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Autoranging amplifier expands computer's A/D sensitivity by two decades

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This device accepts an analog signal from 0 to +14 V, automatically changes gain to condition the analog output to the limits of a ±1 V A/D converter, and transmits the gain mode as two digital bits. A computer with a 10-bit A/D converter and two sense lines uses this device to obtain the dynamic range of a 16-bit A/D converter. The relatively simple principle of the circuit may be of interest to expand the voltage sensitivity range of other analog devices for slowly changing signals.

Current technology offers ample opportunities for measurement to high degrees of precision at corresponding cost; but in the behavioral sciences, measurements are often made over a wide range of conditions with less demand on accuracy. For example, to discern 1% changes at both 10 V and 10 mV, a device with an accuracy of .1 mV at 10 V (.0001%) is not necessary. On the other hand, the 1 part in 512_{10} acurracy of the 10-bit A/D converters commonly used on 12-bit minicomputers may often be insufficient to track psychophysical data over a wide stimulus range. While logarithmic transformation can handle analog voltages from observer response settings under some conditions, the inevitable loss of resolution at the high end may be a problem, particularly if the psychometric data do not correspond to a power function. To solve such problems, we built an autoranging amplifier which transmits 0 to +14 V signal levels at either unity, X10, or X.1 gain, depending on the signal level. The gain is indicated to the computer by a 2-bit code on two sense lines, and to the experimenter by three indicator lights. The autoranger is made with 5 general-purpose 741 operational amplifiers, 4 field effect transistors, 4 small signal diodes, 3 light-emitting diodes, 30 5% ¼-W resistors, and 9 miniature potentiometers, for a total cost of less than $30, including a circuit board and a case.

OPERATION

Operational Amplifier 1 (OA_1) is a voltage follower which provides input buffering of the signal voltage. Its output is fed to the programmable gain amplifier, OA_2, and two voltage comparators OA_3 and OA_4.

OA_2 inverts the input signal and operates in one of three possible gain modes, depending on the signal level: for low-level signals, it operates at a nominal (see below) gain of X10 through the R_1 feedback loop; when the signal level exceeds .19 or 1.9 V, the gain is reduced to X1 or X.1, respectively, by opening of the field effect transistor gates (JFETs) in feedback loops R_2 or R_3. (Since the JFET source terminal is at the summing point of OA_2, which remains at virtual ground as referenced at the noninverting input of OA_2, gate-source voltage is at zero during the JFET on state, thus obviating need for bootstrapping the JFET gate.)

OA_3 and OA_4 serve as summing mode voltage comparators. Their outputs drive the JFET gates in the feedback loops of OA_2, drive JFET gates on the computer sense lines, and drive the three indicator light-emitting diodes. OA_3 outputs +15 V unless the input signal exceeds its comparison voltage of 1.9 V (adjustable by P_5), whence it outputs −15 V. The +15 V output state closes the JFET gate in Feedback Loop R_3 of OA_2. The −15 V state opens that JFET gate as Diode D_1 and Resistor R_4 clamp the gate voltage at zero. OA_3 controls the JFET gate on Sense Line B in the same manner to transmit or sink a positive logic output. (For negative logic, D_2 should be reversed; and the roles of Sense Lines B and A become reversed.) Light-emitting Diode L_1 connected to OA_3 indicates when OA_2 is operating at X.1 gain. OA_4 operates similarly for X1 gain, having a .19 V comparison threshold. When OA_4 is outputting +15 V, L_3 is turned on, indicating OA_2 is at X10 gain.

OA_5 reinverts the signal to its original polarity, permits adding an offset voltage, and produces a final corrective gain for the signal output. Adding an offset voltage permits single-polarity signals to maximally utilize bipolar A/D converters. OA_5 operates at a gain of X.2 in order that the Feedback Resistance R_3 can be made large with respect to the JFET on-resistance to avoid nonlinearities while R_1, larger by a factor of 100, must remain within practical limits. (A sixth operational amplifier in the voltage follower configuration of OA_1 may be added at the output of OA_5 to provide output buffering if necessary.)

ADJUSTMENTS

Adjustments of the three gain modes, the two gain breakpoints, hysteresis of the breakpoints, and offset

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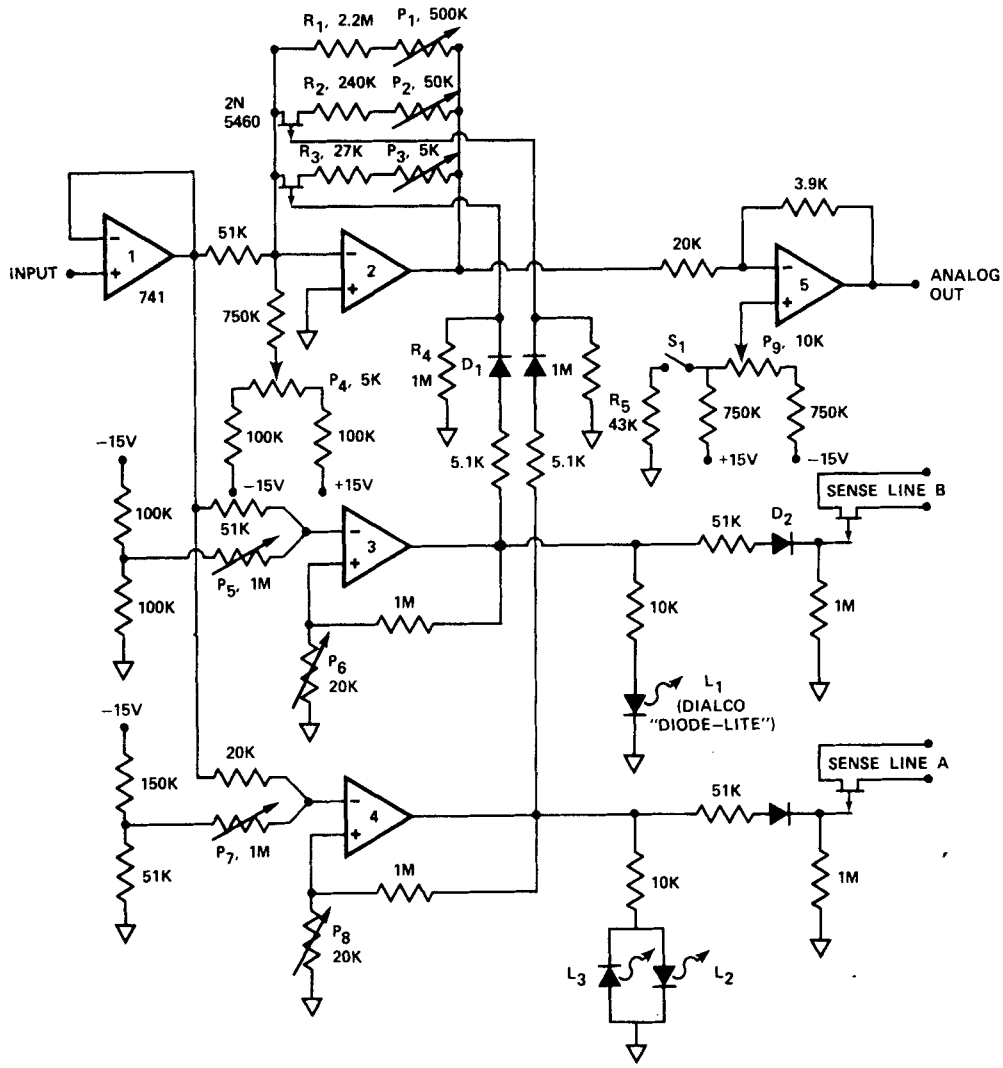

Figure 1. Circuit schematic of the autoranging amplifier.

is accomplished with nine 20-turn miniature potentiometers. Mounting all the potentiometers along the front edge of the circuit card facilitates trimming through labeled holes in the case.

P_1, P_2, and P_3 adjust the X10, X1, and X.1 gain modes of OA_2. For some users, it may be more convenient to use binary gain modes such as X8, X1, and X1/8, also adjusting P_5 and P_7 accordingly.

P_4 provides current offset to the input of OA_2 to compensate for voltage offsets resulting from any previous signal processing and from the non-negligible gate to source current of the JFET gates in the feedback loop (Graeme, 1973; Todd, 1968).

P_5 and P_7 control the approximate (see below) reference voltage at which comparators OA_3 and OA_4 alter the gain modes of OA_2. The required reference voltages are determined by the existing range of the A/D converter, the desired expansion, and whether output offset is used.

To eliminate chatter when the signal is near the comparator's switching thresholds, hysteresis is provided through positive feedback. P_6 and P_8 control the magnitude of hysteresis, which should be set greater than the magnitude of signal noise (Tobey, Graeme, & Huelsman, 1971). (For a threshold voltage of 1.9 V, a .1 V hysteresis prevents imposed transients of less than .1 V from switching the comparator; an increasing signal switches the comparator at 1.95 V, while a decreasing signal switches it at 1.85 V). If desired, P_6 and P_8 may be replaced with fixed resistors (a 10K resistor provides approximately .15 V hysteresis).

In addition to providing adjustment of output offset voltage, P_9 is used in the zero offset mode to correct for any unwanted offset voltage introduced by the circuit. Zero offset is useful in calibrating the gain modes of the circuit even when it is to be used with output offset. Switch S_1 selects R_5 for an output of −1.0 V, P_9 trims offset to this value after the gain is calibrated.

For other offsets, select an R_5 value to minimize the adjustment of P_9 from the zero offset state.

CALIBRATION

Since certain adjustments interact, calibration is most easily achieved by the following iterative sequence. If a variable voltage reference and a digital voltmeter or two matched meters are available, it should only take about 10 min. The stated calibration values are for using the circuit with 0 to +10 V signal levels at decade gains to a ±1 V A/D converter. To calibrate:

(1) Throw the output offset switch to the zero position.

(2) Set the comparator reference voltages: (a) Adjust P_5 so that L_1 comes on when the input signal rises to about 1.9 V. (b) Adjust P_6 so that L_1 goes off when the input falls to about 1.8 V. (c) Adjust P_7 so that L_2 comes on when the input rises to about .19 V. (d) Adjust P_8 so the L_2 goes off when the input falls to about .18 V.

(3) Set the X.1 gain: (a) Set the input signal to 9.0 V. (b) Adjust P_3 for a .9 V output signal. (c) Set the input to 2.0 V. (d) Adjust P_9 for a .2 V output. (e) Repeat steps a-d.

(4) Set the X10 gain: (a) Set input to .175 V. (b) Adjust P_1 for a 1.75 V output. (c) Set the input to .020 V. (d) Adjust P_4 for a .2 V output. (e) Repeat steps a-d.

(5) Set the X1.0 gain: (a) Set the input to 1.75 V. (b) Adjust P_2 for a 1.75 V output.

(6) Repeat Steps 3, 4, and 5.

(7) Set the output offset: (a) Throw the offset switch to the −1.0 V position. (b) Adjust P_9 for a −.100 V output.

(8) Repeat Step 2, though normally no adjustment will be necessary.

USE

The circuit should be calibrated, allowed to "burn in" by being left on for a week, and then calibrated again. Our autoranger has operated flawlessly and continuously for over 1 year. The only time it required recalibration was after we had changed power supplies. A good quality ±15 V ⩾ 50 mA supply is essential for stable operation. The modular power supplies offered by several manufacturers of operational amplifiers such as Analog Devices, Burr-Brown, etc., or the ±15 V supply in most computers is adequate.

Table 1
Summary of Autoranger Functions With −1 V Offset and Required Calculation

Input Voltage	Autoranger Gain	Indicator Lights L1	L2	L3	Output Voltage	Sense Lines A	B	Computer Should
0 to .2	X10	Off	Off	On	−1 to 1	+	+	+1; ÷10
.2 to 2	X1	Off	On	Off	−.8 to 1	0	+	+1
2 to 14	X.1	On	On	Off	−.8 to +.4	0	0	+1; × 10

Table 1 summarizes the function of the autoranger and the corrective calculation which the computer should perform to obtain the original signal value. To be certain the signal has not changed across a gain mode between sampling the A/D and testing the sense lines, it may be advisable to test sense line status before and after an A/D sample and resample if the status has changed.

Our device was designed for and has been used to monitor voltage levels changing at less than 1 Hz. With inexpensive 741 amplifiers, its inherent frequency response extends accurately to a few kilohertz. When the device is used with a computer, however, the maximal useful frequency will generally be much less than 1 kHz due to the rate at which sense lines and A/D converter can be interpreted together with allowance for a repetition of readings when the gain changes.

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