As we have noted in the chapter on Data Acquisition, and elsewhere, it is often necessary to retrieve millivolts of analog data from volts of common-mode interference. In some cases, it is also necessary to galvanically isolate the amplifier's input from its output and the power source, either to protect the amplifier from high voltage, to protect the device being measured (viz., a hospital patient) from stray leakage current, or simply to obtain better common-mode rejection.

The instrumentalities for achieving these objectives are called *instrumentation amplifiers*, and they include a special subclass of *isolation amplifiers*. Although amplifiers of this class often contain operational amplifiers, they are distinguished from op amps in being *committed* devices with a definite (set of) output-input relationship(s) and an essentially fixed configuration. They are designed to meet the specific objectives of high CMRR, low noise and drift, moderate bandwidth, and a limited range of gains (usually 1 to 1000, programmable by a single resistor).

Although there are a wide variety of frills and added-cost "extras" in the $250+ range on the market, ranging from digitally-programmed gain to autoranging (primarily for use in low-level-multiplexed systems), simple instrumentation amplifiers are becoming available at such low cost* that they seem destined to encourage the growth of per-channel amplification in instrument applications. For example, as this is written, the AD520 Monolithic

*both from manufacturers, such as Analog Devices, and built in-house using low-cost IC op amps*
Instrumentation Amplifier has just been introduced (Spring, 1972) at an initial price of $12 in 100's.†

Accordingly, this chapter will focus on the properties, specification, and application of simple instrumentation and isolation amplifiers, while recognizing that more-complex devices exist and do have a role (albeit somewhat limited) in A/D conversion systems.

**INSTRUMENTATION AMPLIFIERS**

The instrumentation amplifier is a committed-gain amplifier with internal high-precision feedback networks. Its excellent drift, linearity, and noise-rejection capability make it a natural choice for extracting and amplifying low-level signals in the presence of high common-mode-noise voltages.

These devices are commonly used as transducer amplifiers for thermocouples, strain-gage bridges, current shunts, and biological probes. As preamplifiers, they are capable of extracting small differential signals superimposed on large common-mode voltages. Wideband designs are also available for data-acquisition systems.

**Design**

Figure 1 shows a number of commonly-used circuit-design approaches. All require that only one resistor be adjusted to control the gain. Most commercially-available types have feedback sense and reference terminals for lead compensation, current-output sensing, and adjustable offset reference voltage. A few uses of these terminals are discussed under Applications.

The simple subtractor (1a), uses only one operational amplifier. It has the disadvantage of poor source unbalance characteristics, because of its low input impedance, for normal values of $R_1$ (CMR

†The AD520J, in a 14-pin hermetically-sealed DIL package (small size, environmentally protected), is not an op amp but a true-differential instrumentation amplifier, with $2 \times 10^5 \Omega$ $Z_{in}$, 90dB minimum CMRR at gain of 100 (0-100Hz, 1kΩ source unbalance), 50kHz full-power bandwidth, single-resistor gain adjustment.
Instrumentation Amplifiers

depends critically on resistance matching). If a FET-input amplifier is used with very large values of resistance, noise and bandwidth characteristics will suffer.

![Diagram](image)

*a. Simple Subtractor*

![Diagram](image)

*b. Buffered Subtractor*

![Diagram](image)

*c. Buffered Subtractor With Gain*

![Diagram](image)

*d. High-Input-Impedance Image of Subtractor*

![Diagram](image)

*e. Current-Feedback Type (AD520)*

*Figure 1. Instrumentation-Amplifier Designs*
The buffered subtractor (1b) gets around the problem, at the cost of two additional op amps. Bipolar types are ordinarily adequate, but FET-input types would be used with signal inputs having high source impedance. Matched input-followers will provide low drift and keep high CMRR, if the main amplifier’s drift is low and the resistances are well-matched.

Reliance on resistance match for CMR is reduced, and bandwidth is improved in high-gain applications by using the buffered subtractor-with-gain (1c). The first stage has unity gain for the common-mode signal, thus increasing overall CMR by the differential gain of the first stage. (Separate followers-with-gain would not be capable of this improvement, because they would amplify differential and common-mode signals equally.) Matched amplifiers will help CMR and drift-stability.

The two-amplifier circuit (1d) has high input impedance, saves the cost of an amplifier, but it also increases dependence on resistance match for high CMR.

Unlike all of the other schemes, the differential current-feedback circuit (1e) has high-impedance sense and reference input terminals, allowing them to play a more important part in a wider range of applications. (It will be noted, in all of the other circuits, that resistance in series with either of those terminals, unless matched at the other, will cause common-mode errors.) The scheme also has a simple relationship between the gain and the resistance used to adjust it. The ability to match transistors and current-sources, and the close spacing on the monolithic chip, tend to make this approach feasible at low cost.

Applications

In data systems, instrumentation amplifiers are used primarily for pre-amplification and for adapting the input signal range to the usually-fixed range of the A/D converter. Because they ideally respond only to the difference between two voltages, they can be used in both balanced and unbalanced systems. Balanced implies that the output of the signal source appears on two lines, both
having essentially equal source resistances and output voltages in relation to either ground or the local common-mode level, e.g., bridge outputs (Figure 2a); unbalanced means that inherent symmetry is not a property of the configuration — in fact, a major application of instrumentation amplifiers is in eliminating the effects of ground-potential differences in non-ideal single-ended systems (Figure 2b).

![Diagram of Balanced and Unbalanced Inputs](image)

\[ CMV = E_{CM} + \frac{3}{8} (E_1 + E_2) \quad E_0 = G (E_1 - E_2) \]

*a. Balanced Input*  
*b. Unbalanced Input*

**Figure 2. Balanced and Unbalanced Inputs**

Because instrumentation amplifiers can measure voltage differences at any level within their specified range, they are useful in current measurement. Typically, they will measure and amplify the voltage appearing across a low-resistance shunt, often in the "high" line (Figure 3).

![Diagram of Current Measurement](image)

\[ E_0 = G I_{LOAD} R_S \]

**Figure 3. Current Measurement**
If the reference terminal is available, it may be used for biasing the location of the pen in chart-recorder applications; it may be used to bias out dc normal-mode voltages, e.g., contact potentials; or it may be used to bias relay or comparator trip points. The reference terminal may be driven by the output of an operational amplifier with either constant or variable voltage; in addition, if the amplifier has high input impedance at the reference terminal, it may be driven passively by a voltage divider or a potentiometer.

In normal applications, the sense and reference terminals are connected to the specific points at which the output is to be accurately maintained; the circuit will then ignore voltage drops in the output signal or ground lines.

The sense terminal is especially useful in circuits employing current-booster followers, since the booster may then be included within the feedback loop, and its offsets, drifts, and gain errors nullified (Figure 4). The sense and reference terminals, if high enough in impedance to avoid significant loading, are also useful for driving current to either floating or grounded loads. (In the circuit of Figure 5, for floating load, the reference is grounded, for grounded load, the sense terminal is connected to the output.)

For circuits employing the sense and reference terminals in other than “straight” differential amplification, it is essential to consider the possibility of and, if necessary, to take proper precautions to avoid dynamic instabilities: overshoots, ringing, or oscillation.
Specifications

The table on the following page indicates specifications for typical instrumentation amplifiers. In many respects they appear similar to those for operational amplifiers. Differences include:

Gain An open-loop gain specification is unnecessary; However, gain nonlinearity and instability are specified.

Offset Offset drift specifications are given, referred to the input, at the two extremes, 1 and 1000. To determine the corresponding specification at any arbitrary value of gain, referred to the output, the following formula is used, to an excellent approximation:

\[ \text{Drift}_{|G} \approx \frac{1000 \cdot \text{Drift}(\text{rti})|_{1000} - \text{Drift}|_{1}}{1000} \cdot G + \text{Drift}|_{1} \]

Other specifications are listed at specific values of gain. Intermediate values may usually be interpolated. Unless noted otherwise, specifications not associated with a gain value are essentially independent of gain.

An Example

Since errors from all sources, though not individually significant, can add up to a substantial amount, it is important to perform an
### Table 1. Capsule Specifications – Instrumentation Amplifiers

<table>
<thead>
<tr>
<th>Model</th>
<th>High CMR, Low Drift 0.005% Linearity 605</th>
<th>Wideband, Low Drift 25µs Settling to 0.01% 604</th>
<th>Economy Monolithic ADS20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>J K L</td>
<td>J K L</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>1 to 1000</td>
<td>1 to 1000</td>
<td>1 to 1000</td>
</tr>
<tr>
<td>Formula</td>
<td>G = 1 + (200kΩ/Rg)</td>
<td>G = (3 x 10^7)/Rg</td>
<td>G = 10^7/Rg</td>
</tr>
<tr>
<td>Deviation From Formula, max</td>
<td>±0.1%</td>
<td>±0.1%</td>
<td>±0.05%</td>
</tr>
<tr>
<td>vs. Temp, max</td>
<td>±15ppm/°C</td>
<td>±15ppm/°C (±1ppm/°C typ)</td>
<td></td>
</tr>
<tr>
<td>vs. Time</td>
<td>10,000µA/°C</td>
<td>10,000µA/°C</td>
<td></td>
</tr>
<tr>
<td>Nonlinearity, max</td>
<td>±0.005%</td>
<td>±0.01% (0.005% typ)</td>
<td>±0.02% typ</td>
</tr>
<tr>
<td>Rated Output, min</td>
<td>±10V@10mA</td>
<td>±10V@10mA</td>
<td>±10V@5mA</td>
</tr>
<tr>
<td>Frequency Response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unity Gain, Small Signal, (-3dB)</td>
<td>G = 1</td>
<td>G = 1000</td>
<td>G = 1000</td>
</tr>
<tr>
<td>G = 1000</td>
<td>300kHz</td>
<td>50kHz</td>
<td>300kHz</td>
</tr>
<tr>
<td>Full Power Response, min</td>
<td>1.5kHz typ</td>
<td>5kHz typ</td>
<td>5kHz</td>
</tr>
<tr>
<td>Sew Rate</td>
<td>0.1V/µs</td>
<td>5V/µs</td>
<td>60kHz typ</td>
</tr>
<tr>
<td>Unity Gain Settling Time to 0.1%</td>
<td>13µs (0.01%, G = 1)</td>
<td>25µs (to 0.1%)</td>
<td></td>
</tr>
<tr>
<td>Offsets Referred to Input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Offset Voltage</td>
<td>Adjust to 0</td>
<td>Adjust to 0</td>
<td>Adjust to 0</td>
</tr>
<tr>
<td>vs. Temp, max G = 1</td>
<td>±150µV/°C</td>
<td>±50µV/°C</td>
<td>±1.0µV/°C typ</td>
</tr>
<tr>
<td>G = 1000</td>
<td>±10µV/°C</td>
<td>±5µV/°C</td>
<td>±0.2µV/°C typ</td>
</tr>
<tr>
<td>vs. Supply G = 1</td>
<td>±20µV/°C</td>
<td>±10µV/°C</td>
<td>±0.2µV/°C max</td>
</tr>
<tr>
<td>G = 1000</td>
<td>±4µV/°C</td>
<td>±2µV/°C</td>
<td>±0.2µV/°C max</td>
</tr>
<tr>
<td>Input Bias Current, G = 1</td>
<td>0, ±100nA</td>
<td>0, ±100nA</td>
<td>±100nA</td>
</tr>
<tr>
<td>Input Bias Current</td>
<td>0, ±100nA max</td>
<td>0, ±100nA max</td>
<td>±1mA/°C</td>
</tr>
<tr>
<td>Input Bias Current, G = 1</td>
<td>10µA/°C max</td>
<td>±1mA/°C max</td>
<td>±25nA</td>
</tr>
<tr>
<td>Input: Impedance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differential Common Mode</td>
<td>10GΩ</td>
<td>(10Ω/ΩG)/10µF</td>
<td></td>
</tr>
<tr>
<td>Noise Referred to Input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage Noise, 0.01 to 1Hz, p-p</td>
<td>15µV/0.1 to 10Hz</td>
<td>100µV/0.1 to 10Hz</td>
<td>10mV (0.1 to 10Hz)</td>
</tr>
<tr>
<td>Voltage Noise, 10Hz to 10kHz, rms</td>
<td>1.5µV/0.1 to 10Hz</td>
<td>1µV (0.1 to 10Hz)</td>
<td></td>
</tr>
<tr>
<td>Input Voltage Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Differential Input</td>
<td>±10V</td>
<td>±10V</td>
<td>±12V</td>
</tr>
<tr>
<td>Max Differential Input</td>
<td>±20V</td>
<td>±10V</td>
<td>±12V</td>
</tr>
<tr>
<td>Max Common Mode</td>
<td>±10V</td>
<td>±10V</td>
<td>±10V</td>
</tr>
<tr>
<td>CMR @ 10V, DC to 60Hz (±1ΩImbalance)</td>
<td>70Ω</td>
<td>60dB</td>
<td>70dB</td>
</tr>
<tr>
<td>G = 1000</td>
<td>94dB (120Ω typ/DC to 5Hz²)</td>
<td>120dB (200Ω/DC to 5Hz²)</td>
<td></td>
</tr>
<tr>
<td>Reference Terminal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>10GΩ</td>
<td>5 x 10Ω</td>
<td>10Ω</td>
</tr>
<tr>
<td>Output Offset Range</td>
<td>±10V</td>
<td>±10V</td>
<td>±10V</td>
</tr>
<tr>
<td>Gain Offset Range</td>
<td>±1000</td>
<td>±1000</td>
<td>±1000</td>
</tr>
<tr>
<td>Bias Current</td>
<td>±200nA</td>
<td>±200nA</td>
<td>±4µA</td>
</tr>
<tr>
<td>Power Supply Range, ±5VDC (VDC)</td>
<td>(±12 to 18V)</td>
<td>(±12 to 18V)</td>
<td>(±12 to 18V)</td>
</tr>
<tr>
<td>Operating, Rated Specifications (VDC)</td>
<td>±15V@7mA</td>
<td>±15V@7mA</td>
<td>±15V@4mA</td>
</tr>
<tr>
<td>Temperature Range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating, Rated Specifications</td>
<td>0 to +70°C</td>
<td>0 to +70°C</td>
<td></td>
</tr>
<tr>
<td>Package Outline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C ±5</td>
<td>C ±5</td>
<td>C ±5</td>
<td></td>
</tr>
<tr>
<td>Case Dimensions</td>
<td>1.5” x 1.5” x 0.4”</td>
<td>2” x 3” x 0.4”</td>
<td></td>
</tr>
</tbody>
</table>

(Specifications typical @ +25°C and ±5VDC power supply unless otherwise noted.)

1) ±0.1% amplitude accuracy to 1kHz min.
2) Constant with gains from 1VDC to 1000VDC.
3) Minimum CMR with 1Ω imbalance.
Instrumentation Amplifiers

error-budget analysis to find (and if possible reduce) the most significant terms. An example of a circuit application is given in Figure 6.

![Instrumentation Amplifier Equivalent Model](image)

*Figure 6. Instrumentation Amplifier-Equivalent Model When Used as a Bridge Amplifier*

These are the given operating conditions and hypothetical amplifier specifications to be used in the example:

**Operating Conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e_{IN} )</td>
<td>±5mV</td>
</tr>
<tr>
<td>(e_{OUT} )</td>
<td>±5V</td>
</tr>
<tr>
<td>(E_{CM} )</td>
<td>±5V</td>
</tr>
<tr>
<td>(\Delta T )</td>
<td>±20°C</td>
</tr>
<tr>
<td>(T_A )</td>
<td>+25°C (ambient)</td>
</tr>
<tr>
<td>(R_L )</td>
<td>10kΩ</td>
</tr>
<tr>
<td>(R_{BRIDGE} )</td>
<td>500Ω</td>
</tr>
</tbody>
</table>

**Amplifier Specifications**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e_{OS} ) Drift</td>
<td>11mV/°C (G = 1000) at output</td>
</tr>
<tr>
<td>Gain Drift</td>
<td>±0.01% (G = 1000)</td>
</tr>
<tr>
<td>(I_B )</td>
<td>20nA</td>
</tr>
<tr>
<td>(Z_d )</td>
<td>300MΩ</td>
</tr>
<tr>
<td>(Z_{CM} )</td>
<td>1000MΩ</td>
</tr>
<tr>
<td>(CMRR ) (A_D/A_CM)</td>
<td>10^5 (100dB CMR)</td>
</tr>
<tr>
<td>Gain</td>
<td>1000</td>
</tr>
<tr>
<td>Nonlinearity</td>
<td>±0.01%</td>
</tr>
<tr>
<td>(R_o )</td>
<td>10Ω</td>
</tr>
</tbody>
</table>
The error budget is computed as follows:

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Calculation</th>
<th>Value</th>
<th>%F.S.(5V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain Drift (+5° to 45°C)</td>
<td>0.01%/°C × ΔT × E_{OUT}</td>
<td>± 10mV</td>
<td>0.2%</td>
</tr>
<tr>
<td>Offset Drift (+5° to 45°C)</td>
<td>11mV/°C × ΔT</td>
<td>±220mV</td>
<td>4.4%</td>
</tr>
<tr>
<td>Total Drift Error</td>
<td></td>
<td>230mV</td>
<td>4.6%</td>
</tr>
<tr>
<td>Linearity Error</td>
<td>0.01% @ 10V (independent of output)</td>
<td>± 10mV</td>
<td>0.2%</td>
</tr>
<tr>
<td>Common-Mode Error</td>
<td>E_{CM} × A_D/CMRR (adjust to zero)</td>
<td>± 50mV</td>
<td>1.0%</td>
</tr>
<tr>
<td>Offset Error</td>
<td>negligible</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Loading Error</td>
<td>R_{BRIDGE}/R_D</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Output Loading Error</td>
<td>(R_o/R_L) × e_{OUT}</td>
<td>5mV</td>
<td>0.1%</td>
</tr>
<tr>
<td>Total Error at 25°C</td>
<td></td>
<td>± 65mV</td>
<td>1.3%</td>
</tr>
<tr>
<td>Total Error (+5°C to +45°C)</td>
<td></td>
<td>±295mV</td>
<td>5.9%</td>
</tr>
</tbody>
</table>

For the given example, the error is 5.9%. Its largest components are offset drift (4.4%) and CME (1%).

If an amplifier having output drift of 2mV/°C at G = 1000 were used, the offset drift error would be reduced to ±40mV (0.8%). If the common-mode voltage is relatively constant (this is the case for a bridge circuit), then a simple offset adjustment can reduce the common-mode error virtually to zero, a 50mV, or 1% improvement. The total error will then be approximately ±55mV (1.1%).

This error-budget analysis demonstrates the importance of analyzing the problem and applying major error-reduction effort to the most-important sources of error.

**ISOLATION AMPLIFIERS**

There are certain classes of application conditions that require actual galvanic isolation of the amplifier’s input circuit from its output and the power supply.
1. Very-high common-mode voltage, well beyond 500V, between input and output.
2. Safety requirements for medical-electronics equipment
3. Two-wire input, with no ground return for bias current
4. High CMRR required, with appreciable source unbalance

The two most promising approaches to obtaining isolation at the present time appear to be transformer and optical coupling. While optical coupling appears to be quite effective at isolation, since it uses a portion of the electromagnetic spectrum that completely abandons voltage, current, charge, and magnetic flux for energy transmission, the components and techniques applicable to low-cost high-performance linear circuits are still relatively primitive (but developing rapidly).

Recognizing these realities, as well as the present urgent needs, Analog Devices has developed, for sale at low cost, a series of isolation amplifiers, employing transformer coupling, that offers total galvanic isolation, low capacitance (<10pF between input and output ground circuits), high CMR (115dB at 60Hz), and high common-mode voltage ratings (to 5kV). Capable of transmitting millivolt signals in the presence of up to 1000 volts common-mode, with unity gain, or with adjustable gain, these devices (the

![Block Diagram of Unity Gain Isolation Amplifiers](image-url)

*Figure 7. Block Diagram of Unity Gain Isolation Amplifiers*
272, 273, 274 class) are ideal for medical applications (where an ECG waveform is the input signal to the data system), where it is mandatory to isolate hospital patients from potentially-lethal ground-fault currents, and for industrial applications, to interrupt ground loops between transducers and output-conditioning circuits.

Like instrumentation amplifiers, amplifiers of this type have committed gain circuits with internal feedback networks. All models operate from dc to 2kHz. They are designed in two parts: an isolated front-end amplifier section, and a grounded output section (Figure 7). The front end includes the fixed-gain op amp, a modulator, and a dc regulator circuit, all enclosed in a floating guard-shield. The output section contains a demodulator, filter, and power-supply oscillator circuit, operating from a single +15Vdc supply. Operating power is transformer-coupled into the shielded input circuits and capacitively or magnetically coupled to the output demodulator circuit.

A typical connection in a medical-electronics data-acquisition system front end is shown in Figure 8.