AN4889

Using Core Independent Peripherals (CIPs) to Implement a Peltier Cooled Metal Plate

Introduction

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Core Independent Peripherals (CIPs) are specially designed hardware blocks inside a microcontroller (MCU) that add new capabilities, reduce code and improve system performance. Thanks to CIPs, 8-bit microcontrollers can punch well above their weight and tackle applications that normally would require a substantial upgrade in CPU performance. This application note will showcase an example of this by discussing the design elements, decisions and logic that went into building a Peltier Cooled Metal Plate with only one microcontroller: a 20-pin PIC16F17146.

An overview of the application's design, along with the schematics, PCB layouts and CAD files for the prototype, is available at the MPLAB® Discover link below.

Click to view code example on MPLAB DISCOVER

Table of Contents

1. Design Planning

1.1 Overview

The objective of this project was to develop an application that could bring the temperature of a surface down to the point of freezing water or ice cream mix. For safety reasons, it was not possible to work with refrigerants and compressed gas lines. An alternative to this is a Peltier element, which is a solid-state heat pump that gets hot on one side and cold on the other. A metal plate is attached to the cold side of the Peltier element while a heat sink and fan are connected to the hot side to dissipate the pumped heat, as well as the thermal losses from the Peltier element. The temperature of the cooled metal plate is monitored to determine when to run the Peltier element. A user interface allows the user to start, stop, and control the plate settings, such as the target temperature.

1.2 Objectives

For this complex application, it is necessary to define the design requirements. This way, resources such as time, energy and money are efficiently allocated while maximizing the feature set. For the cold plate, the final design requirements were:

- Able to reach 0°C
- Up to 10A cooling current
- Safe to operate outside of a lab environment
  - Ability to detect cooling fan failures
  - Monitors system current
  - Shuts down if the system overheats
- User-adjustable temperature and relevant settings

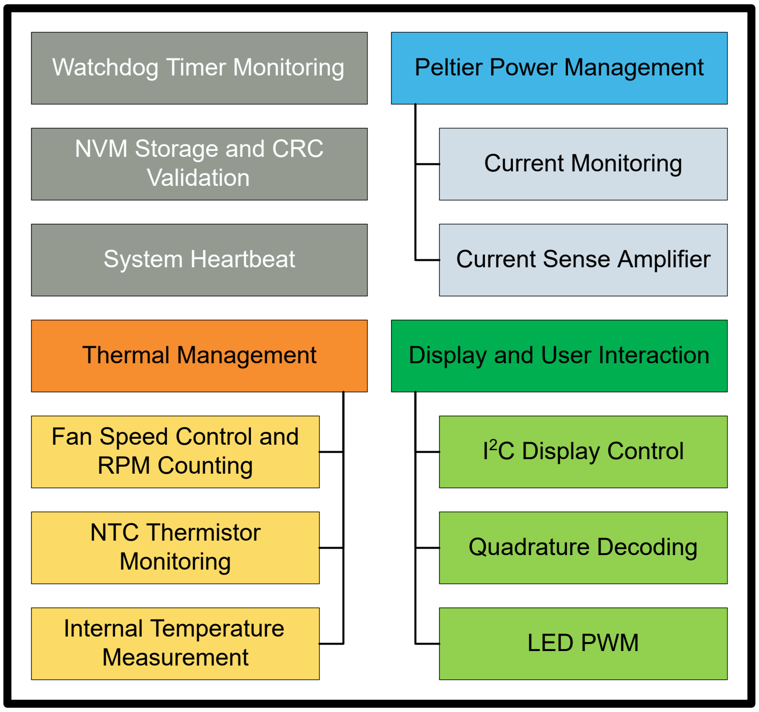
1.3 Simulating with MPLAB® Mindi™ Analog Simulator

MPLAB Mindi Analog Simulator, a free circuit analysis tool from Microchip, was used to help with analyzing the circuit prior to building it. This tool simulates the performance of the Peltier power supply with different circuit parameters without buying parts or building prototypes.

1.4 Splitting the Design

After determining the initial design concept, it was then split into smaller functional blocks that can be developed and tested in isolation. Once a block is confirmed to be functional, the next one can be developed and so on. This approach simplifies troubleshooting most problems before integrating all the parts together, and was used for the hardware, firmware and mechanical design of the system. Figure 1-1 shows the major function blocks of the embedded system.

Figure 1-1. Major Function Blocks of the System



PIC16F17146

Note: See the corresponding chapters for more detailed breakdowns of the blocks.

1.5 Prototyping with Development Boards

For most of the hardware development, the Curiosity Development Board (DM164137) was used with a Dual-Inline Package (DIP) version of the PIC16F17146. This microcontroller was selected for its integrated operational amplifier (”op amp”) with internal resistor ladder. Additionally, this family of MCUs has many other hardware peripherals available to implement additional features without external components.

1.6 Developing with MPLAB® Code Configurator (MCC)

Most of the base firmware of this system was developed using Microchip’s free code generation tool, MPLAB Code Configurator (MCC). MCC provides a graphical user interface to configure the peripherals on the microcontroller. This aids in visualizing the allocation of the microcontroller’s resources while also reducing setup time and allowing for quick pinout changes.

2. Device Utilization

This application implements the following noteworthy features:

- Monitoring Peltier Current
- Measuring Multiple Analog Temperature Sensors
- Controlling Fan Speed and Calculating Fan RPM
- Storing and Verifying User Settings in Nonvolatile Memory
- Displaying Text Menus and LED Indicators
- Processing User Input from a Rotary Encoder and Push Button

2.1 Pin Layout Planning

During the development of this application, pin planning was a critical consideration. Features such as Peripheral Pin Select (PPS) significantly improve digital I/O routing by providing flexibility in pin assignment. However, analog peripheral I/O is generally limited to a few select pins, with the exception of the Analog-to-Digital Converter (ADC) inputs. Additionally, features enabled from configuration bits, like CLKOUT, have fixed pin assignments.

To begin, first route the inflexible signals. In this case, analog signals and the $\overline{\text{MCLR}}$ line were the top priority. Ideally, analog signals should be routed away from fast-switching digital signals, as these may couple noise into the input. See Microchip Application Note AN4225, *“Maximizing the Signal: Tips and Tricks to Properly Acquiring Analog Signals”* (DS00004225) for more information.

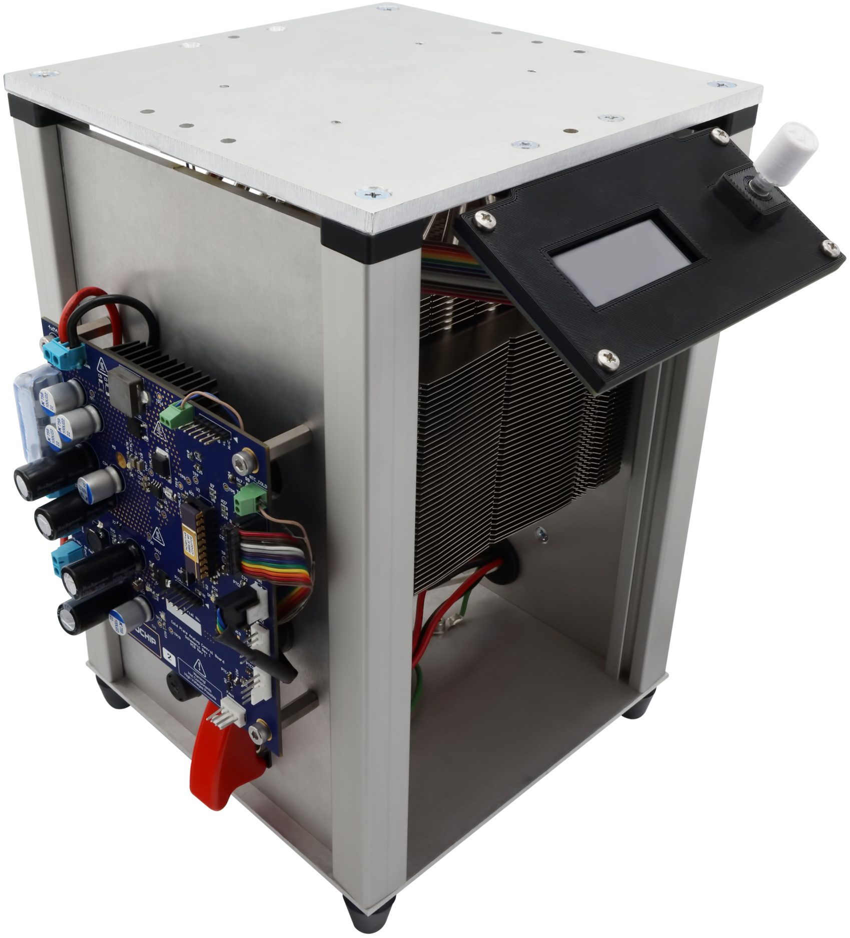
Once the analog signals were assigned, the digital I/O was routed. These pins are more flexible, but still may only be available on specific ports. Note that while creating the Printed Circuit Board (PCB) layout, it is advantageous to use PPS to rearrange digital signals further to optimize layout patterns.

3. Functional Blocks

3.1 Overview

As listed in the design requirements, the microcontroller used must be able to monitor the temperature of the metal plate, control power to the Peltier, detect system failures and manage the user interface. Figure 3-1 shows the assembled demo.

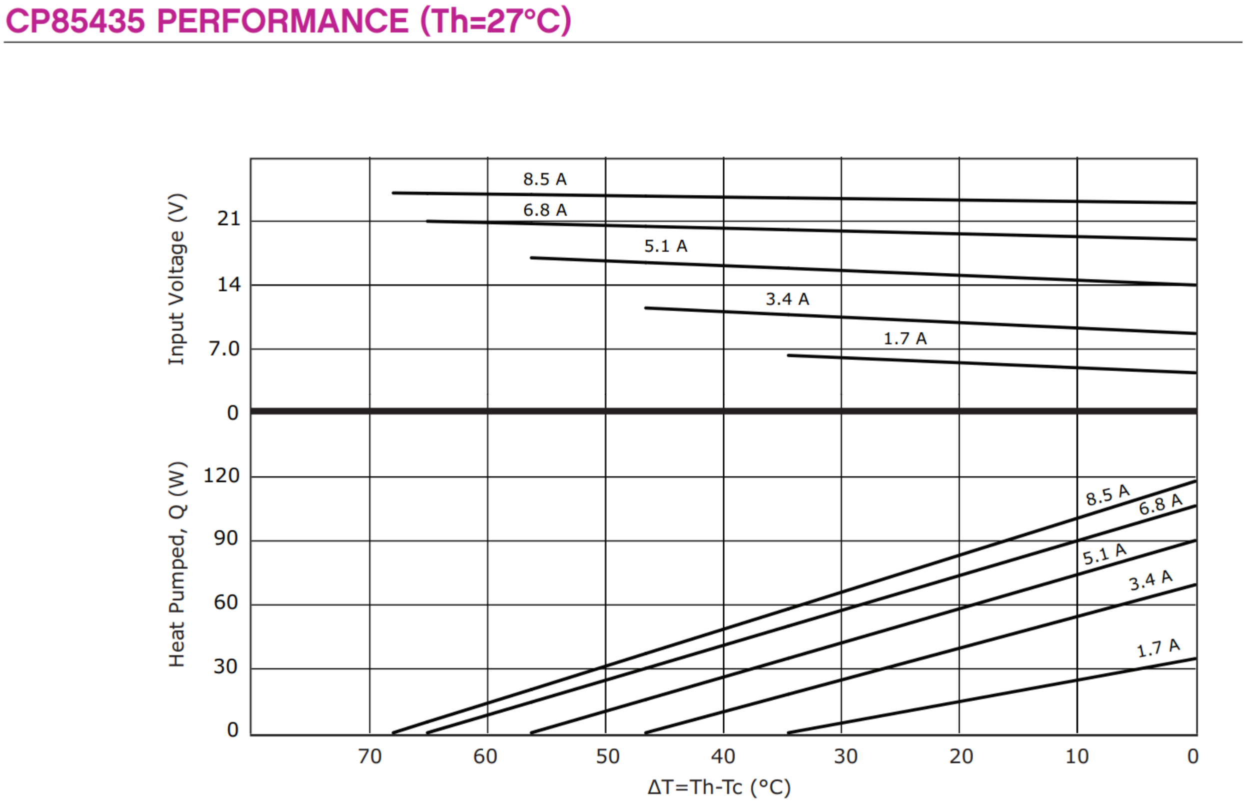
Figure 3-1. Completed Assembly of the Cold Plate



3.2 Theory of Operation

To implement this system, the first element to consider is the Peltier plate. Peltier plates pump heat from one side to the other in response to current flowing through the plate. This generates a thermal gradient as the top and bottom plates are no longer at the same temperature. As the temperature gradient widens, the amount of heat pumped by the Peltier drops. Eventually, the differential temperature will reach steady state, where the system is held in equilibrium. Figure 3-2 shows the amount of heat pumped from the used Peltier element (P/N: CP85435) as the temperature differential changes.

Figure 3-2. Peltier Performance Curves of CP85435 at 27°C

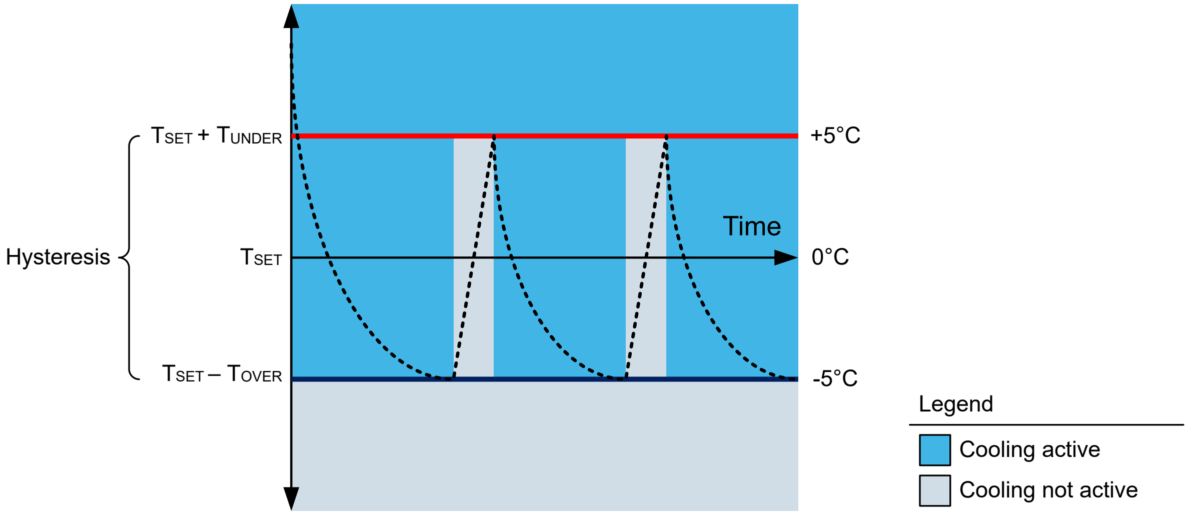


Note: Figure 3-2 is used with permission from CUI Devices, *cuidevices.com*.

If the only objective of this system was to cool as much as possible, then only a power supply would be needed. However, since the objective is to regulate the temperature, it should be assumed the plate is not in equilibrium. Instead, the MCU must sense the temperature of the cold plate and use this value to determine when to supply power to the Peltier element. Temperature control is implemented in the firmware with Bang-Bang control. To prevent rapid control oscillation, programmable hysteresis was implemented to keep the temperature within programmable thresholds. An example is discussed below and shown in Figure 3-3.

Assume the cold plate is not at user-set temperature at t = 0. The system will begin to run current through the Peltier element. As the plate cools, the temperature falls to a value $T_{SET} - T_{OVER}$ where the plate becomes overcooled. When this condition is reached, power to the Peltier element is disconnected. The cooled surface then warms up naturally until it reaches the value $T_{SET} + T_{UNDER}$, at which point power to the Peltier is restarted. This on-and-off cycling allows the MCU to regulate the temperature of the plate.

Figure 3-3. Temperature Regulation Algorithm with Example Values



3.3 Software Design

As mentioned in the beginning of this application note, CIPs drive much of this application, significantly reducing the CPU's overhead. However, software still plays an important role beyond system initialization. The software on the microcontroller is responsible for enabling the Peltier, updating the user-interface, reading rotary encoder counts, converting ADC readings to temperature, and detecting soft errors. In this case, soft errors are failures that can be handled directly by the microcontroller while a hard error would be an issue that trips a physical safety device, such as a fuse.

Due to resource limitations, the software was architected with simple cooperative multitasking, in which an executing task voluntarily yields so another task may run. A heartbeat function, derived from Timer0, is used to run non-blocking tasks periodically. Additionally, the heartbeat function generates flags to indicate instances where a more complex task must run when the system is not busy with another task.

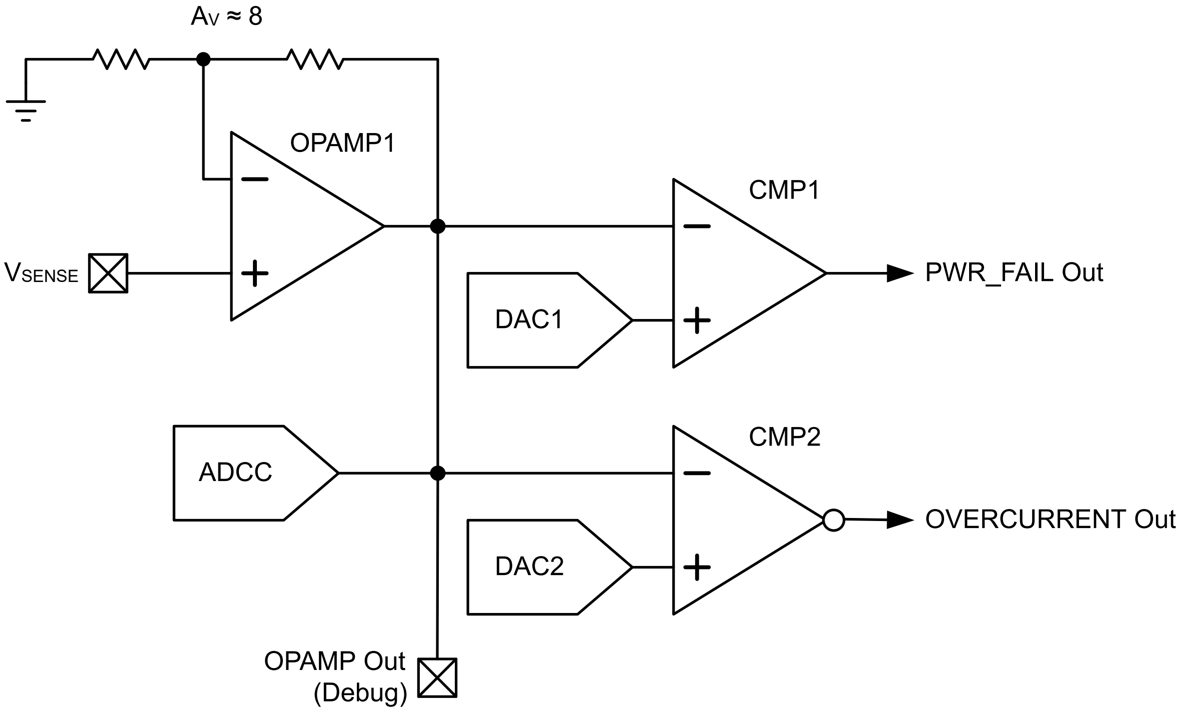
3.4 Peltier Power Management

To control power, a switching FET is used to gate the flow of current through the Peltier element. Since a lot of current is passing through the circuit, it is critical that the transistor is fully saturated, and is not operating in the linear region. To ensure this occurs, a TC1413N MOSFET gate driver is used to switch the FET from the provided enable signal. The enable signal is set/cleared in software by the periodic self-check that manages the system. If a fault occurs, then the system disables the FET, which cuts off power to the Peltier. There's an additional fuse inline with the Peltier circuit in the event of a more severe fault.

3.4.1 Current Monitoring

These functional blocks are responsible for amplifying the analog signal from the current sense resistor and converting it into digital signals that indicate system faults. For reference, Figure 3-4 shows the complete view of the current sense system.

Figure 3-4. Complete View of the Current Monitoring System



3.4.1.1 Current Sense Amplifier

To measure the Peltier current, it is necessary to amplify the value from the current shunt to a value that is more usable by the MCU. Without amplification, the voltage induced on the current shunt is simply Ohm's law:

$$V_{SHUNT} = I_{PLATE} * R_{SHUNT}$$

If the system had a current target of 10A and a shunt resistor of 10 mΩ, this would induce a nominal voltage of 100 mV. For our comparators, we used the internal 8-bit Digital-to-Analog Converters (DACs) with the internal Fixed Voltage Reference (FVR) at 2.048V to set the allowed current conditions. The 2V reference was used instead of the 1V reference due to requirements of the internal Temperature Indicator Module that was also used. By knowing the resolution and voltage reference used for the DAC, the resolution per bit can be found as:

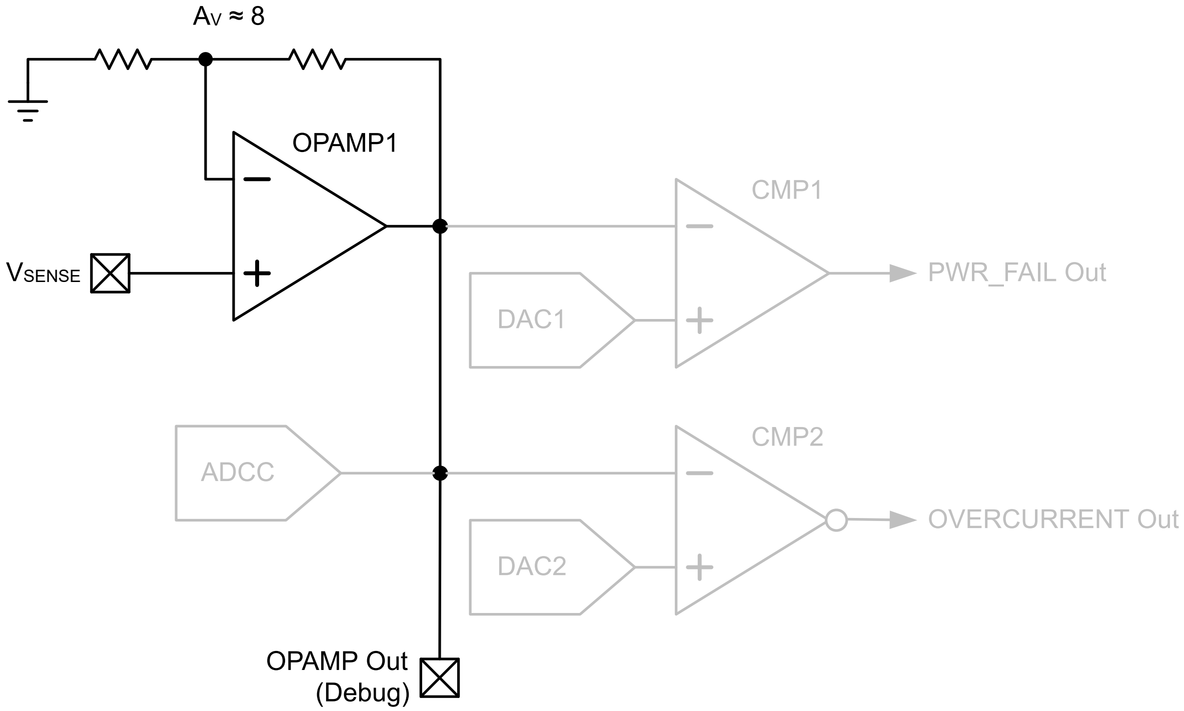
$$\frac{V_{REF}}{2^n} = \frac{2.048V}{2^8} = 8\frac{mV}{bit}$$

Solving for measurement range, it becomes clear that only a small fraction of the available range of the DAC is utilized:

$$\frac{V_{NOM}}{V_{RANGE}} = \frac{100\,mV}{2.048V} \cong 4.88\,\%$$

To improve signal range utilization, the op amp inside of the PIC16F17146 was set up with a gain of 8x using the internal resistor ladder in the configuration shown below, in Figure 3-5.

Figure 3-5. Current Sense Amplifier with the Op Amp Peripheral



This immediately increases the nominal signal range utilization by the gain of 8x to:

$$\frac{800\ mV}{2.048V} \cong 39.06\,\%$$

Which provides a lot more measurement headroom than before.

3.4.1.2 Power Failure Detection

For safety reasons, it is important to detect a power failure on the Peltier side. There is a possibility that a wire comes loose, or the fuse blows on that section, both of which would disconnect the Pelter from power.

A standard approach for this problem would be to implement a voltage divider network and measure the input voltage to the Peltier plate. However, this would make the system unable to detect an open Peltier element, dead switching transistor or damaged current sense resistor. Additionally, this would require an additional I/O pin and add another point of failure.

Instead, the system uses the output of the current sense amplifier to detect a power failure. The amplified value is compared to a set point in a DAC. If the amplified value is below a low-level threshold, then the system considers this a power failure, and shuts down the Peltier circuit. The input to the current sense amplifier is protected by a current-limiting resistor on its input, with additional protection derived from its low-side position in the circuit.

3.4.1.3 Overcurrent Detection

Another implemented protection mechanism was an overcurrent detector. This works in the same way as the power failure detector mentioned earlier, but with an analog comparator monitoring the output of the current sense amplifier with respect to a set point in a DAC. The set value is dependent on the measured gain of the op amp with an additional signal margin.

Unlike most of the errors implemented, the overcurrent error is not cleared automatically when the condition no longer exists. This was done intentionally to prevent users from attempting to restart a failed-short Peltier or other electrical failure.

One flaw with the linear topology for the Peltier element is a brief current surge when the Peltier element starts up. This surge can trip the protector prematurely. To reduce the detector’s sensitivity to the start-up surge, this protection circuit is polled as part of the periodic self-check, rather than being interrupt driven. This allows the start-up current surge to pass, rather than triggering an immediate shutdown. An overcurrent event that lasts longer than the polling cycle will still trigger the circuit.

Note: A soft-start circuit for the Peltier may be necessary to reduce or remove the surge current. See the Soft-Start Circuit section for more information.

3.4.1.4 Gain Self-Check with the Operational Amplifier

To protect against accidental software misconfiguration or an analog fault, the system performs an operational amplifier self-test on start-up. This test calculates the gain of the op amp and verifies that it is within a programmed tolerance.

Note: Any noise in the ADC readings will affect the gain measurement. The MCU is placed in Sleep mode during these measurement steps to minimize noise.

To measure gain (A_V), first consider the formula:

$$A_V = \frac{V_{OUT}}{V_{IN}}$$

From this expression, it is clear the input and output conditions must be measured to determine the gain. For safety and performance reasons, the Peltier current-sense circuit cannot be used for calibration. Instead, the OPAMP input is temporarily connected to DAC 2, which can be programmed to generate an arbitrary voltage.

Next, the output of the DAC must be measured. With the DAC connected to the op amp internally, disable the internal resistor ladder of the op amp and enable unity gain to output the DAC value from the op amp. The output is expressed as:

$$V_{OUT@UG} = V_{DAC} + V_{OS}$$

In this formula, V_{OS} is the offset voltage of the operational amplifier, $V_{OUT@UG}$ is the measured output at unity gain, and V_{DAC} is the input signal. Error from V_{OS} is not an issue, as it divides out later. Next, reconnect the resistor ladder and set the desired gain. The output becomes:

$$V_{OUT@AV} = (V_{DAC} + V_{OS}) * A_V$$

Where V_{OS} is the offset voltage of the operational amplifier, $V_{OUT@AV}$ is the measured output with an unknown gain, A_V is the gain of the operational amplifier and V_{DAC} is the input signal. To calculate A_V, divide the signals:

$$A_V = \frac{V_{OUT@AV}}{V_{OUT@UG}}$$

Since the ADC was kept in the same configuration during both measurements, the digital values from the ADC can be used directly instead of converting to the floating-point voltages for the division.

3.5 Thermal Management

Temperature control of the system’s heat sink and cold plate is critical. The Peltier generates very low and very high temperatures, both of which must be managed to ensure functionality and safety.

3.5.1 Cooling Fans

There are multiple cooling fans that can be implemented on the main board. Fan 0 is the main cooling fan of the Peltier’s heat sink, while Fan 1 is an optional auxiliary fan that is also monitored. All fans in the system share the same speed control signal to minimize their I/O usage.

3.5.1.1 Fan Speed Control

The speed of the main cooling fan is managed by the MCU to reduce noise. A 16-bit Pulse-Width Modulation (PWM) peripheral generates the waveform to control the speed of the cooling fans.

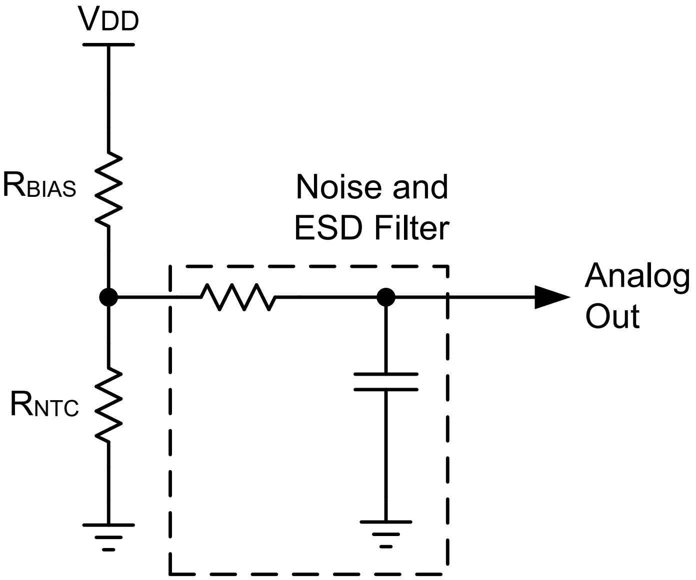
3.5.1.2 Fan Speed Monitoring

To ensure the main cooling fan is functional, the design uses Timer2 to count the number of fan tachometer pulses. If the pulse count is 0 at any point while the system is active, the Peltier is shut down and a soft error is sent to the User Interface (UI). Timer4 is also used to monitor Fan 1 but does not shut down the system if no pulses are detected, as this is an auxiliary fan.

3.5.2 Temperature Monitoring with NTC Thermistors

To measure the temperature of the heat sink and cold plate, Negative Temperature Coefficient (NTC) thermistors were used. These devices provide variable resistance directly correlated to the temperature of the environment in which they are placed. To bias the NTC thermistors, a resistor divider network is implemented where the NTC thermistor forms the lower element, as shown in the schematic below.

Figure 3-6. NTC Measurement Circuit



Another benefit of using the NTC on the low side of the voltage divider is the ability to implement Over-Temperature Protection (OTP) for the current regulator. This is discussed in the Current Regulator OTP with NTC Sensing chapter. Additionally, a simple low-pass RC filter network reduces input noise and provides a bit of Electrostatic Discharge (ESD) protection. With the resistor divider, the voltage across the thermistor will equal:

$$V_{TEMP} = \frac{R_{NTC}}{R_{NTC} + R_{BIAS}} * V_{DD}$$

With thermistors, the temperature resistance ratio is not linear. For accuracy and computation simplicity, a look-up table was implemented to convert measured voltages into temperatures. The manufacturer of the NTC thermistors provides a spreadsheet of resistance versus temperature. Later, the thermistor resistance versus temperature was measured to further refine the look-up table. By knowing the parameters of the NTC (and the surrounding circuit), ADC values could be converted into temperature directly. To search the look-up table more efficiently than a linear search, a version of the quicksort algorithm was implemented. This algorithm is described in detail in Section 3.5.2.1. Quicksort Algorithm for Table Searching.

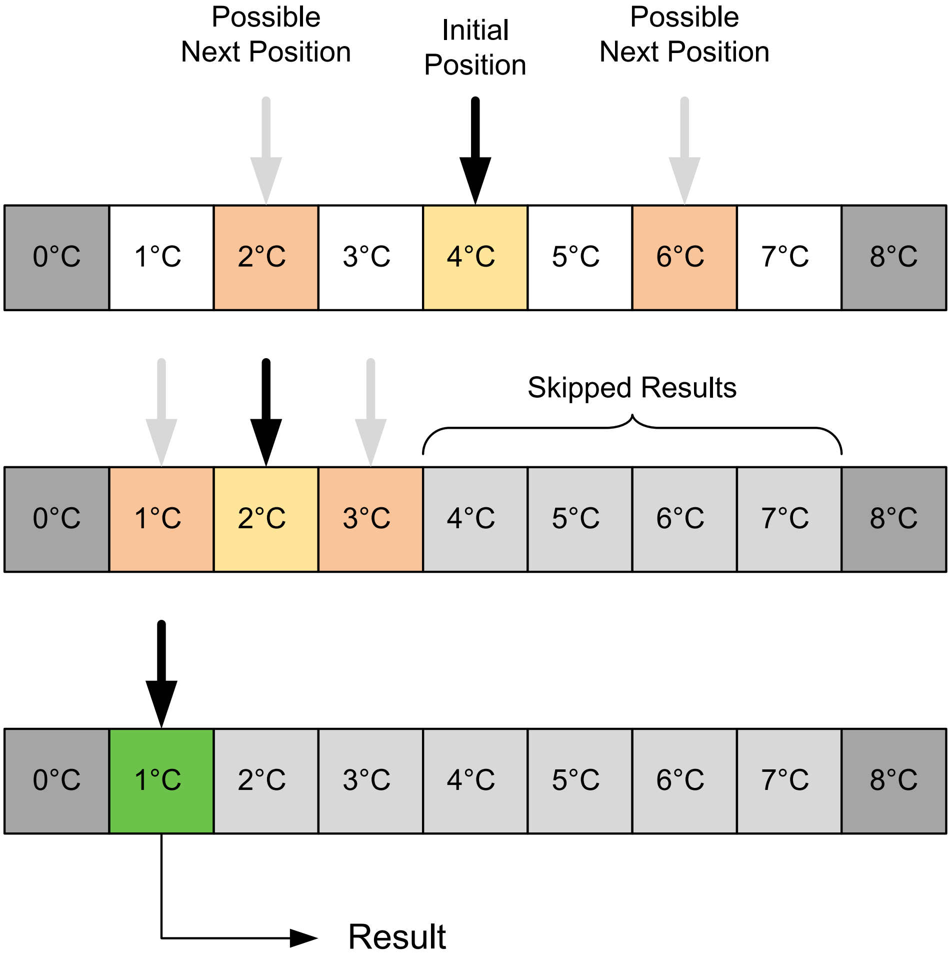
Important: Mounting is extremely important for NTC thermistors. Various sensor packages and positions were experimented with before finding a good setup.

3.5.2.1 Quicksort Algorithm for Table Searching

Internally, this demo computes the temperature at each of the NTCs by using an array (table) of presorted values. Each value in the array is the expected value of the ADC indexed by temperature. By using precomputed values, we can save CPU time and avoid approximating the non-linear response curve.

To determine the temperature, first start in the middle of a table with $2^N + 1$ elements. The extra element is to ensure the table is odd. The value at this index is compared to the search value. If they are equal, then the search is complete. If they are not equal, then go either up or down ½ of the remaining table, depending on whether the term was bigger or smaller. When the table has no remaining elements, return the value at the last index. This algorithm does not have any rounding, so accuracy is limited to ±1°C, depending on the value. Additionally, the elements at the ends of the table are not accessible to the search algorithm, although these can be checked prior to the search, if desired. A simple example is shown below. With this algorithm, the time complexity is improved from $O(n)$ to $O(\log n)$ time.

Figure 3-7. Example of a Search for 1°C



3.5.3 Internal Temperature Monitoring

The microcontroller includes an internal temperature indicator that can be used as an additional temperature monitor. This temperature value provides some additional telemetry.

3.6 Watchdog Timer Monitoring

During operation, it is important to ensure the system does not crash or enter an unexpected state. In this design, very high and low temperatures, along with high currents are present and must be constantly monitored. To ensure the software is functioning, a Watchdog Timer (WDT) must be periodically cleared by the application. If the system deadlocks, and the timer isn’t cleared, then the system will reset. The watchdog timer is enabled when the system is not in Idle.

3.7 Safely Storing and Validating User Settings with CRC and Internal EEPROM

In this system, user settings are retained across power-cycles. The internal EEPROM data memory within the microcontroller is used to store these settings. First, the microcontroller validates the EEPROM version ID, which is written by the application when settings are saved. On start-up, the version control byte is compared to a constant defined by the developer at compile time. If the values mismatch, then either:

- The EEPROM formatting has changed, or
- The EEPROM does not contain user settings

In either case, the settings are erased and reprogrammed with compile-time defaults. If the version ID passes, then a Cyclic Redundancy Check (CRC) is performed on the user settings and an embedded checksum. If the CRC is not zero, then it could be assumed that the memory is corrupted, and the settings are subsequently erased and reprogrammed with compile-time defaults. One modification made to the CRC configuration was to set an initial value of 0xFF. This ensures that if the CRC fails to run, the value will remain non-zero and can be easily detected.

3.8 Periodic Task Timer (Heartbeat)

To signal various events, a “heartbeat” timer was used to generate a periodic interrupt at a known frequency. This timer effectively serves as the heartbeat of the system – state machines are updated, values are measured and complex tasks are staged to run. This timer could be implemented by any of the built-in timers, but this example uses Timer0 at a frequency of 1 kHz.

3.9 User Interface and Display

3.9.1 Overview

The user interface is responsible for displaying current system conditions, alerting the user to any errors, and configuring the set temperature and other parameters. Upon system boot-up, a standby menu shows the current cold plate temperature and the last set temperature. Pushing the rotary encoder button allows the user to change numerous settings including the target temperature, hysteresis parameters, displayed units, and demo mode, which limits the minimum temperature for safety reasons. Once the “Start” menu option is chosen, the UI calls the start function for the Peltier control code and begins to display temperature telemetry. If the Peltier control functions detect a system error, the system is stopped automatically and the error code is displayed on the UI, which requires the user to acknowledge. After acknowledgment, the UI returns to the standby menu.

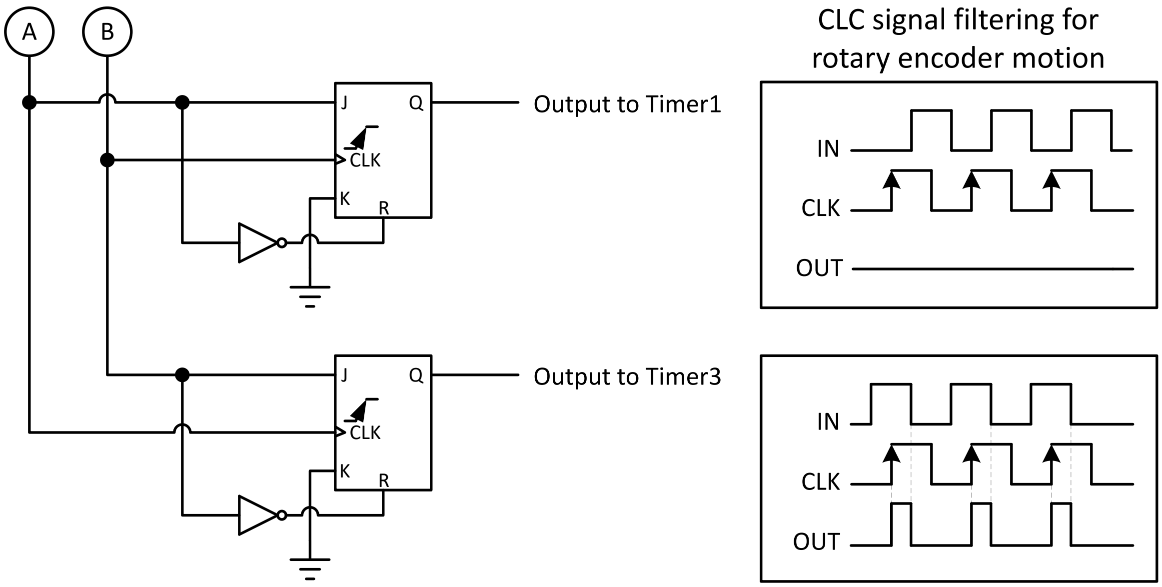
3.9.2 I^{2}C Display Control

The display used in this demo is an Organic Light Emitting Diode (OLED) display in a glass package. This particular display requires a dedicated +12V input for the panel itself, in addition to the standard logic level power supply. Since a +12V supply is already generated for the switching FET and cooling fans, this did not add to the Bill of Materials (BOM). The MCU communicates with the display using two I/O lines for the Inter-Integrated Circuit (I^{2}C) and an additional I/O for controlling the display Reset during start-up.

3.9.3 Quadrature Decoding

Users interact with the system using a rotary encoder with a built-in push button. The encoder generates a quadrature encoded signal which must be decoded by the MCU into left or right rotation pulses. Two Configurable Logic Cells (CLCs), Timer1 and Timer3 are used to perform this action in hardware, with only periodic software reads to obtain the net rotation. As shown in Figure 3-8, the CLCs filter the quadrature encoded signal, so rotational pulses only show up on the output, depending on the encoder direction. The output is fed into a timer, which counts the number of pulses. The software then periodically calculates the difference in the timer values since last read to know how many pulses the rotary encoder turned.

Figure 3-8. Quadrature Decoder Implementation



3.9.4 LED Lighting

To avoid information clutter on the UI display, additional status information is displayed through a blue and an orange LED built into the rotary encoder. Table 3-1 shows the LED colors versus activity correspondence.

Table 3-1. LED Colors Versus System State

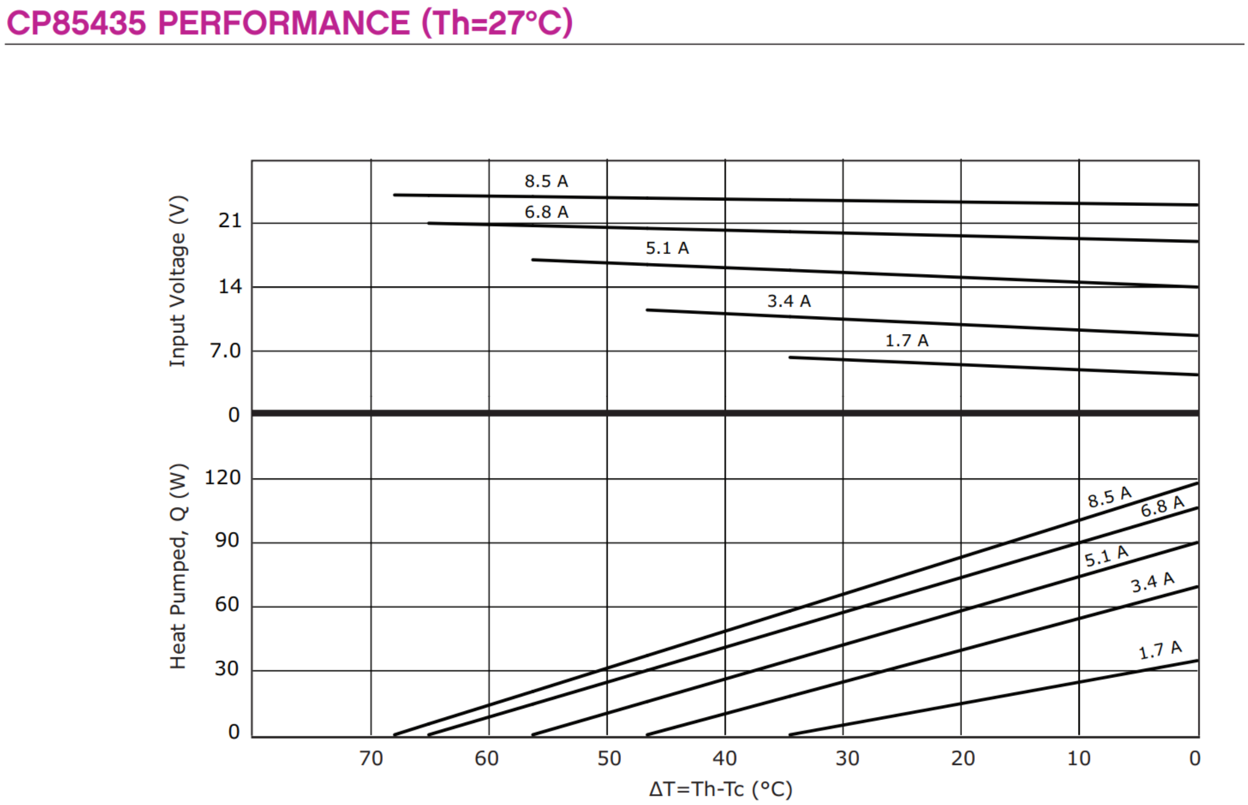
Color	Cold Plate Status
Breathing Purple	Standby
Breathing Blue	Actively Cooling
Solid Blue	At the Target Temperature
Solid Orange	Error

Both LEDs could be controlled via different slices of the same PWM signal, so controlling them was as simple as loading a new duty cycle into the correct register. The breathing effect was implemented using a simple state machine that loaded varying duty cycles into the PWM to create the illusion.

3.10 Thermal Design

As mentioned earlier, Peltier plates are a thermoelectric heat pump that moves heat from one side to another in response to current flowing through the plate. However, Peltier plates cannot support infinite temperature gradients across the surface – the larger the gradient is, the less heat is pumped by the Peltier. Figure 3-9 shows the amount of heat pumped as a function of the temperature differential for the Peltier element (P/N: CP85435) used in this application.

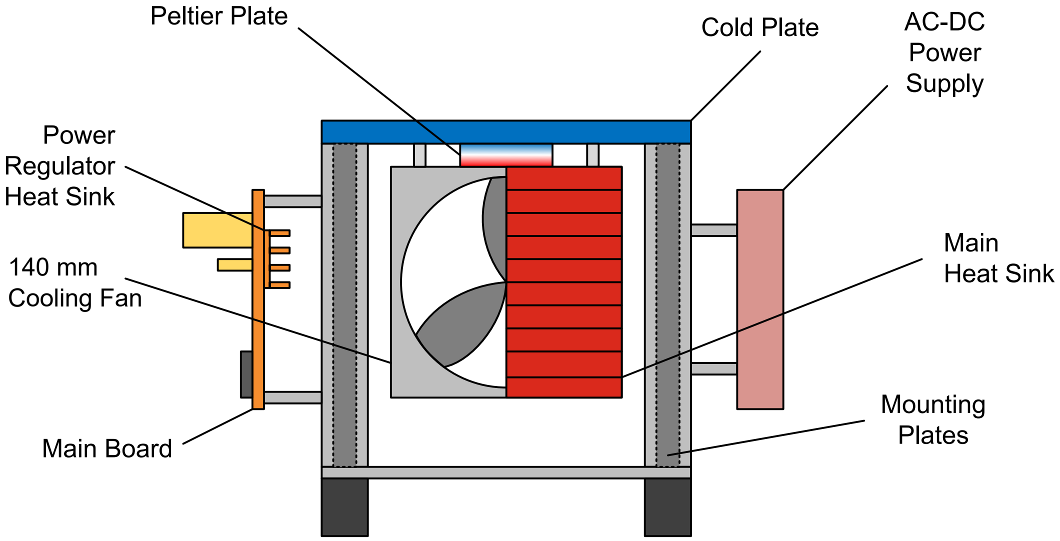
Figure 3-9. Typical Peltier Performance Curve of CP85435 at 27°C



Note: Figure 3-9 is used with permission from CUI Devices, *cuidevices.com*.

To minimize the thermal gradient, the Peltier element is connected to a large CPU heat sink (a Noctua NH-D15S) with a 140 mm cooling fan. This fan is crucial – despite the size of the heat sink, the heat sink temperature quickly rises without active airflow. A basic model of the system elements is shown below in Figure 3-10.

Figure 3-10. Simplified Diagram of the System



One other source of heat is the power stage for the Peltier plates. A MOSFET is used to turn ON and turn OFF the power to the Peltier modules. At almost DC-level switching, the primary source of heating in the MOSFET is from R_{DS} (resistance from drain to source). Another source of power dissipation is from the current shunt resistor.

A future improvement for this system is to implement the OTP from the power-switching circuit. A possible method of implementing the OTP in the microcontroller without using any I/O is discussed in the Current Regulator OTP with NTC Sensing chapter.

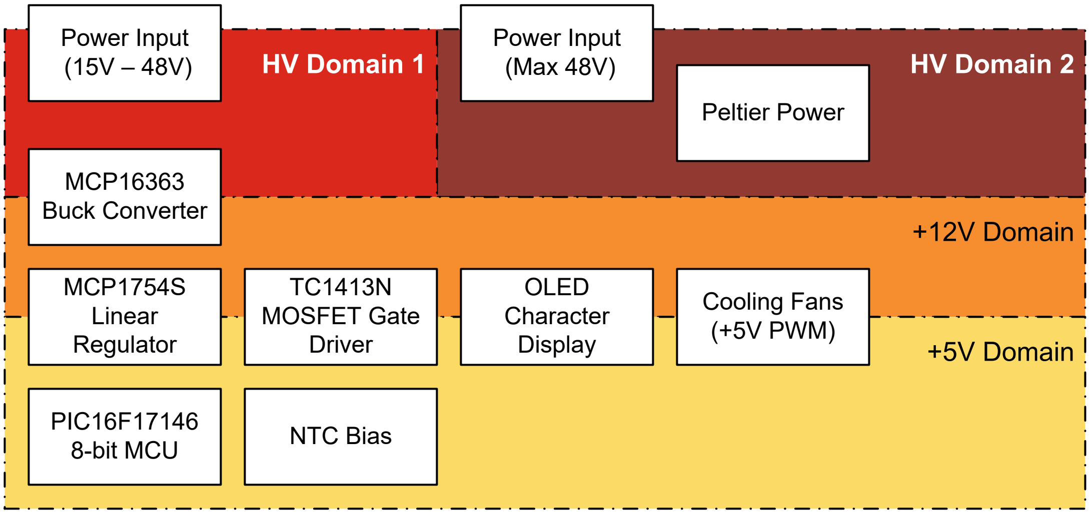
3.11 PCB Design

This system is built with two PCBs ; the main control board has the current regulator, digital power, fan and logic, while the daughter board only contains the OLED display and rotary encoder with a built-in push button. Given the simplicity of the daughter board, this chapter will focus on the main one.

3.11.1 Digital-Side Power Supplies

From the high-voltage power input, it is necessary to convert to the +12V used by the fans and the TC1413N MOSFET gate driver. To do this efficiently, a MCP16363 Buck Converter was used. The MCP16363 has a maximum input rating of 48V, providing a wide range of operating conditions. Next, a +5V rail for the digital logic and analog circuits is needed. Since the +5V rail does not pull a lot of current, an MCP1754S fixed output linear regulator was used to convert the +12V rail to +5V. The diagram below shows how power is distributed.

Figure 3-11. Power Distribution Network



Note: The Peltier power input is separate from the digital power input. In this example, the same power supply is used for both, but they can also be separated.

3.11.2 Power Supply Protections

Multiple short-circuit protection circuits are built into this system. Starting from the AC side, there is a mains-side fuse for the commercial-grade AC-DC power supply. If the main power supply ever faults, this fuse will trip. This provides additional protection for the system in the event of water ingress or other unexpected conditions.

Continuing on the DC side, there is a fuse on each of the power inputs to the main board. The Peltier side (HV Domain 2) uses a user-replaceable 3AG fuse while the digital logic side (HV Domain 1) uses a board-mount SMD fuse. Different fuses were selected because the Peltier module consumes a lot of current with current spikes, while the digital logic side should never see such large transients. It is expected that if the logic side fuse trips, something failed catastrophically, thus requiring the board to be repaired before it could be used again.

Next, Positive Temperature Coefficient (PTC) self-resetting fuses were added to each of the fan headers on the board. This ensures that if a fan short-circuits, the +12V rail will also not be shorted. Another protection for the +12V rail is from the MCP1754S linear regulator. This linear regulator contains short-circuit protection with current-foldback limiting. The last power protection on the board are two PTCs on the +5V and +12V outputs to the display board. This ensures that if the connector is short circuited, the current is limited.

3.11.3 Capacitor Selection

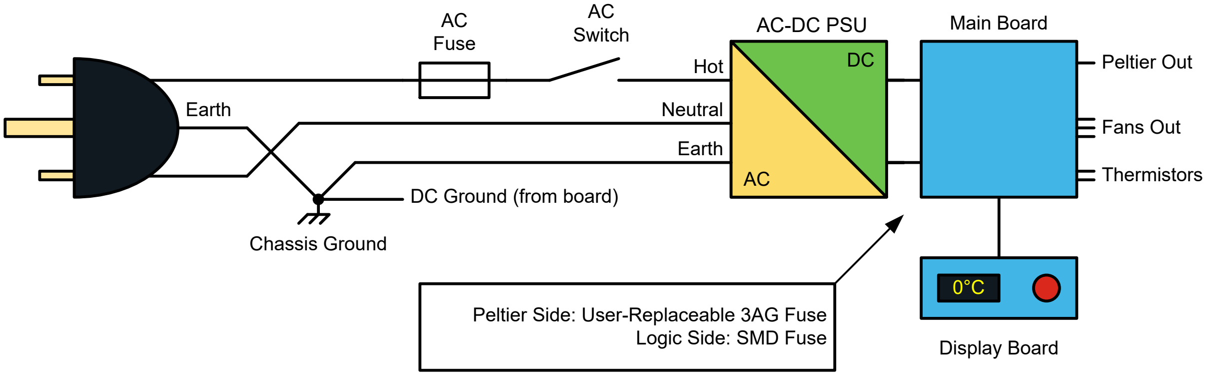
The capacitor bank is connected from Peltier+ to GND after the fuse. It is composed of a mix of large electrolytic capacitors, solid-state aluminum capacitors and ceramic capacitors. This bank is used to start the regulator and must be appropriately rated for the highest ripple possible. However, it is important not to store excessive amounts of energy in this bank. Too much capacitance would exceed the limits the AC-DC converter.

The selected mix of capacitors is intended to balance ripple with energy storage. Two 270 μF electrolytic capacitors provide bulk energy storage, while six 22 μF solid-state capacitors add extra high-frequency ripple capacity, but not a lot of capacitance. Finally, two 1 μF ceramic capacitors are added to give some extra ripple capacity and handle the surge current.

3.12 Wiring Diagram

The diagram below shows how the cold plate is wired together.

Figure 3-12. Wiring Diagram for the Cold Plate



4. Design Constraints

4.1 I/O Pin Count

One of the limiting factors of this design is the I/O count. With a few more I/O pins, more functionality could be implemented. Some possibilities include:

- Peltier Hot/Cold Inversion
  - By flipping the polarity of the Peltier plate, the cold side becomes hot and vice versa
- Peltier Power Supply Temperature Monitoring

4.2 Memory Constraints

This system uses a sizable amount of memory – because of this, the code was tweaked to reduce memory usage where possible. Another option is to enable professional compiler optimization, but this isn't an option for every user. The chapters below discuss some of the ways memory usage was reduced.

4.2.1 Reducing Memory Usage of `printf`

Among the biggest users of memory were the `printf` statements. These statements are not required for functionality but provides useful debugging and telemetry data for us to view while the system is operating. However, in this case, the memory requirements of using `printf` statements were too great for this application. Thus, simple string prints with a few functions for integer to string conversion were implemented.

4.2.2 Reducing Stack Depth

Another encountered issue was the stack. PIC® microcontrollers use a hardware stack to store function calls. Since this is a hardware implementation, there is a finite limit to the number of stack positions. With the overhead of our interrupts plus the UI software executing, the stack could exceed the maximum size and cause a stack overflow.

To resolve this, the menu for the UI was re-engineered to reduce the stack depth, which helped, but did not fully resolve the issue. A compile-time option called *Compiled Stack* in the XC8 compiler options was used to optimize the stack usage to within the limits of the hardware. Refer to Section 5.2.4.2.1 **"Compiled Stack Operation"**of the *"MPLAB® XC8 C Compiler User's Guide for PIC® MCU"* (DS50002737) for more information.

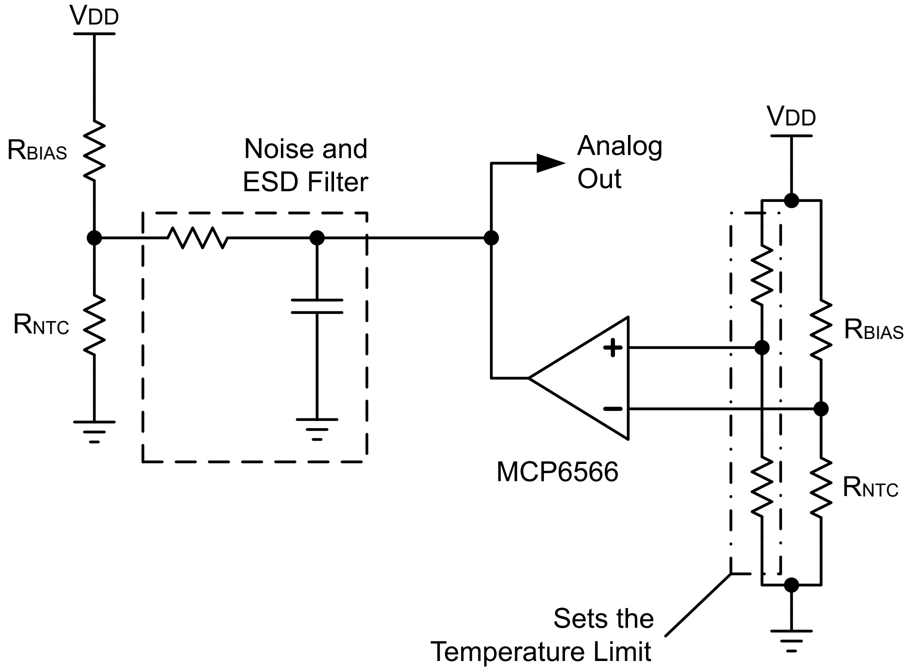
5. Future Improvements

5.1 Current Regulator OTP with NTC Sensing

One of the concerns with this first version of the design is that there is no way to directly measure the temperature of the current regulator without losing another feature that was implemented. However, for future versions this simple circuit can implement Over-Temperature Protection (OTP) without using an I/O pin on the MCU.

Rather than directly measuring the temperature at the current regulator, instead use an external MCP6566 analog comparator with a temperature sensor, as shown in Figure 5-1. This comparator is open-drain, rather than push-pull. Since the output is usually high-Z, the comparator can sit on the NTC thermistor line for the heat sink. If the current regulator reaches a high temperature and activates the comparator, then the comparator will pull the line to ground. Since NTCs reduce their resistance with temperature, the microcontroller will detect this state as a very high temperature on the main heat sink and activate a shutdown of the system.

Figure 5-1. NTC Measurement Circuit with OTP



5.2 Soft-Start Circuit

When the Peltier element starts up, there is a brief surge of current through the element. This problematically tripped the overcurrent protection circuit during development, but the issue was resolved by switching to a polling-based approach, rather than continuous monitoring. However, with the Peltier element, a soft-start circuit would be a good addition. The circuit could slowly start the current through the plate, preventing the surge from occurring in the first place.

6. Conclusion

This application note explored the design and implementation of a Peltier Cooled Metal Plate using a PIC16F17146 MCU. The purpose of this demo was to demonstrate the broadening capabilities of 8-bit microcontrollers, also displaying how CIPs allow MCUs to punch above their weight and tackle challenges that normally would require a substantial upgrade in CPU performance. The functional blocks of this design are adaptable and can be applied in many applications.

7. Appendix A - Revision History

Revision	Date	Description
A	2/2023	Initial Revision
B	2/2023	Modified Introduction Link

8. Appendix B – CIP Glossary

Peripheral Name	Definition
8-bit DAC	8-bit Digital-to-Analog Converter
12-bit Differential ADCC	12-bit Differential Analog-to-Digital Converter with Computation
16-bit PWM	16-bit Pulse Width Modulators with Compare
CCP	Capture Compare PWM
CLC	Configurable Logic Cell
CLKREF	Reference Clock Output
CMP	Comparator
CRC	Cyclic Redundancy Check
CWG	Complementary Waveform Generator
EEPROM	Electronic Erasable Programmable Read Only Memory
EUSART	Enhanced Universal Synchronous Asynchronous Receiver
FVR	Fixed Voltage Reference
MSSP	Host Synchronous Serial Port (capable of either Serial Peripheral Interface (SPI) or I^2C)
NCO	Numerically Controlled Oscillator
OPAMP	Operational Amplifier
PPS	Peripheral Pin Select
Temperature Indicator	Temperature Indicator
TMR0	Timer0
TMR1/3	Timer1/3/…
TMR2/4	Timer2/4/…
WWDT	Windowed Watchdog Timer
ZCD	Zero-Cross Detection

9. Appendix C – Pin Assignments

Physical Pin	Pin Name	Application Use
1	V_{DD}	+5V Input
2	RA5	Fan Tachometer Input 1
3	RA4	Fan Tachometer Input 2
4	$\overline{\text{MCLR}}$/V_{PP}/RA3	$\overline{\text{MCLR}}$ and Reset
5	RC5	Switching Transistor PWM
6	RC4	Fan Control PWM
7	RC3	Quadrature Decoder Input
8	RC6	Quadrature Decoder Input
9	RC7	I^2C Serial Data (SDA)
10	RB7	I^2C Serial Clock (SCL)
11	RB6	Debug Universal Asynchronous Receiver Transmitter (UART) TX
12	RB5	OPAMP In+
13	RB4	Display Reset
14	RC2	OPAMP Output
15	RC1	Push button Input
16	RC0	Heat Sink Thermistor
17	RA2	Cold Plate Thermistor
18	RA1/ICSPCLK	LED Status/ICSPCLK
19	RA0/ICSPDAT	LED Error/ICSPDAT
20	V_{SS}	Ground

10. Appendix D – CIP Usage

Memory, I/O and Safety Features

Peripheral	Available on Device	Used by Application	Remaining
EEPROM	256B	11B	245B
PPS	Yes	Yes	N/A
CRC	Yes	Yes	N/A
WWDT	Yes	Yes	N/A

Timers and Waveform Generators

Peripheral	Available on Device	Used by Application	Remaining
TMR0	1	1	0
TMR1/3	2	2	0
TMR2/4	2	2	0
NCO	1	0	1
CCP	2	0	2
16-bit PWM	2	2	0
CWG	1	0	1
CLC	4	2	2
CLKREF	1	0	1

Analog

Peripheral	Available on Device	Used by Application	Remaining
12-bit Differential ADCC	Yes	Yes	N/A
Temperature Indicator	Yes	Yes	N/A
FVR	2	2	0
8-bit DAC	2	2	0
Operational Amplifier (OPAMP)	1	1	0
CMP	2	2	0
ZCD	1	0	1

Serial Communications

Peripheral	Available on Device	Used by Application	Remaining
MSSP (SPI/I^{2}C)	2	1	1
EUSART	2	1	1

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