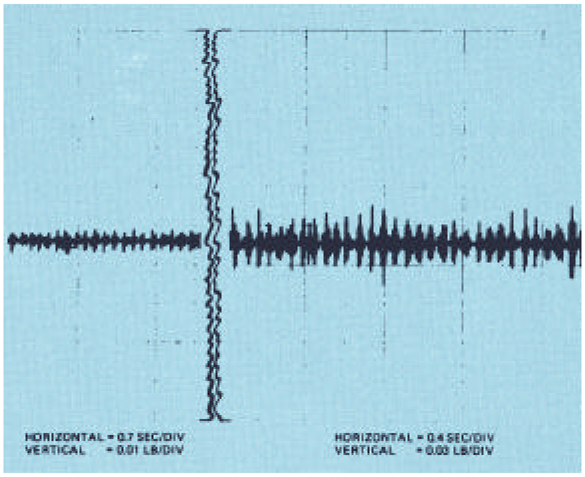


Fig. 2—"Weighing" a heartbeat is possible due to the scale's 0.01-lb resolution. These ac-coupled chart recordings were taken from the output of A3. On the left is a normal heartbeat; on the right, the rhythm after a short, but fast, run.

bridge yields only 18 mV F.S. Thus, one least significant digit (0.01 lb) is only 600 nV at the transducer output.

Although the clinical operating temperature range is quite narrow (20 to 30°C), overall system accuracy requirements dictate a pre-amplifier that drifts 120 nV/°C, max.—200x better than a 741-type op amp. Chopper stabilization techniques combined with stable feedback resistors, attention to grounding and avoidance of thermal EMF's afford this performance. The signal, once amplified, must be filtered. Without filtering, small accelerations in the form of body motion and even heartbeat will cause jitter in the display (Fig. 2). While a simple R-C low-pass filter can provide the necessary smoothing, its long time constant means that the scale will require minutes to settle to five decimal places on the readout. The filter used avoids this problem by switching its time constant from short to long when it has acquired almost 100% of the pre-amplifier's output. The signal from the filter then drives the digital panel meter which provides a 300.00-lb F.S. display.

Achieve precision by attention to details

As previously mentioned, the 1N829 temperature-compensated zener is the key to the high-stability reference supply (**Fig. 3**). The zener owes its very low drift (typically 5 ppm/°C at 6.2V and 7.5 mA) to junctions with opposing temperature coefficients. However, any individual diode has its own "ideal" current at which the two junctions' temperature coefficients very precisely cancel out. Once this current has been experimentally established, drift performance of 0.1 ppm/°C can be achieved.

Our method for establishing the true zero-drift point involves first running the manufacture 's recommended 7.5 mA through the diode under test, placing it in a 50°C oven, and reading its voltage. We then take another reading at 0°C, noting the difference (drift). Changing the diode current, we repeat the experiment. Iterating this procedure yields the current that produces the least drift—the "ideal" current.

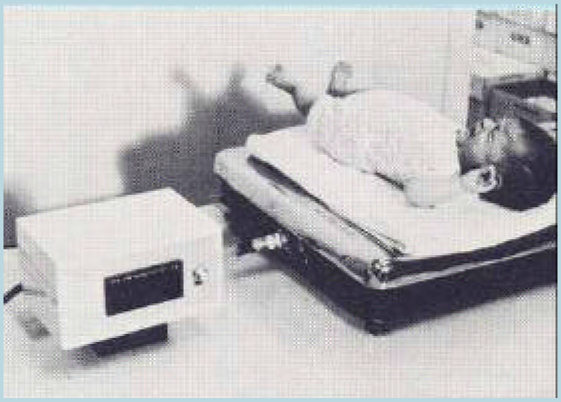
To age the diode we burn it in at the ideal current for 1000 hrs. Finally, we repeat the

A vast improvement over conventional instruments

Body-weight change is an extremely important parameter of body composition in clinical studies, particularly those concerned with the estimation of protein and energy utilization and the assessment of human requirements. Because the scale described in this article can be transported and, at the same time, offers improved sensitivity, accuracy and automatic data recording, it should prove extremely valuable in metabolic research.

For example, this scale permits precise, frequent monitoring of body-weight changes over short as well as long-term periods, important measurements in studies of energy balance. The device also can measure miniscule, previously undetectable water losses.

Since the scale employs body-motion filtering, it is ideal for weighing restless infants and young children. Normally, motion on a scale makes stable readings difficult, if not impossible, to obtain.



Besides providing an unambiguous, ultrahigh precision readout, the scale eliminates human-factor errors since it needs no adjustment, can be easily interfaced to computers and other circuitry, and can withstand overload and rough handling.

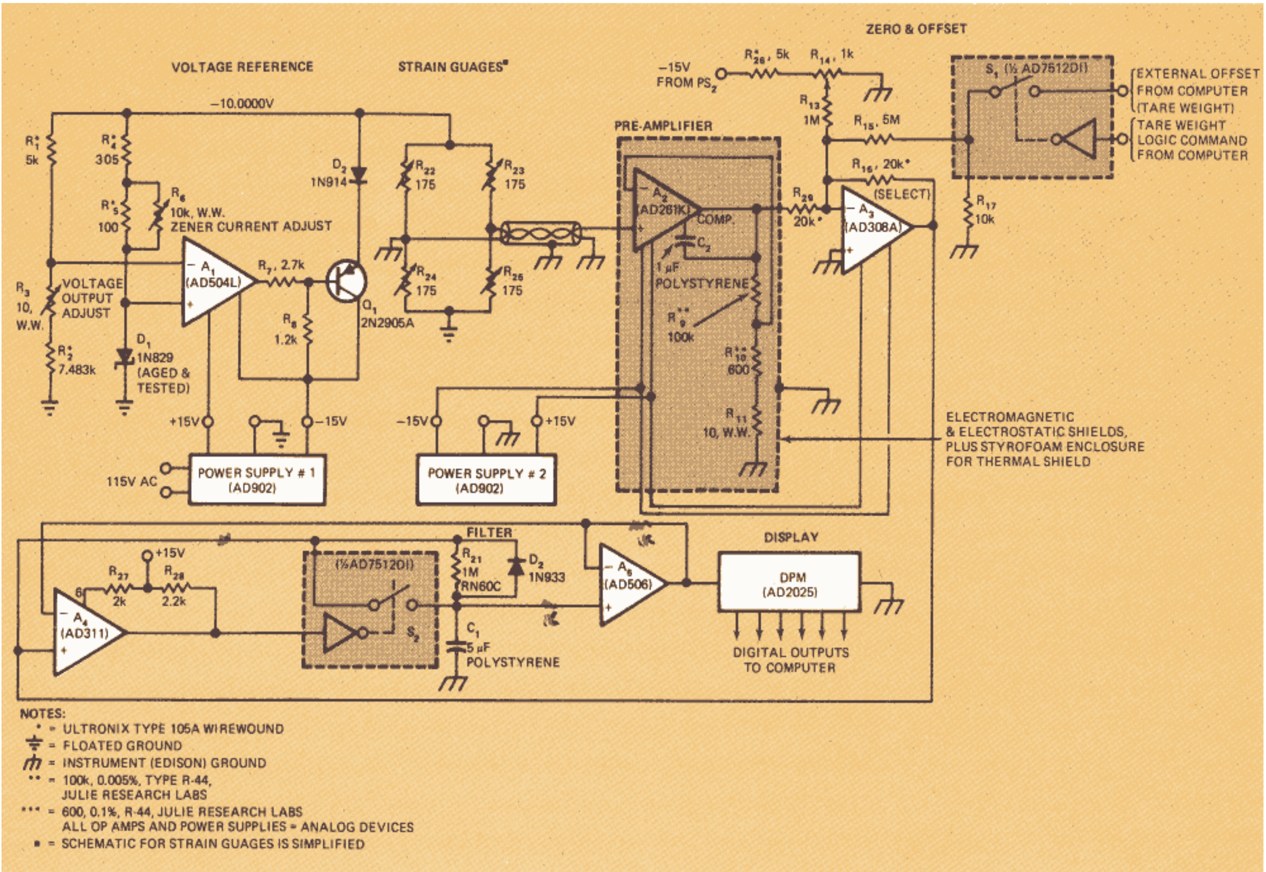


Fig. 3—Only standard, readily available components are used in the scale's circuitry. For proper operation, at least 10^8O of insulation must exist between the common terminals of the power supplies.

temperature tests to fine-tune the final minimum drift current.

The aged and tested reference diode is installed in a bridge circuit buffered by a low-drift amplifier (A, in **Fig. 3**). The zener's potential biases A1's positive input, while R1, R2 and R3 provide the precise feedback necessary to obtain -10.0000V at the op amp's output. Note that the zener constant current is "bootstrapped" from the circuit's output. R,; adjusts this current.

Since the strain-gauge bridge presents a 200cc load, Q, is included inside the feedback loop to provide current-driving capability. D2 and R8 guarantee that the circuit will "start up" correctly, while also ensuring that the reference diode can never become reverse-biased under any conditions. (Reverse biasing of reference diodes for even a few msec can introduce long-term low-level drifts.)

The low temperature drifts of the D1, A1 and the wirewound resistors produce a -10.0000V reference supply with a total drift of only 0.25 ppm/°C. Because this is 150x the required system stability, reference drift effectively drops out of the error budget.

Noninverting chopper serves as pre-amp

Load-cell manufacturers offer the strain-guage bridge, its associated calibration resistors and the platform as a pre-trimmed assembly. Electrically, it can be modeled as a bridge of four 175O strain-dependent resistors. Because of these low impedances, the bridge supply can be floated from instrument ground without introducing serious pick-up noise into the bridge output.

In this circuit, pre-amp A2 must extract a 600-nV signal (least significant digit) from a 5V dc level. Thus, a precision amplifier with low noise, <120-nV/°C drift and 140-dB CMR is required. Unfortunately, no instrumentation amplifier with such a combination of specifications exists—even the best differential instrumentation amplifiers offer only 250-nV/°C T.C.'s, 2-µV/day drifts and 120-dB CMR's. Therefore, to achieve the desired performance you must use a single-ended, non-inverting chopper-stabilized amplifier such as the Analog Devices' 261K (100 nV/°C over 0 to 70°C with almost negligible time drift). This approach has one major trade-off, though: Because one leg of the bridge is grounded, the instrument cannot take a ratiometric measurement; i.e., the bridge and the panel meter require separate voltage references.

Observe from **Fig. 3** that R9, R10, and R11 determine the pre-amplifier's gain. These components are of wirewound construction to obtain

Make sure that you are on solid ground

Proper grounding is critical to this circuit. Separate ground returns are required for each ground path, and all ground returns should be terminated at a single point at each power-supply common.

The power supplies used are standard modular types (Analog Devices Model 902). We mounted them outside the unventilated readout box to minimize heat rise and to prevent the transformer magnetics from influencing the pre-amplifier. Because one of the supplies floats, note that at least $10^8\Omega$ of insulation should exist between the ground terminals of the two supplies. The 902's are more than adequate in this respect.

the required stability. The op amp and its associated components should be both electrostatically and electromagnetically shielded from other circuitry, and careful attention must be paid to proper grounding (*see box*). We also recommend that you use low thermal noise solder for all connections. Finally, we advise wrapping the entire pre-amplifier assembly in styrofoam to provide a nearly isothermal environment.

The output of the pre-amplifier feeds a unity-gain inverting amplifier that sums in the system "zero" adjustment as well as externally generated "tare" signals. Note that R11 serves to trim the overall gain of both A2 and A3 to 166.667. This scales a 600-nV LSB (0.01 lb) to equal 100 µV at A3's output, so that 300 lbs. F.S. equals 3.0000V to the DPM.

For fast settling, use a 2-step filter

For the signal from A3 to be usable, filtering is absolutely necessary. The instrument is so sensitive that any body motion or floor vibration will mask true readings. Experimentation revealed that a simple 0.2-Hz R-C low-pass filter would provide adequate averaging. Unfortunately, this filter also would require almost 100 sec to settle out to the point where it no longer affected the system's accuracy. Clearly this time delay was unacceptable.

We considered using active and/or high-order filters to address this problem, but discarded them as being unnecessarily complex. Our final solution was to modify the basic R-C low-pass filter to incorporate a controllable time constant.

With no weight on the scale, the output of A3 is zero, so no drop exists across R21 and A5's output is also zero. Normally the output of comparator A4 under these conditions would be indeterminate. However, the unorthodox use of the offset null adjustment (pin 6 connected to +15V through 2k) effectively "bends up" A4's front end by introducing approximately 15 mV of offset. Therefore the amplifier's output saturates negative under no-weight conditions.

Placing a weight on the scale causes the output of A3 to rise much faster than the voltage across C1, so A4's output goes positive, closing CMOS switch S2. C1 now charges quickly toward A3's output voltage. When C1's voltage rises to within 15 mV of A3's output, A4 switches its output negative and shuts off S2. C1 now charges to its final value through R21. Amplifier A5, a low-drift FET op amp, buffers C, and drives the DPM.

At the completion of the weighing process, removal of the weight causes A3's output to drop to zero. In turn, D3, a low forward-drop germanium diode, becomes forward-biased, providing a low-impedance path that rapidly discharges C1. This ensures that the scale is quickly ready for the next measurement. ÿ

References

1. *Williams, J., "Fine-tune voltage reference zeners,"* *Electronics, May 16, 1974, pg. 134.*
2. *Sheingold, D.H., Editor, "Analog-Digital Conversion Handbook," Analog Devices, Inc., Norwood,* MA, *pg. 11-42.*
3. *Little, W., "Private Communication," Charles Stark Draper F.B.M. Standards Laboratory.*
4. *Williams, J., "Prevent low-level amplifier problems," Electronic Design, February 15, 1975, pg. 62.*
5. *Brokaw, A. Paul, "Designing sensitive circuits? Don't take grounds for granted!" EDN, October 5, 1975, pg. 44-50.*
6. *Julie, L., "Specifying and Selecting Precision Resistors," Bulletin B-2, Julie Research Labs, New York, NY.*
7. *Tobey, G.E., Graeme, J.G. and Huelsman, L. P., Editors, "Operational Amplifiers, Design and Applications," McGraw-Hill Book Co., New York, NY.*
8. *Williams, J., "Comparator IC forms 10-bit A-D converter," Electronics, April 17, 1975, pg. 146.*

Author's biography

Jim Williams, a senor engineer in the instrumentation laboratory of Department of Nutrition and Food Science, designs and develops experimental biomedical instrumentation. He received his BS in psychology at Wayne State Univ., holds three patents, and is a consultant to industry in several companies including Consultek, a Wellesley, MA consulting firm. Jim lists among his many hobbies sculpture, travel, art, skiing, tennis and collecting antique scientific instruments.

Article evaluation: Please circle one on R.S. card. Read Some—No. 307 Read Most—No. 308