EET 438a
Automatic Control Systems Technology
Laboratory 1
Analog Sensor Signal Conditioning

Objectives: Use analog OP AMP circuits to scale the output of a sensor to signal levels commonly found in practical control systems. Use OP AMP analog circuits to combine several simulated sensor inputs according to a predefined input signal formula. Produce an error signal using an OP AMP differential amplifier.

Theoretical Background

Sensors used in control systems may produce outputs that are not compatible with the other control elements in the automatic control system. The sensor many not even produce a usable electrical output. The signal level could be so low that the electrical output may be masked by the electrical noise in the environment before it reaches the next stage in the system. Other types of sensing elements, such as thermistors, may produce non-linear outputs to the change in the measured quantities. Signal conditioning circuits amplify, linearize, and scale the output of sensors to match the requirements of the next control device in the automatic control system.

It may also be necessary to combine the results of several control inputs into a single analog signal based on some control scheme. A simple combination is the averaging of several widely separated temperature measurements across a large duct that carries a heated gas. The fluid temperature will vary over the dimensions of the duct, so the average of several temperature probe inputs will give a better estimate of the actual gas temperature than a single probe. Common OP AMP circuits that use the inexpensive LM741 can perform all these functions

The figures below show OP AMP circuits that can be used to perform analog signal conditioning.

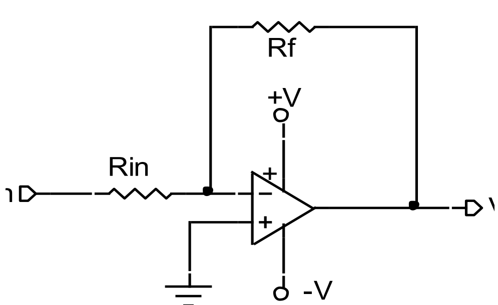


Figure 1. Inverting OP AMP Circuit

Figure 1 shows a simple inverting OP AMP circuit. This circuit can be used to scale the output of sensors. It is direct coupled, so it can amplify dc signals. The output voltage of the circuit is give by Equation 1.

$$V_0 = -\left(\frac{R_f}{R}\right) \cdot V_i \qquad (1)$$

This circuit introduces a sign change in a dc signal level. The values of R_f and R_{in} can be adjusted to give gains greater than or less than 1. Gains less than one are the equivalent of dividing by a value. (e.g. A gain of -0.3333 = dividing by -3.) One of the limits to this circuit is the input impedance of the circuit. The negative feedback produced by coupling the output voltage to the input current reduces the input resistance of the OP AMP to almost zero, so the input resistance of the amplifier is determined by the value of R_{in}. To prevent loading effects, R_{in} should be made as high as possible when dealing with sensors that are voltage sources. A good design rule is to make R_{in} 10 times greater than the resistance of the previous stage.

Figure 2 shows an OP AMP circuit that introduces no sign change in the signal and has a high input impedance. This circuit is a non-inverting OP AMP amplifier. It has the limitation that it cannot produce gain of less than 1. The gain formula for the circuit is given by Equation 2.

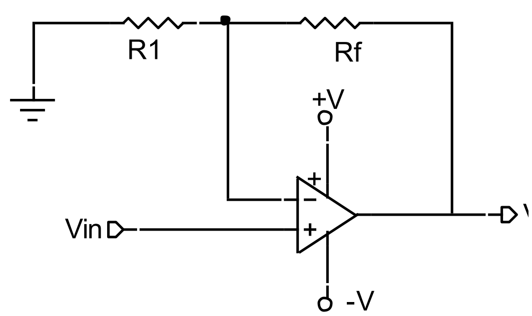


Figure 2. Non-inverting OP AMP amplifier

$$V_o = \left[1 + \frac{R_f}{R_1}\right] V_i \qquad (2)$$

This circuit can be used to buffer the output of a sensor from the load effect of the next stage and to introduce a gain of greater than 1 to the signal. The value of input impedance depends on the type of technology used in the construction of the OP AMP. For the LM741, R_i is between 1 and 2 MΩ. The output impedance R_o is approximately zero. When a gain of 1 is desired but the buffering effect of the high to low impedance is still necessary, the voltage follower circuit in Figure 3 can be used.

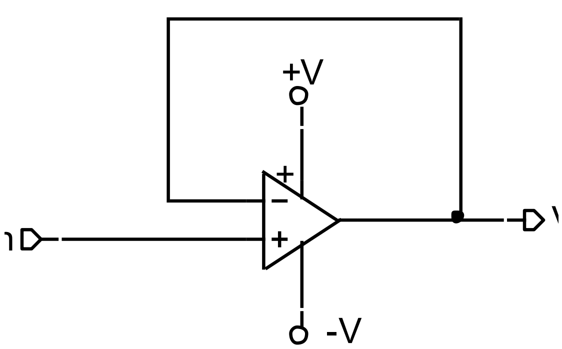


Figure 3. Voltage Follower Circuit.

The voltage follower circuit has a gain of 1, but has very high input impedance. This reduces the loading effects that stages have on each other. This type of circuit is ideal for couple to sensor arrangement such as the thermistor voltage divider circuits covered in the lecture. The high impedance of the amplifier input will draw little current from the divider circuit, so the voltage drops across the resistor will follow the voltage divider formulas more precisely.

When more than one input signal must be combined to produce an output, the inverting summer circuit of Figure 4 can be employed.

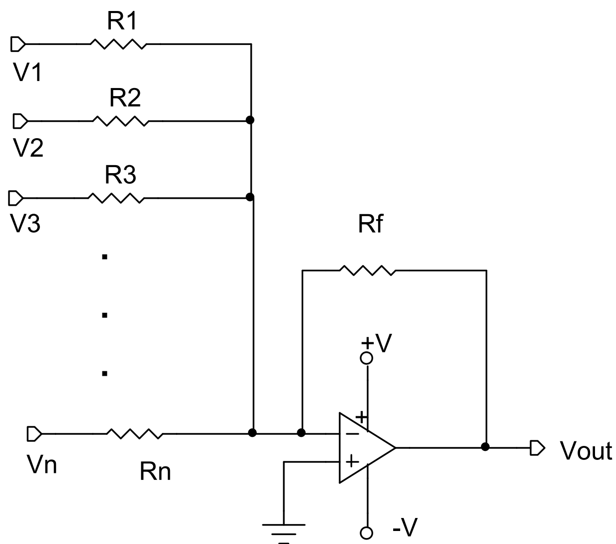


Figure 4. Inverting Summing Amplifier

The gain formula for this OP AMP circuit is given by the following equation.

$$V_o = -R_f \cdot \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + ... + \frac{V_n}{R_n} \right) \tag{3}$$

Just as with the single input inverting amplifier, the voltage sense-current summing feedback reduces the input impedance of the OP AMP to approximately zero This means that the input impedance is determined by the input resistors R_1 to R_n. For any input, i, the resistance looking into the input will be given by

$$R = R_i + R_1 \| R_2 \| R_3 \| \cdots R_{i-1} \| R_{i+1} \| \cdots R_n \tag{4}$$

This is the parallel combination of the remaining resistors added to the input resistance of the i-th input. For equal values of input resistances in an n input summing amplifier, Equation 4 simplifies to

$$R = R_i + \frac{R_i}{n} \tag{5}$$

Where, $R_1 = R_2 = R_3 .... = R_{i-1} = R_i ... R_n$

If all the input resistors on a inverting summing amplifier are equal, then the output will be a scaled average of the input voltages. If the input voltages are the outputs of transducers, then the output voltage will be the analog average of the control variable measurements. When all the input resistors of an n input summing amplifier are equal, the output voltage formula given by Equation 3 reduces to

$$V_o = -\left(\frac{R_f}{R_i}\right)\cdot(V_1 + V_2 + V_3 + ... + V_n) \qquad (6)$$

Where R_i is the value of any of the input resistors and n is the total number of inputs. To create an output that is the exact average of the input values, R_f must be equal to R_i/n. Values of $R_f > R_i/n$ will scale the output voltage up while values of $R_f < R_i/n$ will scale the average value down.

A non-inverting amplifier circuit can also simulate the mathematical operation of averaging. The circuit below shows a three input, non-inverting summing amplifier circuit. When the values of resistors R1-R3 are equal the output is a scaled value of the average of the input voltages, V1-V3. The following equation shows that the scaling factor of the averager is set by the ratio of the resistors R_f and R_4.

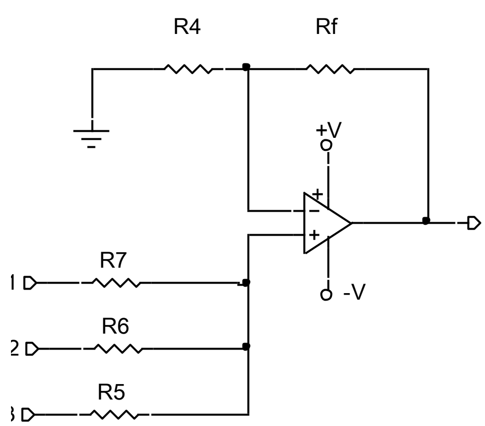


Figure 4. Non-inverting Summing Amplifier.

$$V_0 = \left(1 + \frac{R_f}{R_4}\right)\left(\frac{V_1 + V_2 + V_3}{3}\right) \qquad (7)$$

When,

$$R_1 = R_2 = R_3$$

The inverting summing amplifier can also simulate linear equations. Linear equations are used to scale a transducer's output. This procedure was shown in the lecture for outputs that had minimum values of zero. Linear equations also model proportional control. In this type of control, the control error is modified by a constant bias value and

$$V_o = -\left(\left(\frac{R_f}{R_1}\right)V_1 + \left(\frac{R_f}{R_2}\right)V_2\right)$$

$$y = m \cdot x + b$$

$$\frac{R_f}{R_1} = m$$

$$\left(\frac{R_f}{R_2}\right)V_2 = b$$

a constant gain term. This can be represented by the formulas above. The value of V_2 is a constant in this case and V_1 is the error signal. Changing either R_f or R_1 will increase the gain of the system and it performance. To simplify the design of the scaling circuit make R_f=R_2. The voltage V_2 then takes the value of the constant b.

When simulating linear equations with the summing amplifier, remember that it introduces a sign change in the output. To get positive outputs, the inputs must be negative.

The difference amplifier is another useful circuit for signal conditioning. This circuit is shown in Figure 6. Both inputs are above ground potential in this circuit. This circuit only amplifies the difference in potential (V_2 -V_1) at its inputs. This configuration rejects common mode (signals on both inputs) noise signals that are common on transducer inputs in practical control systems. The output voltage of this circuit is defined by the following equation.

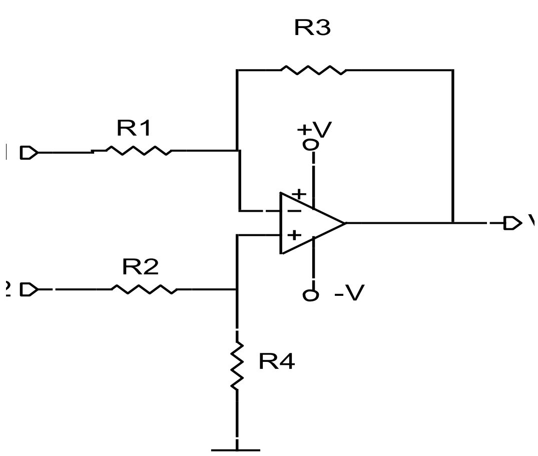


Figure 5. OP AMP Differential Amplifier Circuit.

$$V_o = \frac{R_3}{R_1} \cdot (V_2 - V_1) \tag{7}$$

Where R_1 = R_2 and R_3 = R_4.

Difference amplifiers can produce the error signals necessary for automatic control. The conditioned transducer output is placed on the inverting input (V_1) and the setpoint signal on the non-inverting (V_2) terminal.

This arrangement is shown in Figure 7 below. It is easy to see how the block diagram summing node relates to the differential amplifier circuit.

The difference amplifier can also be used as a subtraction circuit. The sum of the currents that appear on the inverting terminal will be subtracted from the sum of the currents that appear on the non-inverting terminal. Figure 8 show this type of circuit.

If all the resistors have equal value, the output voltage, V_o, is given by:

$$V_o = V_1 + V_2 - V_3 - V_4$$

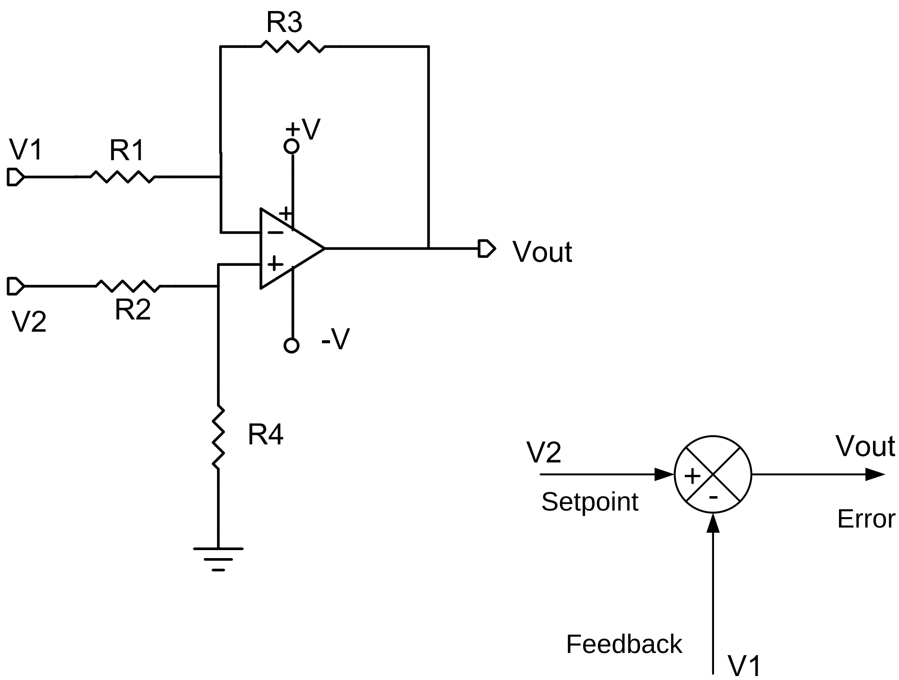


Figure 6. Differential Amplifier Realization of the Block Diagram Summing Block.

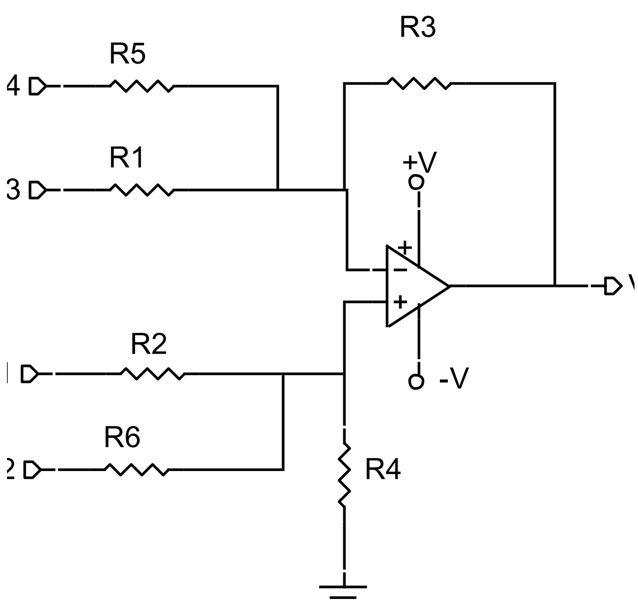
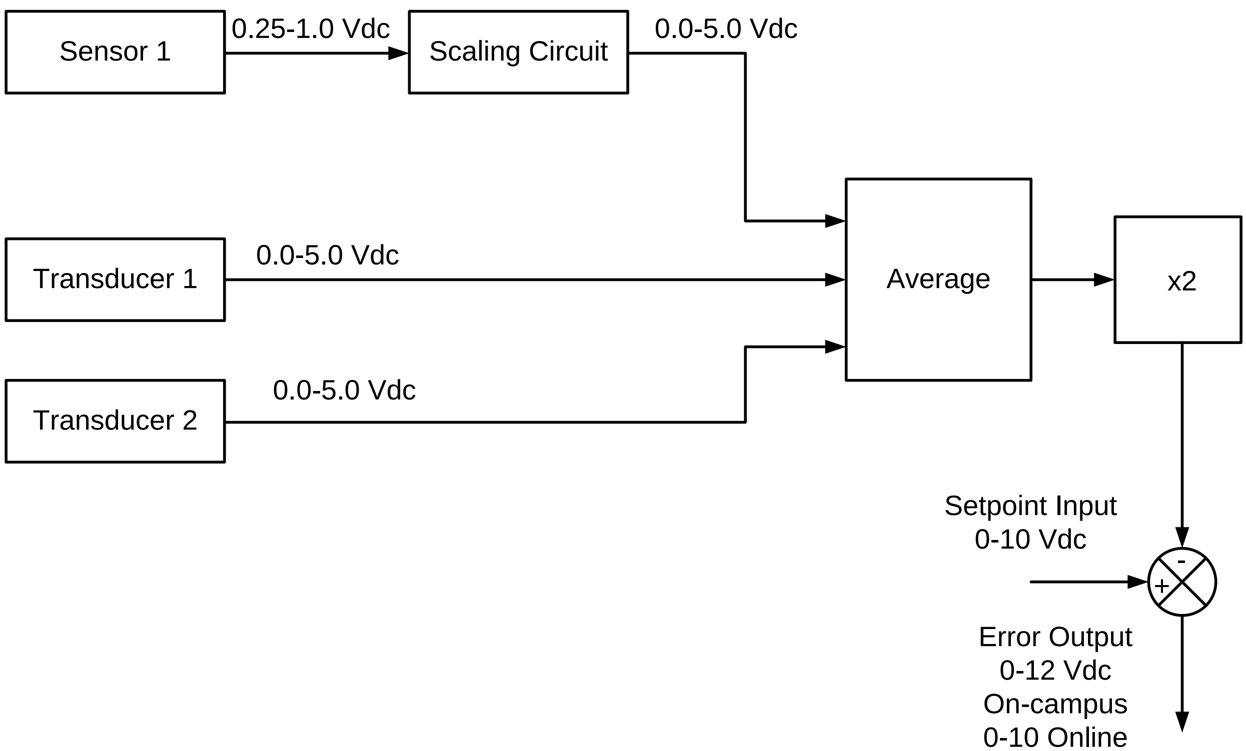


Figure 7. Addition and Subtraction Using the Difference Amplifier.

Design Project

In this lab, the circuits to realize the block diagram shown below will be developed and tested in the lab. Data will be taken to verify the design's operation. The actual data values will be compared to the theoretical values expected and systematic errors discussed.

The block diagram shows a three transducer sensor array that is used to measure an environmental variable used in an automatic control system. The electrical output of two transducers are dc levels that range from 0 - 5 Vdc. The third input is a sensor that must be scaled to the standard input range of 0 -5 Vdc. These three signals must be averaged and the average value multiplied by two. A setpoint value, derived from a potentiometer has a range of 0 - 10 Vdc. It is combined with the scaled average of the three transducers to produce an error signal. The error signal must vary over a range of -12 to +12 Vdc. (on-campus students. For online students 0-10 Vdc)



In the lab, use potentiometers to simulate the outputs of sensor 1 and transducers 1 and 2. The remaining blocks can be constructed from a combination of the basic OP AMP circuits discussed above.

After the circuit is completed, test it and collect performance data. Test the scaling and averaging performance by filling in the data required in Table 1. This test will use ten different combinations of inputs and a fixed setpoint value of 10 Vdc. Measure and record the error signal and the inputs. Use the desired values to compute the theoretical values of the error voltage output. A spreadsheet calculation will make easy work of these repetitive calculations. Test the differencing circuit by setting the sensor and transducer inputs to the values shown in Table 2 and then varying the setpoint value. Table 2A gives a set of 10 setpoint values for use in this test. Measure and record the actual values of setpoint and input voltages in the tables provided. Compute the theoretical values of output using the desired values of both input and setpoint.

Compare the lab measured values to the values expected from the analysis of the circuits. Compute the error between the measured and theoretical values using the following formula and include these in the report.

$$\text{error\%} = \frac{\text{Theoretical} - \text{Actual}}{\text{Theoretical}} \bullet 100\%$$

Where e% = the percentage error

In the lab report, discuss what causes these errors and how they could be reduced.

Tables similar the one shown below can be used to display the data in the final report.

Inputs (Vdc)				Error Voltage		
Sensor 1	Transducer1	Transducer2	Setpoint	actual	Theoretical	% Error
0.25	0.50	3.00	1.00			
0.35	1.00	3.50	2.00			
0.45	1.50	4.00	3.00			
0.55	2.00	3.50	4.00			
0.65	2.50	3.00	5.00			
0.75	3.00	2.50	6.00			
0.85	3.50	2.00	7.00			
1.00	4.00	1.50	8.00			
0.75	3.50	1.00	9.00			
0.50	3.00	0.50	10.00			

Table 1 –Fixed Setpoint Data

Inputs (Volts)						Setpoint (Volts)	Error Voltage (Volts)		% Error
Sensor 1		Transducer 1		Transducer 2					
Desired	Measured	Desired	Measured	Desired	Measured		Measured	Theoretical	
0.25		0.5		0.5		10.0			
0.25		1.0		1.0		10.0			
0.50		1.5		1.5		10.0			
0.60		2.0		2.0		10.0			
0.60		2.5		2.5		10.0			
0.60		3.5		3.5		10.0			
0.70		4.0		4.0		10.0			
0.80		4.0		4.0		10.0			
0.90		4.5		4.5		10.0			
1.0		5.0		5.0		10.0			

Table 2 – Fixed Transducer and Sensor Value Data

Inputs (Volts)					
Sensor 1		Transducer 1		Transducer 2	
Desired	Measured	Desired	Measured	Desired	Measured
0.50		2.5		2.5	

Table 2A-Output Values

Setpoint (Volts)		Error Voltage (Volts)		% Error
Desired	Measured	Measured	Theoretical	
1.00				
2.00				
3.00				
4.00				
5.00				
6.00				
7.00				
8.00				
9.00				
10.00				