AN844

Simplified Thermocouple Interfaces and PICmicro® MCUs

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INTRODUCTION

Thermocouples are the simplest form of temperature sensors. Thermocouples are normally:

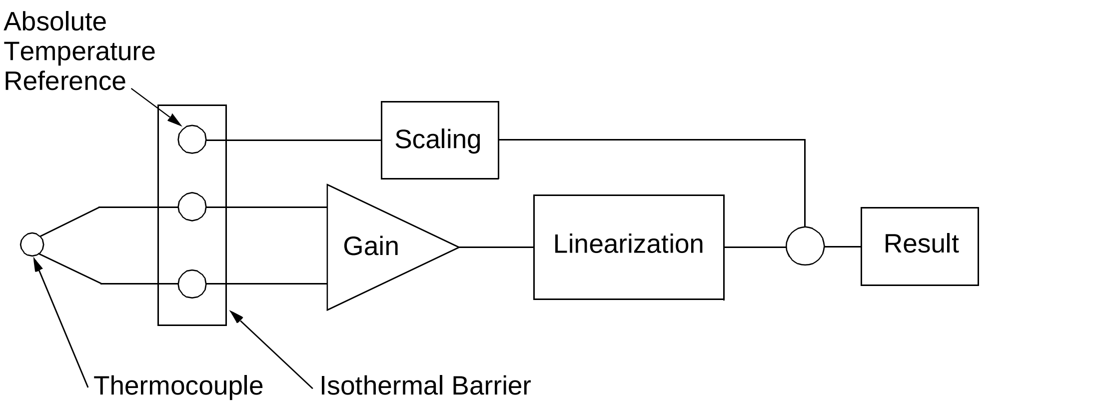
- Very inexpensive
- Easily manufactured
- Effective over a wide range of temperatures

Thermocouples come in many different types to cover nearly every possible temperature application.

In Application Note AN684, thermocouple basics are covered along with some circuits to measure them. This Application Note begins where AN684 leaves off and describes methods of obtaining good accuracy with minimal analog circuitry. Also covered in this Application Note are:

- Different linearization techniques
- Cold junction compensation
- Diagnostics

FIGURE 1: THERMOCOUPLE CIRCUITS



All thermocouple systems share the basic characteristic components shown in Figure 1. The thermocouple must pass through an isothermal barrier so the absolute temperature of the cold junction can be determined. Ideally, the amplifier should be placed as close as possible to this barrier so there is no drop in temperature across the traces that connect the thermocouple to the amplifier. The amplifier should have enough gain to cover the required temperature range of the thermocouple. When the thermocouple will be measuring colder temperatures than ambient temperatures, there are three options:

1. Use an Op Amp that operates below the negative supply.
2. Bias the thermocouple to operate within the Op Amp's supply.
3. Provide a negative supply.

Some thermocouples are electrically connected to the device they are measuring. When this is the case, make sure that the voltage of the device is within the Common mode range of the Op Amp. The most common case is found in thermocouples that are grounded. In this case, option 2 is not appropriate because it will force a short circuit across the thermocouple to ground.

Linearization

Linearization is the task of conversion that produces a linear output, or result, corresponding to a linear change in the input. Thermocouples are not inherently linear devices, but there are two cases when linearity can be assumed:

1. When the active range is very small.

2. When the required accuracy is low.

Pilot lights in water heaters for example, are typically monitored by thermocouples. No special electronics is required for this application, because the only accuracy required is the ability to detect a 600 degree increase in temperature when the fire is lit. A fever thermometer on the other hand, is an application where the active range is very small (90° F - 105° F). If the temperature gets higher than the effective range, either the thermometer is not being used correctly, or the patient needs to be in the hospital.

There are many ways to linearize the thermocouple results. Figure 1 shows linearization following the gain stage. Sometimes, the linearization follows the addition of the absolute temperature reference. No matter where it occurs, or to what degree, linearization is critical to the application.

Absolute Temperature Scaling

Thermocouples are relative measuring devices. In other words, they measure the temperature difference between two thermal regions. Some applications are only interested in this thermal difference, but most applications require the absolute temperature of the device under test. The absolute temperature can be easily found by adding the thermocouple temperature to the absolute temperature of one end of the thermocouple. This can be done at any point in the thermocouple circuit. Figure 1 shows the scaling occurring after the linearization.

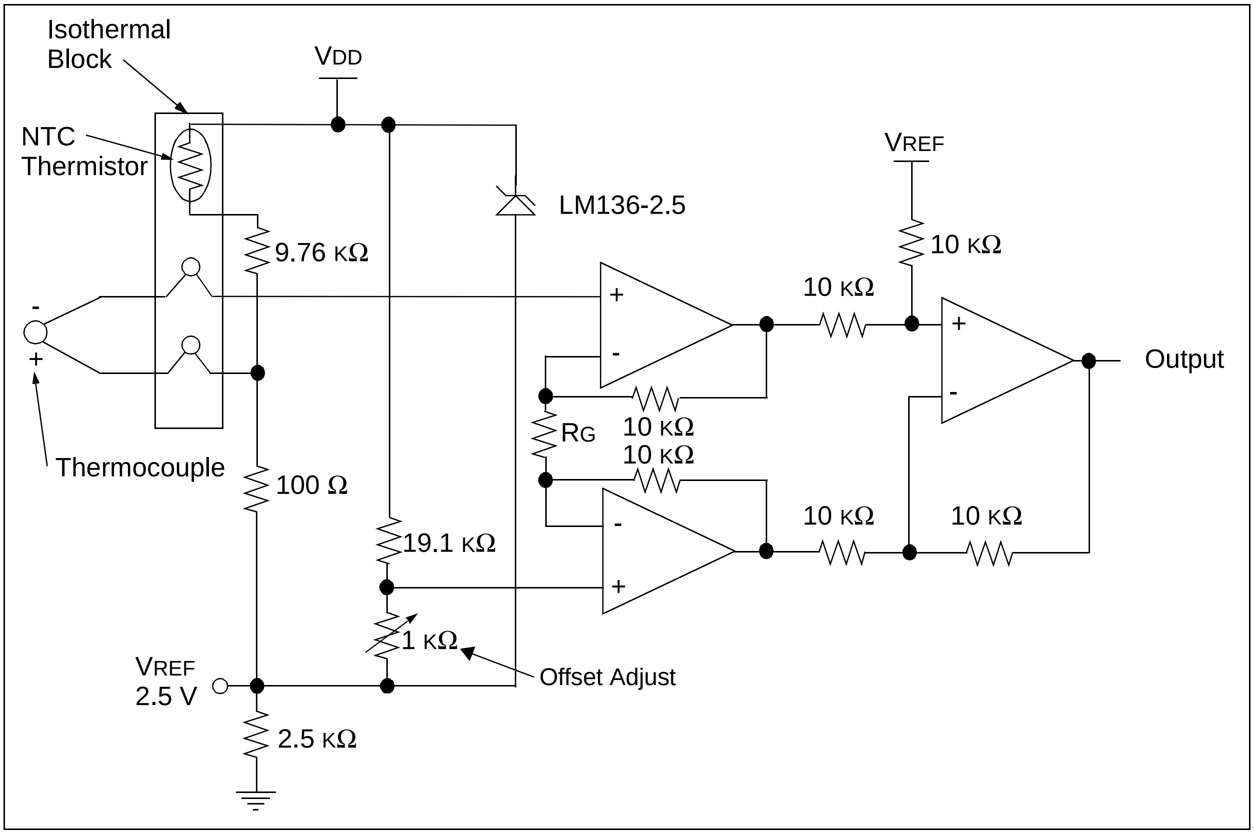
Results

The result of the thermocouple circuit is a usable indication of the temperature. Some applications simply display the temperature on a meter. Other applications perform some control or warning function. When the results are determined, the work of the thermocouple circuit is finished.

Pure Analog Circuit

A pure analog solution to measuring temperatures with a thermocouple is shown in Figure 2.

FIGURE 2: PURE ANALOG SOLUTION

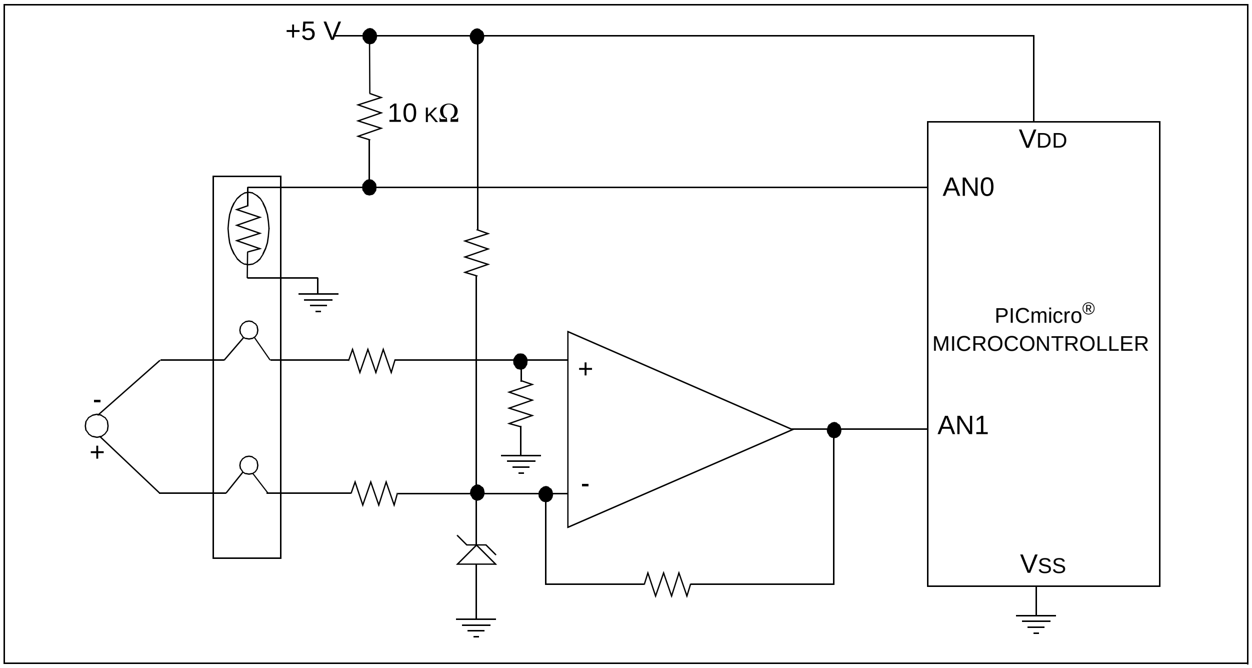


In the analog solution, the thermocouple is biased up 2.5V. This allows the thermocouple to be used to measure temperatures hotter and colder than the isothermal block. This implementaion cannot be used with a grounded thermocouple. The bias network that biases the thermocouple to 2.5V contains a thermistor. The thermistor adjusts the bias voltage making the thermocouple voltage track the absolute voltage. Both the thermistor and the thermocouple are non-linear devices, so a linearization system would have to be created that takes both curves into account.

Simplified Digital

Most analog problems can be converted to a digital problem and thermocouples are no exception. If an analog-to-digital converter (ADC) were placed at the end of the analog solution shown in Figure 2, the result would be a simple digital thermometer (at least the software would be simple). However, the analog/linear circuitry could be made less expensive to build and calibrate by adding a microcontroller.

FIGURE 3: SIMPLIFIED DIGITAL CIRCUIT

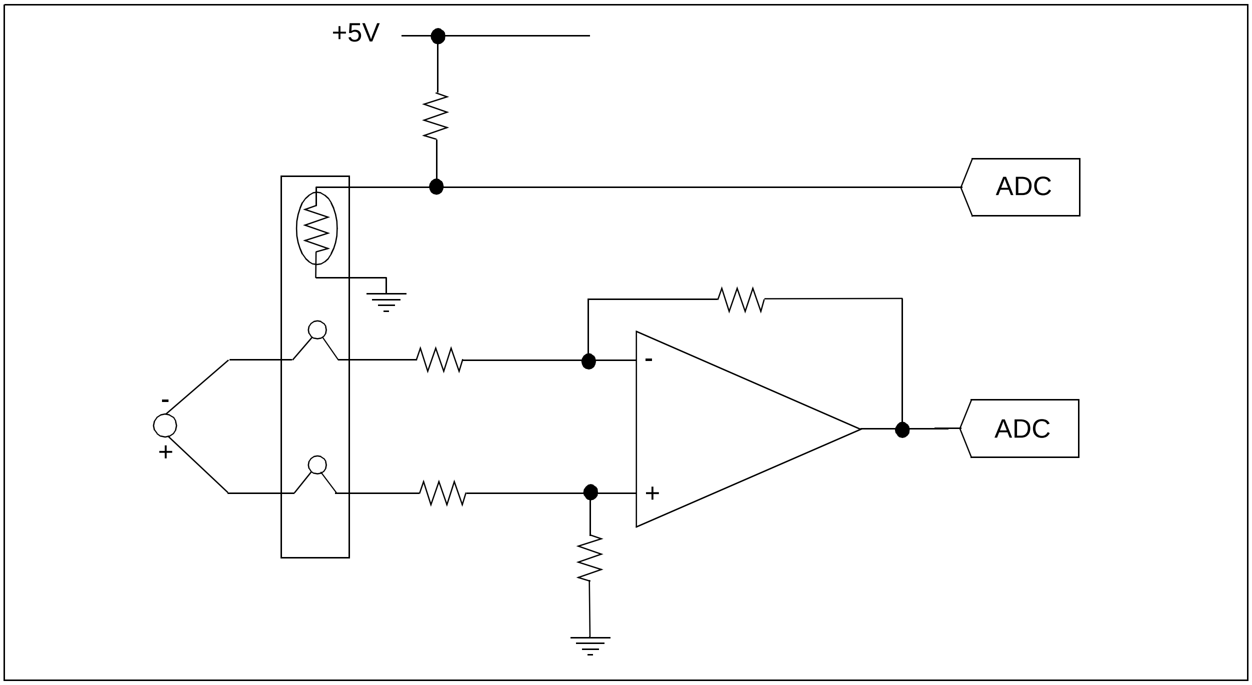


As you can see, the circuit got a lot simpler (see Figure 3). This system still uses a thermistor for the absolute temperature reference, but the thermistor does not affect the thermocouple circuit. This makes the thermocouple circuit much simpler.

Hot Only or Cold Only Measurement

If the application can only measure hot or cold objects, the circuit gets even simpler (see Figure 4). If only one direction is going to be used in an application, a simple difference amplifier can be used. The minimum temperature that can be measured depends on the quality of the Op Amp. If a good single supply, rail-rail Op Amp is used, the input voltage can approach 0V and temperature differences of nearly 0 degrees can be measured. To switch from hot to cold measurement, the polarity of the thermocouple wires could be switched.

FIGURE 4: HOT OR COLD ONLY MEASUREMENT



FAULT Detection

When thermocouples are used in automotive or aerospace applications, some sort of FAULT detection is required since a life may be depending on the correct performance of the thermocouple. Thermocouples have a few possible failure modes that must be considered when the design is developed:

1. Thermocouple wire is brittle and easily broken in high vibration environments.
2. A short circuit in a thermocouple wire looks like a new thermocouple and will report the temperature of the short.
3. A short to power or ground can saturate the high gain amplifiers and cause an erroneous hot or cold reading.

Solutions for these problems depend on the application.

Measuring the Resistance of the Thermocouple

The most comprehensive thermocouple diagnostic is to measure the resistance. Thermocouple resistance per unit length is published and available. If the circuit can inject some current and measure the voltage across the thermocouple, the length of the thermocouple can be determined. If no current flows, there is an open circuit. If the length changed, then the thermocouple is shorted. This type of diagnostic is best performed under the control of a microcontroller.

DIGITAL COLD COMPENSATION

Digital cold compensation requires an absolute temperature reference. The absolute temperature reference can be from any source, but it must accurately represent the temperature of the measured end of the thermocouple. The previous examples used a thermistor in the isothermal block to measure the temperature. The analog example used the thermistor to directly affect the offset voltage of the thermocouple. The digital example uses a second ADC channel to measure the thermocouple voltage separately.

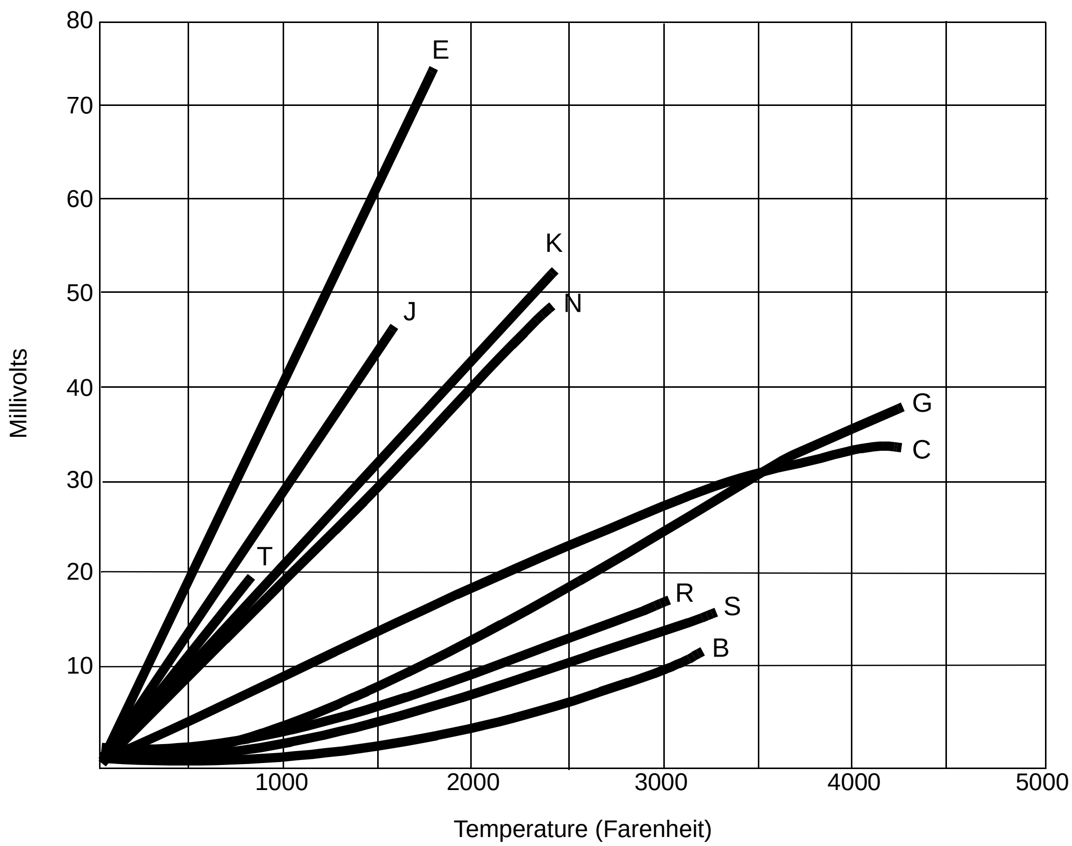
The formula for calculating the actual temperature when the reference temperature and thermocouple temperature are known is:

Actual temperature = reference temperature + thermocouple temperature

Linearization Techniques

Thermocouple applications must convert the voltage output from a thermocouple into the temperature across the thermocouple. This voltage response is not linear and it is not the same for each type of thermocouple. Figure 5 shows a rough approximation of the family of thermocouple transfer functions.

FIGURE 5: THERMOCOUPLE TRANSFER FUNCTIONS



Linear Approximation

The simplest method of converting the thermocouple voltage to a temperature is by linear approximation. This is simply picking a line that best approximates the voltage-temperature curve for the appropriate temperature range. For some thermocouples, this range is quite large. For others, this is very small. The range can be extended if the accuracy requirement is low. J and K thermocouples can be linearly approximated over their positive temperature range with a 30 degree error. For many applications this is acceptable, but to achieve a better response other techniques are required.

Polynomials

Coefficients are published to generate high order polynomials that describe the temperature-voltage curve for each type of thermocouple. These calculations are best performed with floating point math because there are many significant figures involved. If the PICmicro MCU has the program space for the libraries then this is the most general solution.

TABLE 1: J THERMOCOUPLE DATA TABLE - TEMPERATURE TO VOLTS

Coefficient	Temperature -210° C to 760° C	Temperature 760° C to 1200° C
C0	0.0000000000E+00	2.9645625681E+05
C1	5.0381187815E+01	-1.4976127786E+03
C2	3.0475836930E-02	3.1787103924E+00
C3	-8.5681065720E-05	-3.1847686701E-03
C4	1.3228195295E-07	1.5720819004E-06
C5	-1.7052958337E-10	-3.0691369056E-10
C6	2.0948090697E-13	0.0000000000E+00
C7	-1.2538395336E-16	0.0000000000E+00
C8	1.5631725697E-20	0.0000000000E+00
Note: v = c0 * t + c1 * t^1 + c2 * t^2 + c3 * t^3 + c4 * t^4 + c5 * t^5 + c6 * t^6 + c7 * t^7 + c8 * t^8 v = volts t = temperature in C if the above table is used.		

Lookup Table

The easiest method of linearizing the data is to build a 'lookup table.' The lookup table should be sized to fit the available space and required accuracy. A spreadsheet can be used to convert the coefficients into the correct data table. A table will be required for each type of thermocouple used. If high accuracy (large tables) are used, it may be a good idea to minimize the number of thermocouple types.

To minimize the table size, a combination of techniques may be used. A combination of tables and linear approximation could reduce the J or K error to just a few degrees.

BUILDING AN ENGINE TEMPERATURE MONITOR

Background

One application of thermocouples is measuring engine parameters. Air-cooled engines, such as those used in aircraft, require good control of cylinder head temperature (CHT) and exhaust gas temperature (EGT). The control is typically performed by the pilot by adjusting:

- Fuel mixture
- Power settings
- Climb/descent rate.

Because mixture is used to control temperature, fuel economy is directly impacted by the ability to accurately measure the EGT. CHT is critical in air-cooled engines because of the mechanical limits of the cylinder materials. If the cylinder is cooled too fast (shock cooled) the cylinders or rings could crack, or the valves could warp. Typically, shock cooling results from a rapid descent at a low throttle setting.

Device

A good device for measuring these engine parameters should have a range of 300°-900° F for EGT and 300°-600° F for CHT. Additionally, diagnostics for short/open circuits are required to alert the pilot that maintenance is required. The electronics should be placed in a suitable location that has a total temperature range of -40° to +185°. This will allow the thermocouple circuitry to be simplified. The data will be displayed on a terminal program on a PC through an RS-232 interface.

Amplifier

The amplifier circuit is in two stages. First is a differential amplifier that provides a gain of 10 and a high impedance to the thermocouple. This is followed by a single-ended output stage that provides a gain of 25 for K thermocouples and 17 for J thermocouples. The amplifier selected is the MCP619. This device was selected for its rail-rail output and very low V_{OS}. The thermocouple is located in a high frequency/radio frequency environment so small capacitors are used at the input and between the stages to filter out the noise. As with most RF sources, these are normally very well shielded. Since the temperatures don't change quickly, heavily filtering the signal to eliminate the noise does not affect the temperature measurement.

Digital Conversion and Cold Compensation

The signal is converted to digital with a MCP3004 A/D converter chip. The absolute temperature is measured with a TC1046 on the third channel of the MCP3004. The data is received by a PIC16F628 and converted to a regular temperature report over an RS-232 interface. To convert from volts to temperature, the Most Significant eight bits of the conversion are used to index into a 256-entry lookup table. The remaining 2 bits are used to perform linear interpolation on the data between two adjacent points in the lookup table. Three tables are stored in the memory of the PIC16F628. These tables are for:

- J - type thermocouple
- K - type thermocouple
- TC1046A

The TC1046A has linear output, but we could easily substitute a non-linear thermistor for the same task.

Lookup Table Generation

Eight-bit lookup tables are generated using a spreadsheet. The polynomial values of the voltage-to-temperature curve are used to generate a voltage-to-temperature conversion spreadsheet. The voltages are the predicted values from the analog-to-digital converter. A 256-entry table was constructed of ADC counts to temperatures. The temperatures ranged from zero degrees C to 535° C. Because the table can only store eight-bit values of temperature, two points were selected as pivot points. At the first point, the temperature was reduced by 255° C. At the second point, the temperature was reduced by 510° C. The final temperature can be easily reconstructed by adding the two constants back in as appropriate. Additional resolution is obtained by interpolating between two points in the 8-bit table using the extra two bits from the 10-bit conversion. This will result in four times as many data points by assuming a linear response between the points in the lookup table.

CONCLUSIONS

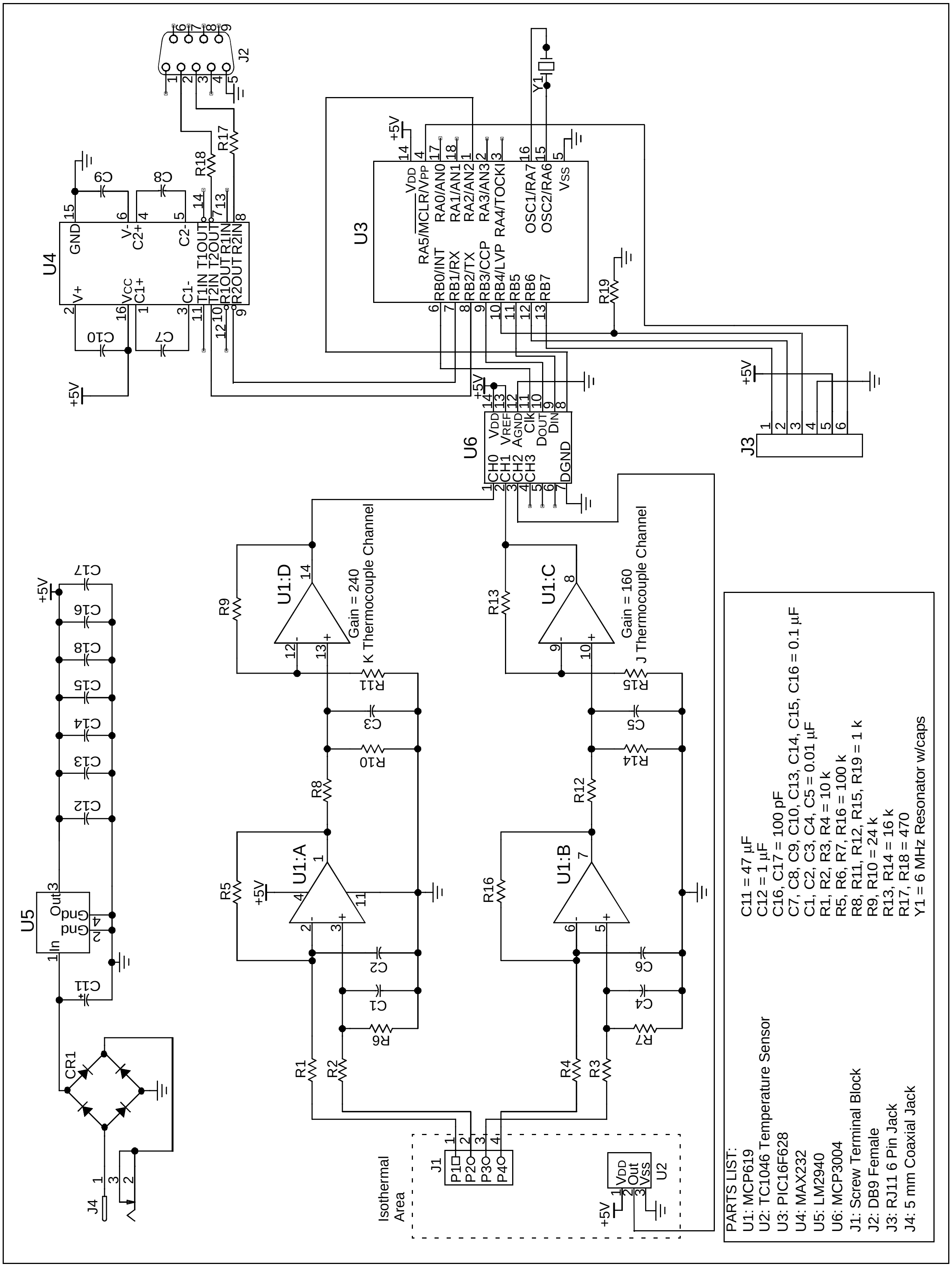
Thermocouples can be tricky devices, but when the problem is shifted from the hardware analog components into the software, they can become a lot more manageable. The only real requirement when using thermocouples is to provide a high quality amplifier to sense and scale the signal before converting it to digital form.

MEMORY USAGE

TABLE 2: SOFTWARE MEMORY USAGE

Program Memory	File Registers	Data EEPROM
1399 Words	28 Bytes	0 Bytes

APPENDIX A: SCHEMATIC OF EXHAUST GAS AND CYLINDER HEAD TEMPERATURE MONITORING DEVICE



REFERENCES

Application Note AN684

Omega Temperature Sensing Handbook

NOTES:

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