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**MCP6N11 and MCP6V2x  
Wheatstone Bridge  
Reference Design  
User's Guide**

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# MCP6N11 AND MCP6V2X WHEATSTONE BRIDGE REFERENCE DESIGN USER'S GUIDE

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# MCP6N11 AND MCP6V2X WHEATSTONE BRIDGE REFERENCE DESIGN USER'S GUIDE

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## Preface

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### NOTICE TO CUSTOMERS

All documentation becomes dated, and this manual is no exception. Microchip tools and documentation are constantly evolving to meet customer needs, so some actual dialogs and/or tool descriptions may differ from those in this document. Please refer to our web site ([www.microchip.com](http://www.microchip.com)) to obtain the latest documentation available.

Documents are identified with a "DS" number. This number is located on the bottom of each page, in front of the page number. The numbering convention for the DS number is "DSXXXXA", where "XXXX" is the document number and "A" is the revision level of the document.

For the most up-to-date information on development tools, see the MPLAB® IDE online help. Select the Help menu, and then Topics to open a list of available online help files.

## INTRODUCTION

This chapter contains general information that will be useful to know before using the MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design User's Guide. Items discussed in this chapter include:

- Document Layout
- Conventions Used in this Guide
- Recommended Reading
- The Microchip Web Site
- Customer Support
- Document Revision History

## DOCUMENT LAYOUT

This document describes how to use the MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design. The manual layout is as follows:

- **Chapter 1. “Product Overview”** – Important information about the MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design.
- **Chapter 2. “Installation and Operation”** – Covers the initial set-up of this board, required tools, board setup and lab equipment connections.
- **Chapter 3. “Analog Circuit”** – Discusses the analog functionality of the circuit on this board.
- **Chapter 4. “Firmware”** – Discusses the firmware on the PIC<sup>®</sup> device.
- **Chapter 5. “Software GUI”** – Discusses the GUI on the PC.
- **Appendix A. “Schematics and Layouts”** – Shows the schematic and board layouts for the MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design.
- **Appendix B. “Bill Of Materials (BOM)”** – Lists the parts used to populate the MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design. Also lists alternate components.
- **Appendix C. “Conversion Polynomials”** – Gives background information on the polynomials used in firmware.
- **Appendix D. “Board Validation Summary”** – Summarizes analog performance of two boards.

## CONVENTIONS USED IN THIS GUIDE

This manual uses the following documentation conventions:

### DOCUMENTATION CONVENTIONS

Description	Represents	Examples
<b>Arial font:</b>		
Italic characters	Referenced books	<i>MPLAB<sup>®</sup> IDE User's Guide</i>
	Emphasized text	...is the <i>only</i> compiler...
Initial caps	A window	the Output window
	A dialog	the Settings dialog
	A menu selection	select Enable Programmer
Quotes	A field name in a window or dialog	"Save project before build"
Underlined, italic text with right angle bracket	A menu path	<u><i>File&gt;Save</i></u>
Bold characters	A dialog button	Click <b>OK</b>
	A tab	Click the <b>Power</b> tab
N'Rnnnn	A number in verilog format, where N is the total number of digits, R is the radix and n is a digit.	4'b0010, 2'hF1
Text in angle brackets < >	A key on the keyboard	Press <Enter>, <F1>
<b>Courier New font:</b>		
Plain Courier New	Sample source code	#define START
	Filenames	autoexec.bat
	File paths	c:\mcc18\h
	Keywords	_asm, _endasm, static
	Command-line options	-Opa+, -Opa-
	Bit values	0, 1
	Constants	0xFF, 'A'
Italic Courier New	A variable argument	<i>file.o</i> , where <i>file</i> can be any valid filename
Square brackets [ ]	Optional arguments	mcc18 [options] <i>file</i> [options]
Curly brackets and pipe character: {   }	Choice of mutually exclusive arguments; an OR selection	errorlevel {0 1}
Ellipses...	Replaces repeated text	var_name [, var_name...]
	Represents code supplied by user	void main (void) { ... }

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

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## RECOMMENDED READING

This user's guide describes how to use MCP6N1X. Other useful documents are listed below. The following Microchip documents are available and recommended as supplemental reference resources.

- **MCP6001 Data Sheet (DS21733)**  
Provides detailed information on the op amp that is used for VREF.
- **MCP6N11 Data Sheet – “500 kHz, 800  $\mu$ A Instrumentation Amplifiers” (DS25073)**  
Provides detailed information on the INA that is used for INA #1.
- **MCP6V26/7/8 Data Sheet – “620  $\mu$ A, 2 MHz Auto-Zeroed Op Amps” (DS25007)**  
Provides detailed information on the auto-zeroed op amps used for INA #2.
- **PIC18F2455/2550/4455/4550 Data Sheet – “28/40/44-Pin, High-Performance, Enhanced Flash, USB Microcontrollers with nanoWatt Technology” (DS39632)**  
Provides information on the USB PIC MCU family.
- **PIC18F2458/2553/4458/4553 Data Sheet – “28/40/44-Pin High-Performance, Enhanced Flash, USB Microcontrollers with 12-Bit A/D and nanoWatt Technology” (DS39887)**  
Provides additional information on the USB PIC MCU devices with 12-bit ADCs.
- **AN1258 Application Note – “Op Amp Precision Design: PCB Layout Techniques” (DS01258)**  
Discusses methods to minimize thermo-junction voltage effects in a PCB design.

## THE MICROCHIP WEB SITE

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- **Product Support** – Data sheets and errata, application notes and sample programs, design resources, user's guides and hardware support documents, latest software releases and archived software
- **General Technical Support** – Frequently Asked Questions (FAQs), technical support requests, online discussion groups, Microchip consultant program member listing
- **Business of Microchip** – Product selector and ordering guides, latest Microchip press releases, listing of seminars and events, listings of Microchip sales offices, distributors and factory representatives



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Users of Microchip products can receive assistance through several channels:

- Distributor or Representative
- Local Sales Office
- Field Application Engineer (FAE)
- Technical Support
- Development Systems Information Line

Customers can contact their distributor, representative or field application engineer for support. Local sales offices are also available to help customers. A listing of sales offices and locations is included in the back of this document.

Technical support is available on the web site at: <http://www.microchip.com/support>.

### **DOCUMENT REVISION HISTORY**

#### **Revision A (January 2012)**

The initial release of this document.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

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NOTES:

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## Chapter 1. Product Overview

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### 1.1 INTRODUCTION

The MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design is described by the following:

- Assembly #: 114-00354-R2
- Order #: ADM00354
- Name: MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

This board uses the following Microchip ICs:

- MCP6001 (op amp)
- MCP6N11-100 (INA)
- MCP6V27 (dual auto-zeroed op amp)
- MCP6V26 (single auto-zeroed op amp)
- PIC18F2553 (USB PIC<sup>®</sup> microcontroller)

Items discussed in this chapter include:

- Purpose
- Description
- What Does this Kit Contain?

### 1.2 PURPOSE

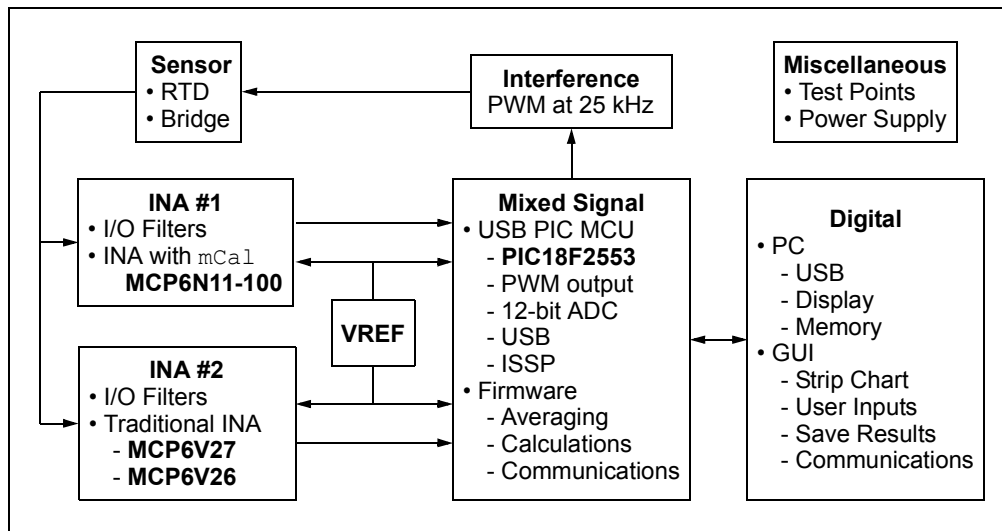
This board demonstrates the performance of Microchip's MCP6N11 instrumentation amplifier (INA) and a traditional three op amp INA using the MCP6V26 and MCP6V27 auto-zeroed op amps from Microchip. The input signal comes from an RTD temperature sensor in a Wheatstone bridge. Real world interference is added to the bridge's output, to provide realistic performance comparisons.

Data is gathered and displayed on a PC, for ease of use. The USB PIC microcontroller and included Graphical User Interface (GUI) show how to implement these functions.

## 1.3 DESCRIPTION

### 1.3.1 Block Diagram

Figure 1-1 shows the overall functionality of this demo board. Detailed information is available in **Appendix A. “Schematics and Layouts”** and **Appendix B. “Bill Of Materials (BOM)”**.



**FIGURE 1-1:** Overall Block Diagram.

This board uses an RTD temperature sensor, in a Wheatstone bridge, to measure the board's temperature. The bridge's output is a small Differential mode (DM) signal with a large Common mode (CM) interference signal superimposed. The CM signal is a PWM waveform generated by the microcontroller, which simulates real world interference.

VREF (not a fixed reference) outputs a voltage level proportional to the analog supply voltage, keeping the INAs' outputs in range.

The two INAs process the bridge's output, rejecting the CM interference and providing large gains for the DM signal. There are R-C low-pass filters at the input and output of each INA.

A pulse-width modulation (PWM) signal at 25 kHz is an optional output of the microcontroller. It shows how the two INAs perform with one type of real world interference. This signal can represent, for instance, interference from an H-bridge motor controller.

Test points simplify bench setups.

The power supply can be provided by the USB or by a lab power supply.

A 12-bit ADC inside the microcontroller converts analog signals to digital data.

The microcontroller's firmware averages the data to achieve noise and data rate reduction. It then subtracts the VREF voltage from the INA outputs (correcting any slow VREF errors), calculates the voltages and temperatures, calibrates the temperature and sends data to the PC via the USB.

The ICSP header allows the user, if desired, to re-program the microcontroller. In many cases, the installed firmware will provide the necessary functionality for an evaluation of this design.

The GUI (Thermal Management Utility) runs on the PC. It handles communications through the USB, displays results on a strip chart, stores single point calibration coefficients on the PIC MCU, tells the PIC MCU how to configure the averaging filter, initiates offset calibration events for the MCP6N11 and exports data to CSV files.

## 1.3.2 Sensor

The RTD converts board temperature to resistance with a nearly linear response. It is placed in a Wheatstone bridge to convert its resistance to a (small) DM voltage. The bridge's characteristics are:

- Ratiometric current (reducing hardware and firmware complexity)
- Sets the CM voltage at mid-supply (2.5V) for the greatest headroom

## 1.3.3 Interference

The PIC device outputs a PWM waveform at 25 kHz (when it is enabled by the GUI and by JP2), which can be coupled onto the top of the bridge using a jumper (JP1); this is a CM interference signal (about  $0.2 V_{P-P}$  at the bridge). The coupling mechanism can be either a capacitor or a resistor with a DC blocking capacitor; the bridge's DC bias point is not affected. This interference demonstrates how bridges are susceptible to CM noise.

The following are options selected with a jumper or in the GUI:

- GUI option:
  - Enable or Disable the PIC MCU's PWM output
- JP1 options:
  - Couple=C uses a capacitor to put the PWM waveform on the bridge
  - Couple=RC uses resistive coupling (with a DC blocking capacitor) to put the PWM waveform on the bridge
  - Couple=Open disconnects the PWM signal from the bridge
- JP2 options:
  - PWM=PIC connects the PIC MCU's PWM signal onto the bridge
  - PWM=EXT connects an external (PWM) signal onto the bridge

## 1.3.4 VREF

VREF (not a fixed voltage reference) provides a buffered ratiometric level (proportional to  $V_{DD}$ ) that keeps the amplifiers in their normal operating range. When at the design point of  $V_{DD} = 5.0V$ , its output is 1.8V.

It has a low-pass filter at the output, whose pole is the same as the DM pole for the INA's input and output filters. This minimizes mismatches in the outputs, due to unequal settling after a  $V_{DD}$  disturbance.

## 1.3.5 INA #1

The input filter provides a low-pass function for both CM and DM signals. They are fast enough to follow supply variations and to let the INA reject CM mains noise (e.g., harmonics of 50 or 60 Hz).

This INA is the MCP6N11-100. It is set at a high DM gain (200 V/V) and has good CMRR at 25 kHz (92 dB, at the PWM frequency). Its  $V_{OS}$  is calibrated using the internal `mCal` function, which has the following (selectable) control options:

- The DUT is calibrated at power up
- The GUI sends a signal to the MCP6N11 via the USB PIC device
- The user presses  $SW_1$  (`mCalSw`)

The output filter provides a low-pass function for both CM and DM signals out of the INA. It is slow to minimize noise and interference.

## 1.3.6 INA #2

The input and output filters are the same as for the INA #1. This input filter is isolated from INA #1's input filter by the input resistors.

The INA is a traditional three op amp instrumentation amplifier. It uses Microchip's auto-zeroed MCP6V27(dual) and MCP6V26 (single). Its performance can be compared to INA #1; it is also set at a high DM gain (200 V/V). It has good CMRR at DC (>100 dB). Its CMRR at 25 kHz (e.g., 96 dB) is also good.

## 1.3.7 Mixed Signal

The USB PIC microcontroller performs the following functions:

- Interfaces with the analog circuitry:
  - 12-bit ADC
  - PWM output for interference
- Does calculations in firmware:
  - Averages data from the ADC
  - Converts voltages to temperature
  - Corrects the RTD temperature using stored calibration coefficients
  - Calculates the RTD resistance from temperature
- Communicates with the PC:
  - Uses the USB port to upload data (averaged voltages, temperatures and resistances)
  - Uses the USB port to download configuration options (calibrate INA #1, number of averages, temperature calibration coefficient)
- Provides easy programming for user designs, if desired:
  - ICSP interface

## 1.3.8 Digital

The PC is a convenient interface for the user. The GUI provides:

- Communications with the demo board (via the USB PIC device)
- Data display (strip chart)
- Data storage (graphics and text files)
- Configuration inputs
  - Temperature calibration (an input sent to the USB PIC MCU)
  - Send an `mCal` calibration signal (to the USB PIC MCU) now
  - Number of averages

## 1.3.9 Miscellaneous

The Test Points are for evaluating analog performance and for connecting a lab power supply:

- The +5.0V power supply is for all components on the PCB, when not connected to the USB
- A remote RTD can be connected via wires (for measuring elevated temperatures)
- The INA outputs (filtered and unfiltered) are available
- An external PWM signal provides for alternate interfering signals

The power supply provides a 5V rail from either lab equipment or from the USB.

### 1.4 WHAT DOES THIS KIT CONTAIN?

This MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design kit includes:

- MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design, 102-00354
- USB cable
- Important Information Sheet



FIGURE 1-2: MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design Kit Contents.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

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NOTES:



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## **Chapter 2. Installation and Operation**

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### **2.1 INTRODUCTION**

This chapter shows how to set up and operate the MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design. Items discussed in this chapter include:

- Required Tools
- Basic Configurations
- Configurations with Modifications
- Configuring the PCB

### **2.2 REQUIRED TOOLS**

#### **2.2.1 Setup With the PC**

The default setup uses the USB bus to connect to the PC. The following is required:

- MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design
- USB 2.0 Cable, A to Mini B
- PC
  - Microsoft Windows XP SP3, Vista, and 7 (64 and 32 bit)
  - .NET2 Framework
- Thermal Management Utility
  - Microchip's GUI for thermal demo boards
  - Version 1.4.0.0, or later

#### **CAUTION**

**When using the PC and USB, do not connect lab supplies to test points TP1 (+5.0V) and TP2 (GND). This avoids contention with the USB.**

#### **2.2.2 Bench Setup**

Measurements on the bench focus on analog performance; they only use the PIC microcontroller to generate the 25 kHz interference signal. The USB is not connected.

- MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design
- Lab Power Supply with single output
  - Generates +5.0V (TP1) and ground (TP2)
- Voltmeter
- Signal Analyzer (oscilloscope, network analyzer, spectrum analyzer, ...)
  - High input impedance (e.g., 1 M $\Omega$  || 10 pF)

#### **CAUTION**

**When using the bench setup (5V supply at TP1 (+5.0V) and TP2 (GND)), do not connect a USB cable to the demo board. This avoids contention with the lab supply.**

## 2.3 BASIC CONFIGURATIONS

The following sections discuss various configurations supported by this board.

### 2.3.1 Out of the Box Setup

The setup for these boards when they are shipped is as follows:

- R2 (RTD) is mounted on the PCB
- JP1 is at position #1 (Couple=C); the PWM signal capacitively couples to the bridge
- JP2 is at position #1 (PWM=PIC); the PIC MCU generates the PWM interference signal
  - The user must enable the PWM output (see #26 in **Section 5.9.2 “Additional Configuration and RTD Temp Tabs”**)
- USB cable connects the PCB and PC and provides power to the PCB
- No external power supply is connected to TP1 and TP2
- Thermal Management Utility (GUI) needs to be running before use
- ICSP connector not used

This is the most convenient setup for the user. Most of the work is handled by the GUI.

### 2.3.2 Other PWM Setups

#### 2.3.2.1 RESISTIVE COUPLING

Changing JP1 to position #2 (Couple=RC) gives a basically resistive coupling into the bridge. For convenience, C2 blocks any change in DC bias point.

#### 2.3.2.2 NO COUPLING

Changing JP1 to position #3 (Couple=Open) produces no coupling (no PWM signal at the bridge); it serves as a baseline that other options are compared to.

#### 2.3.2.3 EXTERNAL PWM

Changing JP2 to position #2 (PWM=EXT) allows the user to input an arbitrary PWM (interference) signal onto the board (using TP16).

<p><b>Note:</b> Changing JP2 to a vertical connection between pins 1 and 3 allows the PIC MCU's PWM signal to be sent off board, via TP16 (Vpwm<sub>x</sub>). This is useful for connecting to other PCBs.</p>
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### 2.3.3 Initiating VOS Calibration Events

At power up, the MCP6N11 internally self-calibrates. The GUI allows the user to send an `mCal` event signal to the PIC microcontroller, which uses an open drain connection to toggle the MCP6N11's (U2) EN/CAL pin. The `mCalSw` switch (SW1) also toggles this pin.

### 2.3.4 Other Power Supply Setup

The USB can be left open (don't use the PC) and a lab power supply connected to TP1 and TP2. This makes analog measurements easier and cleaner, but does not have the convenience of the GUI.

The effects of crosstalk, INA CMRR and analog filters can be examined in detail, using bench equipment.

## 2.4 CONFIGURATIONS WITH MODIFICATIONS

### 2.4.1 External RTD Setup

R2 can be external to the PCB, if desired, for sensing temperatures over a wider range. De-solder R2 from the PCB. Connect wires from TP3 and TP4 to the RTD (preferably the RTD that was de-soldered from the board).

This modification has the advantage of allowing a wider temperature range (you may need to change the INAs' gains). The main disadvantages come from the wiring resistance and connectors:

- The wiring resistance adds directly to the RTD resistance
  - The apparent RTD temperature increases
  - The increase has a significant random component to it
  - Accommodating different wire lengths and gauges in firmware is cumbersome and error prone
  - Wires can change resistance with aging
- Connectors can be less than ideal, due to:
  - Junctions between different metals (creating thermocouple voltages)
  - Vibration (wires become brittle and connections loosen over time)
  - Corrosion (resistance increases plus a DC potential appears over time)

Other circuits take advantage of 3-wire and 4-wire RTDs to solve some of these problems. The MCP6V26 data sheet's Typical Applications section shows one example.

### 2.4.2 Modified Firmware

The PIC microcontroller's firmware can be re-programmed via the ICSP connector. Modifications, that a user might decide to code, include:

- Different averaging scheme (for speed or noise performance)
- Convert  $V_{INA}$  to  $R_{RTD}$ , then  $R_{RTD}$  to  $T_{RTD}$  (if  $R_{RTD}$  is a required output)

### 2.4.3 Component Substitutions

The following component substitutions may be of interest to the user:

- Replace the MCP6V26 with either the MCP6V06 or the MCP6V01 (lower power)
- Replace the MCP6V27 with either the MCP6V07 or the MCP6V02 (lower power)
- Replace the MCP6N11-100 with another MCP6N11  $G_{MIN}$  option (need lower gain)
- Replace the RTD (requires a change in firmware) to evaluate another RTD

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## 2.5 CONFIGURING THE PCB

### 2.5.1 Test Points

Table 2-1 lists the test points and describes their functionality.

**TABLE 2-1: TEST POINTS**

Test Point					Comments
Ref. Des.	Label	Connector	I/O	A/D	
TP1	+5.0V	5.0V	I	A	Power supply (also labeled $V_{DD}$ ) ( <b>Note 1</b> )
TP2	GND	—	I	A	(for TP1)
TP3	Rtd1	Vrtd	I	A	Connected to external RTD (R2)
TP4	Rtd2	VL	I	A	
TP5	Vo1	Vo1	O	A	Un-filtered output of U2 (INA #1)
TP6	Vad1	Vad1	O	A	Filtered signal output of INA #1
TP7	Vad2	Vad2	O	A	Filtered reference output of INA #1
TP8	GND	—	I	A	(for TP5, TP6, TP7)
TP9	Vo2	Vo2	O	A	Un-filtered output of U3, Side A
TP10	Vo3	Vo3	O	A	Un-filtered output of U3, Side B
TP11	Vo4	Vo4	O	A	Un-filtered output of U4
TP12	GND	—	I	A	(for TP9, TP10, TP11)
TP13	Vad3	Vad3	O	A	Filtered signal output of INA #2
TP14	Vad4	Vad4	O	A	Filtered reference output of INA #2
TP15	GND	—	I	A	(for TP13, TP14, TP16)
TP16	Vpwms	Vpwmx	I	D	External PWM signal (couples onto bridge)

**Note 1:** Use this test point for only one of two purposes: to measure power supplied by the USB or to provide 5V power when the USB is not connected. **Do not** provide power to the USB and this test point at the same time.

### 2.5.2 Jumper and Switch Settings

Table 2-2 gives the jumper settings.

**TABLE 2-2: JUMPER SETTINGS**

Jumper				Comments
Identity		Position		
Ref. Des.	Label	No.	Label	
JP1	Couple=	1	C	Uses capacitive coupling between PWM source and bridge
		2	RC	Uses resistive coupling between PWM source and bridge; a DC-blocking capacitor avoids DC bias shifts and has low step response droop
		3	Open	No coupling of PWM source to bridge
JP2	PWM=	1	PIC	Use PIC MCU as source for PWM signal
		2	EXT	Use external source (via TP16) for PWM signal

**Note 1:** Changing JP2 to a vertical connection between pins 1 and 3 allows the PIC microcontroller's PWM signal to be sent off board, via TP16 (Vpwmx). This is useful for connecting to other PCBs.

## 2.5.3 Schematic Connectors

Table 2-3 shows the connector labels used in the schematic.

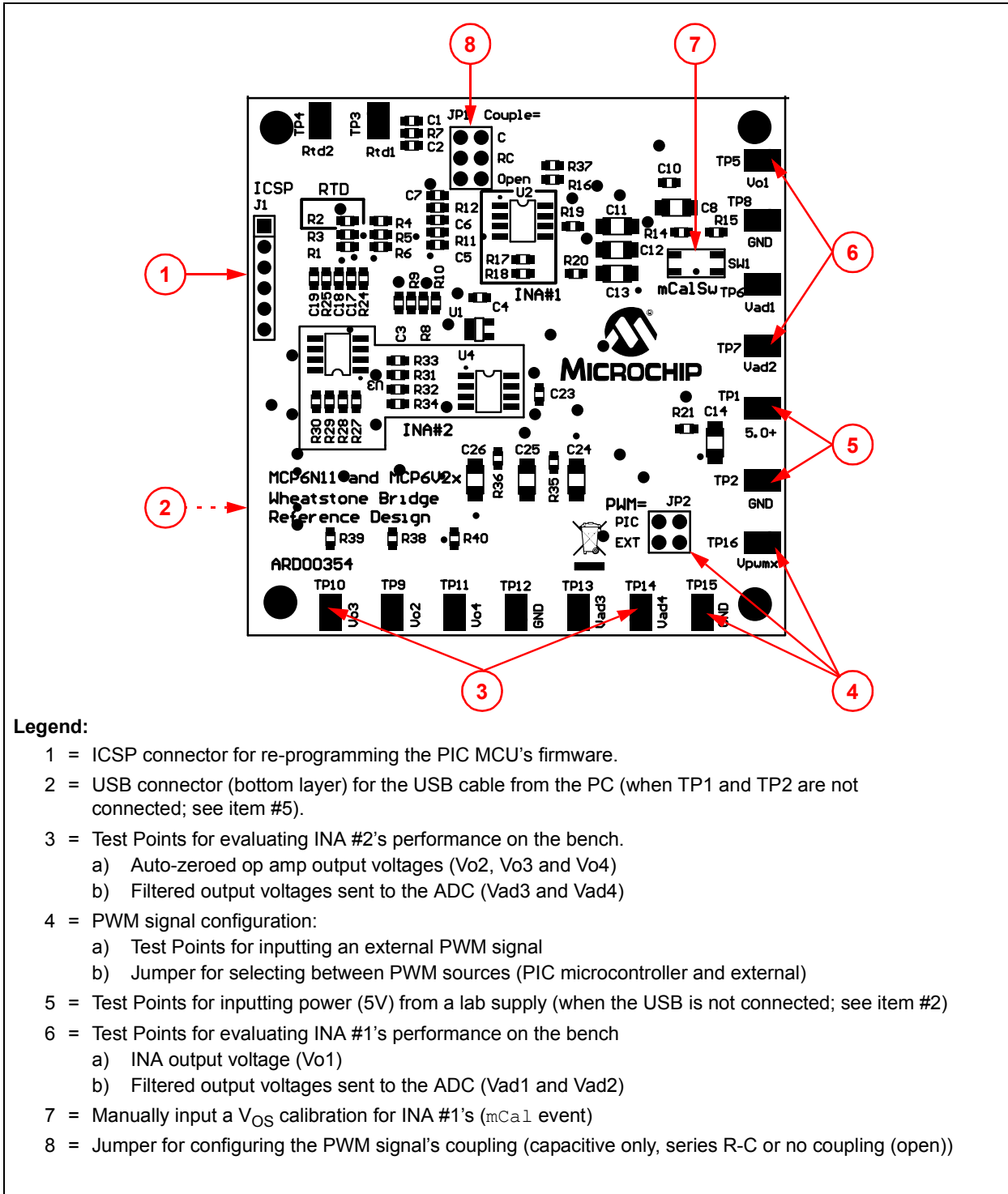
**TABLE 2-3: CONNECTOR LABELS**

External Signals			Internal Signals	
Label	Test Point	Description	Label	Description
5.0V	TP1	Power Supply	Vdd1	Filtered lab power supply; analog supply (PCB's power plane)
Vrtd	TP3	Connection to RTD	Vdd2	Filtered USB power; digital power
VL	TP4	Connection to RTD and negative output of bridge	Vdd3	USB power
Vad1	TP6	INA #1's signal output	VR	Positive output of bridge
Vad2	TP7	INA #1's ref. output	Vpwm	PWM output from PIC MCU
Vad3	TP13	INA #2's signal output	Vref	Buffered 1.8V reference
Vad4	TP14	INA #2's ref. output	E/C	mCal signal (EN/CAL) sent by PIC MCU
Vo1	TP5	U2's output		
Vo2	TP9	U3, Side A's output		
Vo3	TP10	U3, Side B's output		
Vo4	TP11	U4's output		
Vpwmx	TP16	External PWM input		

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## 2.5.4 Connection and Configuration Points on the PCB

Figure 2-1 shows the points on the PCB where equipment is connected, and where the configuration is altered.



**FIGURE 2-1:** Equipment Connection Scheme.

## Chapter 3. Analog Circuit

### 3.1 INTRODUCTION

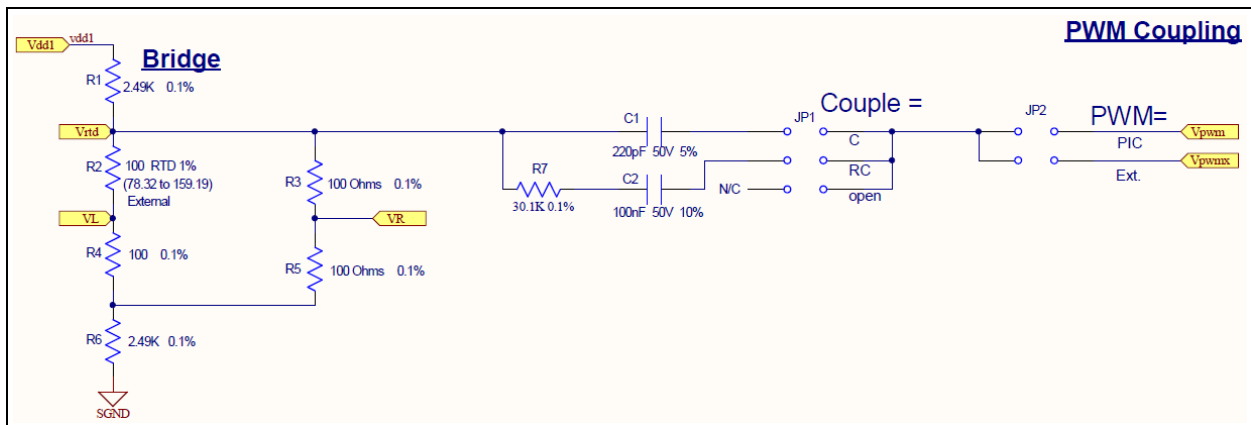
This chapter discusses the performance of the analog circuitry. Items discussed in this chapter include:

- Bridge With PWM Interference
- Signal Processing Circuitry
- PIC Microcontroller

### 3.2 BRIDGE WITH PWM INTERFERENCE

Figure 3-1 shows the Wheatstone bridge with one RTD element (R2) and three other resistors (R3, R4 and R5). R1 and R6 set the current, which is ratiometric with the 5.0V supply. R1 and R3-R6 are 0.1% resistors to minimize the gain error (they can be lower precision, if the user modifies the firmware to calibrate offset and gain errors).

V<sub>pwm</sub> is a 5 V<sub>P-P</sub> PWM signal generated by the PIC MCU (U3), which is set at 25 kHz and 50% duty cycle. JP1 selects a capacitive feedthrough (C1), a resistive feedthrough (R7, with C2 for DC-blocking) or no feedthrough (open). The first two methods produce roughly 0.2 V<sub>P-P</sub> at the top of the bridge (V<sub>rtd</sub>), while the last produces no PWM signal at V<sub>rtd</sub>. Inputting an external PWM signal (JP2, position #2) will give different results.



**FIGURE 3-1:** Bridge with PWM Interference.

The RTD's resistance is a quadratic polynomial in temperature (see **Appendix C. "Conversion Polynomials"**). It can be approximated as a linear polynomial, with a temperature error less than  $\pm 1.3^{\circ}\text{C}$ , but that is not accurate enough for applications requiring an RTD. The point is that the resistance to temperature conversion is a non-linear relationship.

The RTD's resistance (R2) appears in the denominator of the equation describing the bridge's differential output voltage (VR – VL) as a function of Vdd1 and the resistors R1 to R6. This means that the relationship between R2 and VR – VL is also non-linear.

Fortunately, as will be discussed later, the firmware does the necessary calculations to overcome these non-linear relationships.

## 3.3 SIGNAL PROCESSING CIRCUITRY

This circuitry includes two INAs, a VREF and corresponding filters. The MCP6N11's performance is contrasted with a three op amp INA based on the MCP6V27 and MCP6V26 auto-zeroed op amps.

### 3.3.1 Voltage Reference

Figure 3-2 shows the VREF block (not a fixed reference), which produces a buffered ratiometric (proportional to  $V_{DD}$ ) voltage ( $V_{ref}$ ).  $V_{ref}$  keeps the INAs within their range, even when  $V_{DD}$  changes. Errors in  $V_{ref}$  are subtracted out later in firmware.

The pole set at VREF's input matches Input Filter #1 and #2's Differential Mode (DM) poles so that power supply disturbances will be treated the same. Its output is 1.80V, which gives good output headroom for both INAs. The filter on the supply helps keep  $V_{ref}$  quiet. R8 and R9 are 1% resistors to minimize circuit cost; the error in  $V_{ref}$  is corrected in firmware (subtraction of  $V_{ref}$  from INA output voltages).

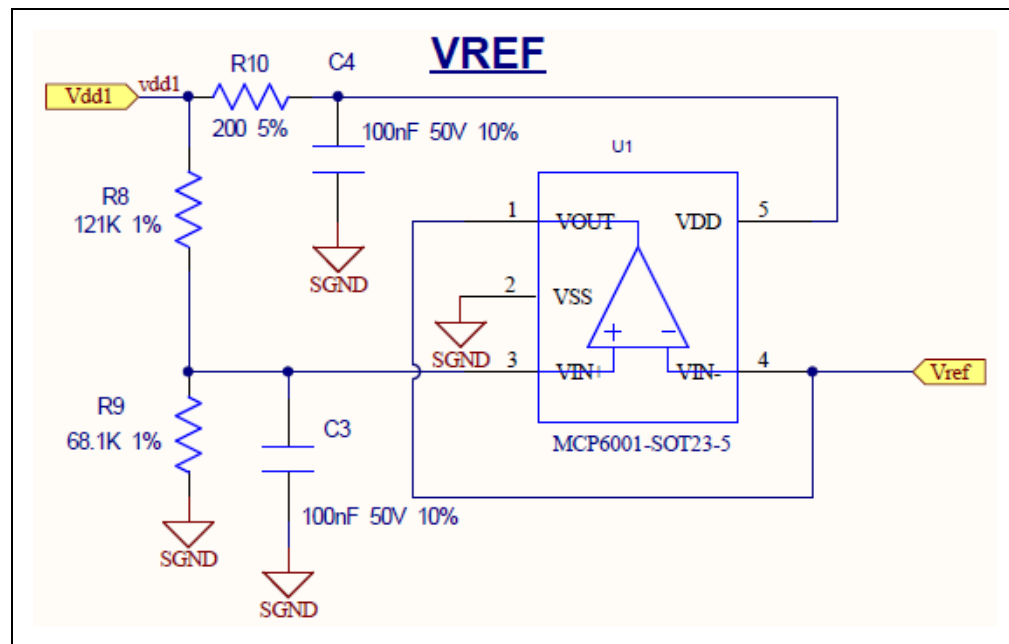


FIGURE 3-2: Voltage Reference.



### 3.3.2 First INA

Figure 3-3 shows INA #1, which includes the Input Filter #1, mCal #1 and Output Filter #1 blocks.

Input Filter #1 is a Differential Mode (DM) and Common Mode (CM), low-pass filter. The CM pole is at 800 Hz, so that INA #1 will reject mains interference (at 50 Hz or 60 Hz); its CMRR is very good at low frequencies. The DM pole is at 38 Hz, for low CM-to-DM conversion error, at a reasonable price. R11 and R12 are small enough to have good EMI performance; C5-C7 are sized for the desired poles.

INA #1 (U2) is set to a DM gain of 201 V/V, and has its output shifted up by 1.80V (Vref), producing an output that uses most of the ADC's input range. INA #1's CMRR at 25 kHz is excellent (e.g., 92 dB). INA #1's PSRR rejects mains interference (e.g., harmonics of 50 Hz or 60 Hz). R17 and R18 are 0.1% resistors to minimize gain error (they can be lower precision, if the user modifies the firmware to calibrate offset and gain errors).

To minimize thermo-junction voltage effects, at INA #1's input, R11 and R12 are close together and in parallel. See AN1258 (*Op Amp Precision Design: PCB Layout Techniques*) for more information on this topic.

Output Filter #1 is a DM and CM, low-pass filter. The CM pole is at 8 Hz, for further rejection of CM interference. The DM pole is at 2.7 Hz; it is faster than the RTD, but slow enough to limit the output noise. C12 is large enough to cause minimal gain error (it causes a voltage division as it interacts with the ADC's input sampling capacitor, C<sub>HOLD</sub> = 25 pF). R19 and R20 are small enough to have good EMI performance; C11-C13 are sized for the desired poles.

mCal #1 triggers an internal calibration event in U1 (MCP6N11), which corrects its V<sub>OS</sub>; the pole is set for SW1's maximum bounce time (10 ms). R16 makes the EN/CAL pin of INA #1 act as a wired-OR logic input; an E/C signal can be sent from the PIC MCU independent of mCalSw's state.

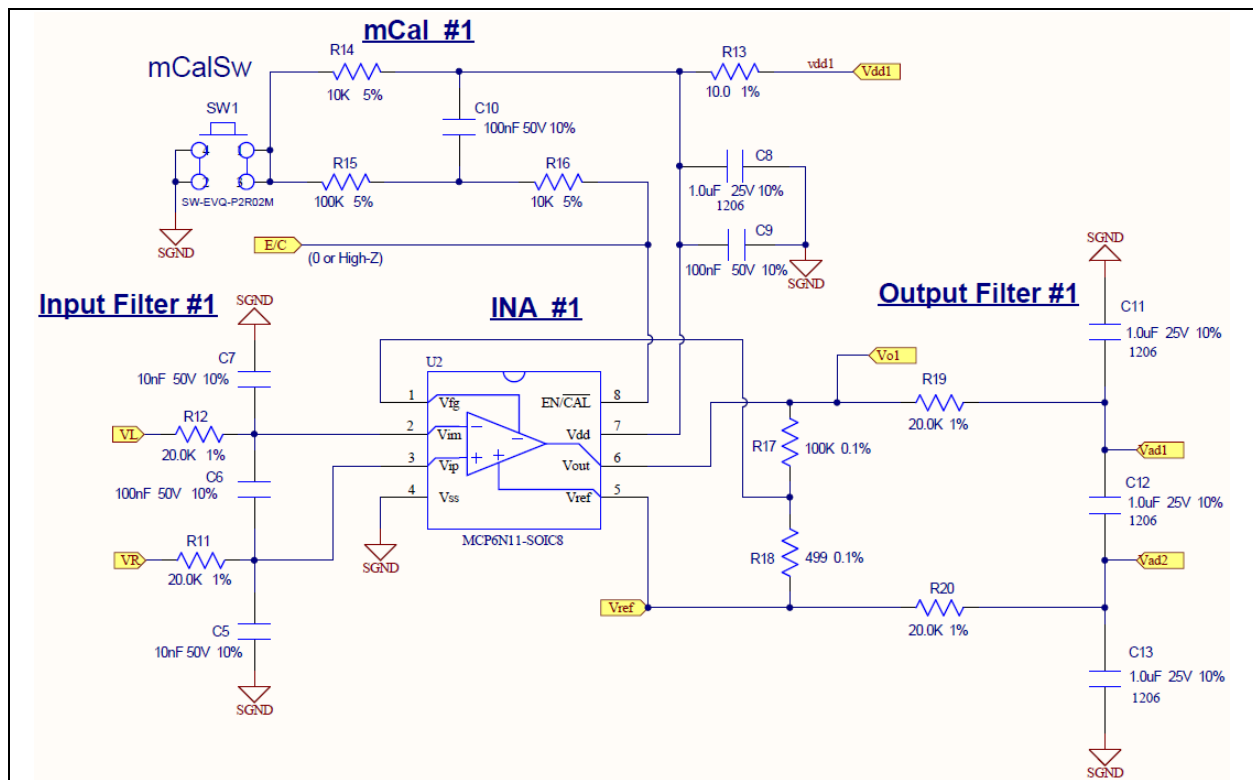


FIGURE 3-3: First INA.

## 3.3.3 Power Supply

Figure 3-4 shows the power supply connections and filters. Power is provided at either the Lab Power Supply or by the USB connection. The R-C low-pass filters have a pole at 0.80 kHz, which reduces ripple and crosstalk from the PWM interference; they are symmetrically placed so that applying power at either end works well. L1 isolates the analog and digital supplies, to prevent digital signals from interfering with the analog signals; it produces an L-C pole at 23 kHz (a compromise between performance and cost). R23 is a bleed-off resistor that discharges the bypass capacitors when no power supply voltage is present; its power drain is not significant. The signal connectors shown are:

- 5.0V = An external connection to the analog power supply voltage
  - When the USB powers the board (no lab supply connected), it provides a convenient point to measure the USB's 5V power
  - When a lab supply powers the board (USB is not connected), it is connected here (at TP1)
- Vdd1 = Analog power supply voltage
- Vdd2 = Digital power supply voltage
- Vdd3 = USB 5V power

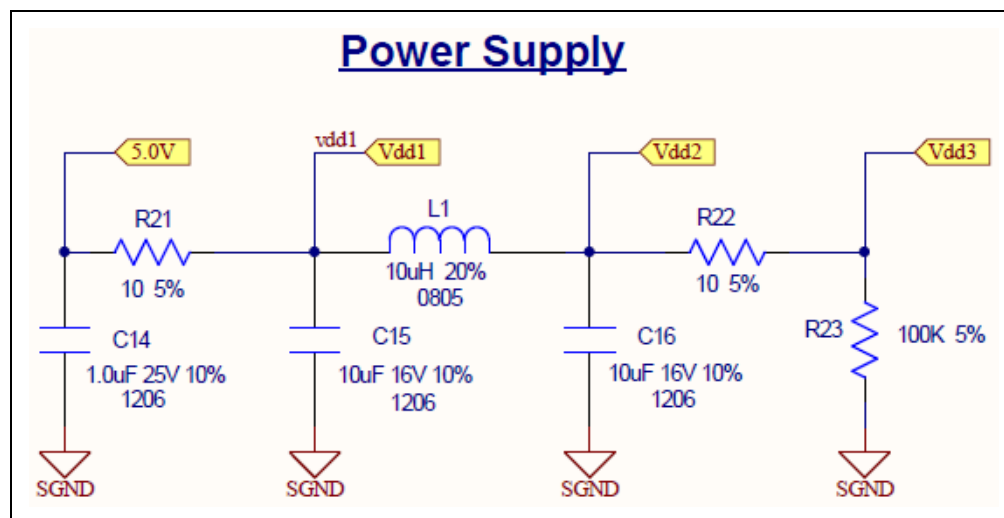


FIGURE 3-4: Power Supply.

### CAUTION

When using the PC and USB, **do not** connect lab supplies to test points TP1 (+5.0V) and TP2 (GND). This avoids contention with the USB.

When using the bench setup (5V supply at TP1 (+5.0V) and TP2 (GND)), **do not** connect USB to the demo board. This avoids contention with the lab supply.

### 3.3.4 Second INA (Traditional Three Op Amp Implementation)

Figure 3-5 shows INA #2, which provides a means of comparing the MCP6N11 to a traditional INA.

Input Filter #2 is the same as Input Filter #1, for ease of comparison. R24 and R25 provide a separate signal path, so that U3's input bias currents and U2's input bias currents don't interact.

INA #2 (U3, U4) is set to a DM gain of 201 V/V, and has its output shifted up by 1.80V (Vref), producing an output that uses most of the ADC's input range. INA #2's CMRR at 25 kHz is excellent (e.g., 96 dB). INA #2's PSRR rejects mains interference (e.g., harmonics of 50 Hz or 60 Hz). R27-R30 are 0.1% resistors to minimize gain error (they can be lower precision, if the user modifies the firmware to calibrate offset and gain errors). R31-R34 are 0.1% resistors to minimize gain error and maximize CMRR.

To minimize thermo-junction voltage effects, at INA #2's input, R24 and R25 are close together and in parallel. The gain resistors for U3 (R27-R30) are also close together and in parallel; R28 and R29 have not been combined into one resistor, to make this possible. The gain resistors for U4 (R31-R34) are also close together and in parallel.

See AN1258 ("Op Amp Precision Design: PCB Layout Techniques") for more information on this topic.

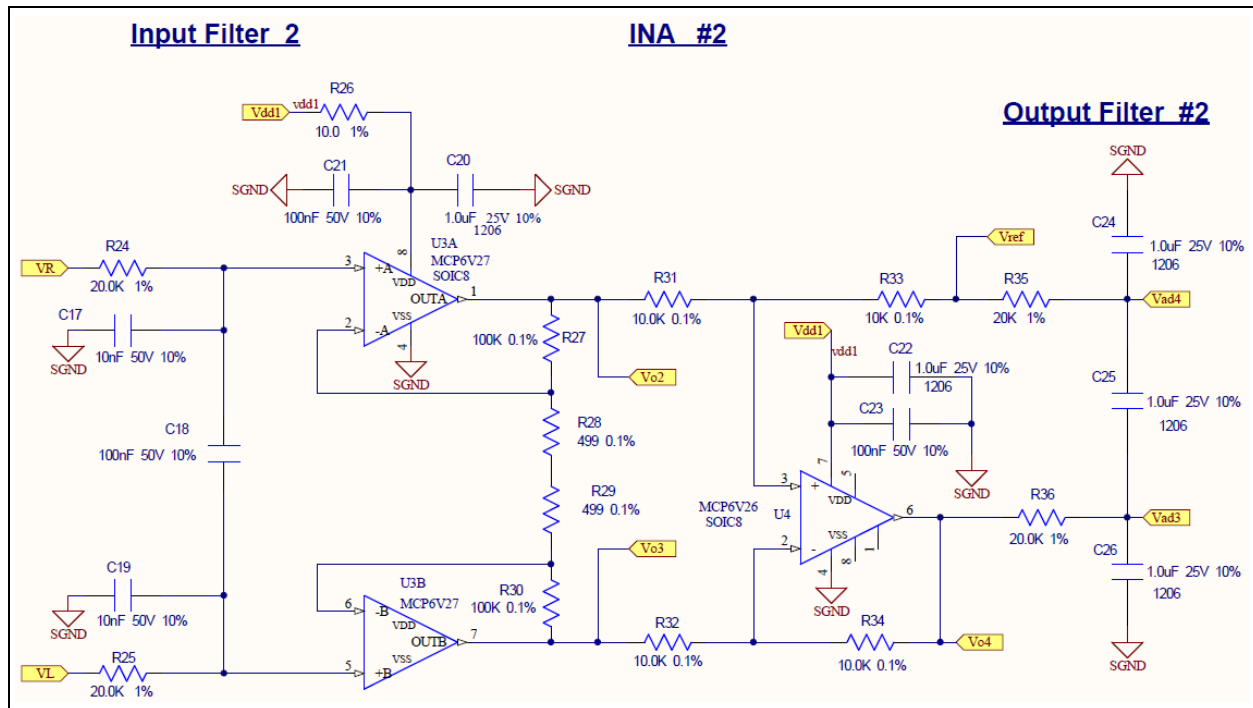


FIGURE 3-5: Second INA.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## 3.4 TEST POINTS

Figure 3-6 shows the test points available to the user. See Table 2-1 for a list of their functions.

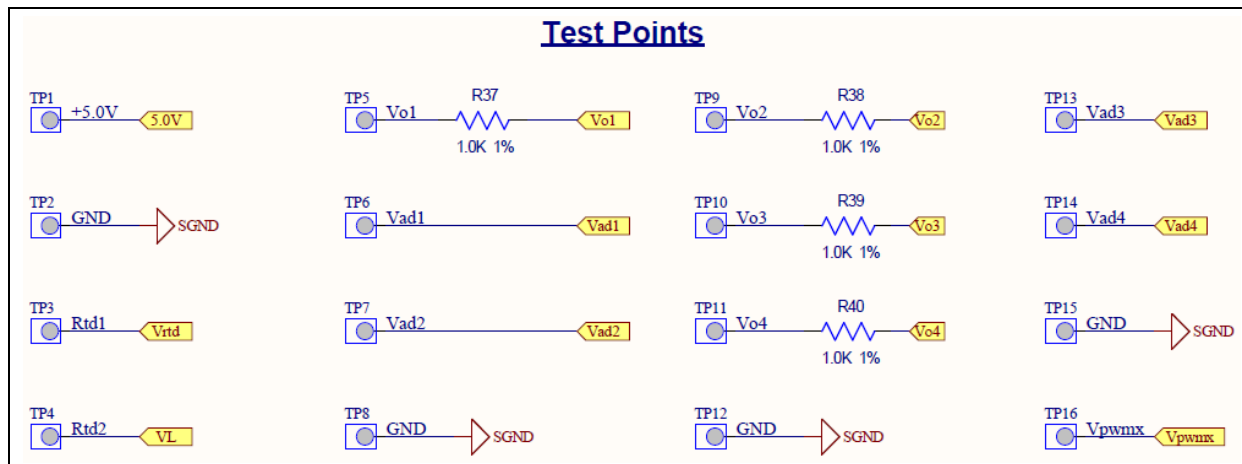


FIGURE 3-6: Test Points.

## 3.5 PIC MICROCONTROLLER

Figure 3-7 shows the PIC microcontroller (USB PIC MCU) with analog connectors to the blocks previously shown, local supply bypassing, a 20 MHz ceramic resonator, ICSP header and USB header.

The four ADC inputs (Vad1 to Vad4) are multiplexed into the USB PIC MCU's internal 12-bit ADC. As discussed later on, the firmware takes the differences Vad1 – Vad2 and Vad3 – Vad4, which corrects VREF's output error (present at Vad2 and Vad4). Since the analog signal processing circuitry does not totally eliminate interference from the 25 kHz PWM signal or the mains (50 Hz or 60 Hz), some will appear at the ADC inputs. The 12-bit ADC supports a typical temperature resolution better than 0.09°C.

The PWM output (Vpwm) is a 5 V<sub>P-P</sub> digital signal at 25 kHz and 50% duty cycle. It emulates the CM interference from a motor control application.

The 20 MHz ceramic resonator runs the USB PIC MCU at a rate that supports the firmware tasks' overhead and the USB. An internal PLL Prescaler divides by 5, to produce a 4 MHz clock. The internal PLL then locks onto this clock and produces a 96 MHz output, which is divided down for the USB module's operation.

Use a low ESR capacitor for C27.

The ICSP header makes it possible to program the USB PIC MCU in circuit, for further user experiments.

The USB header provides the data link to the PC, where data is displayed on the included GUI.

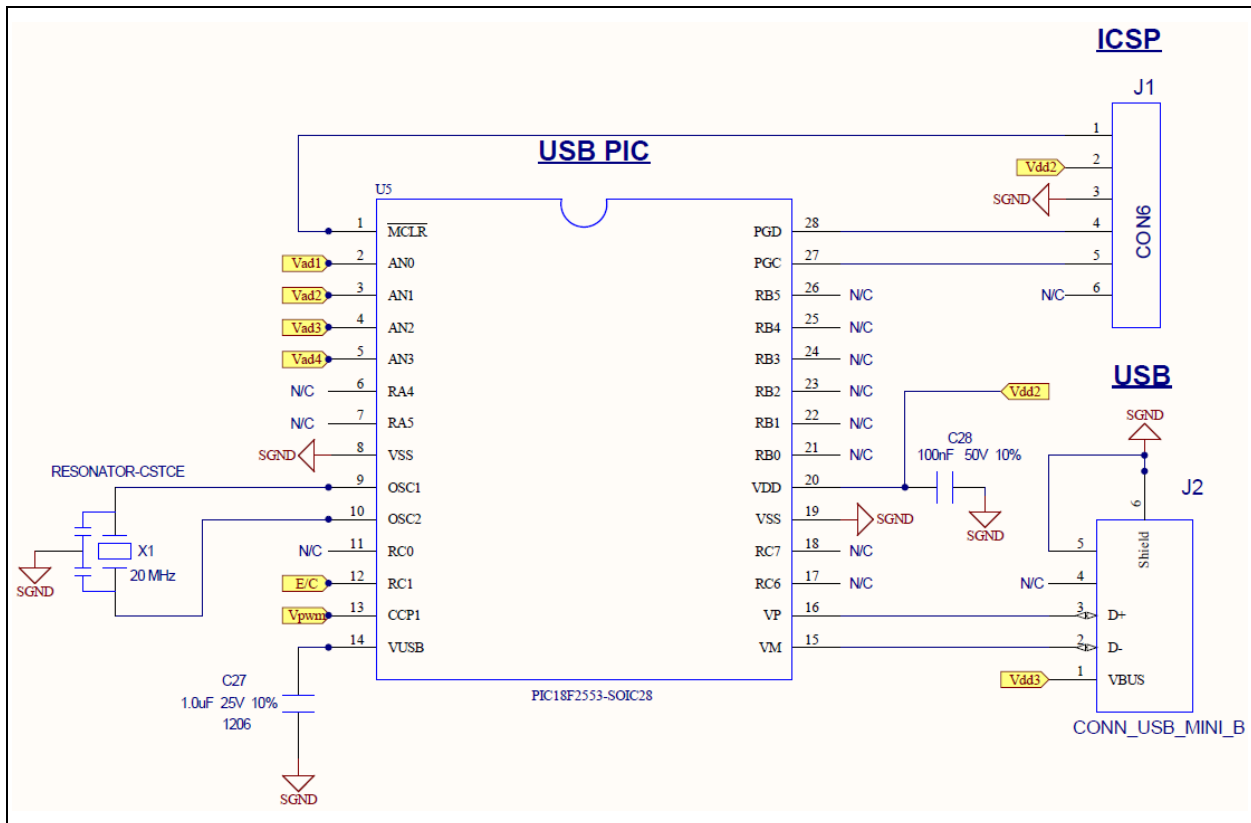


FIGURE 3-7: PIC Microcontroller.

Section Chapter 4. “Firmware” and Section Chapter 5. “Software GUI” discuss in detail how the digitized data is processed, displayed and stored.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

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## **Chapter 4. Firmware**

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### **4.1 INTRODUCTION**

This chapter discusses the PIC microcontroller's firmware. Items discussed in this chapter include:

- Analog Signals at the ADC Inputs
- Data Conditioning
- Temperature Calculations
- Resistance Calculations
- Calibrating the MCP6N11
- Temperature Calibration
- PWM Output
- USB Communications

### **4.2 ANALOG SIGNALS AT THE ADC INPUTS**

As discussed in **Section 3.2 “Bridge With PWM Interference”**, the relationship between the RTD temperature and RTD resistance is non-linear, as is the relationship between the RTD resistance and the bridge's differential output voltage. These non-linearities are corrected in firmware, because that minimizes the design cost.

**Section 3.3 “Signal Processing Circuitry”** mentions that interference from the 25 kHz PWM signal and the mains (50 Hz or 60 Hz) is reduced significantly, but not totally eliminated, at the ADC inputs. The firmware uses averaging to reduce the effect of these interfering signals.

The 12-bit ADC supports a temperature resolution that could be as good as 0.05°C. Since the analog inputs do not go rail-to-rail, for a more robust solution, the resolution is reduced somewhat. The non-linear relationships mentioned above make the resolution change, depending on the RTD temperature. The firmware solution gives a resolution between 0.06°C and 0.09°C. Obviously, the ADC is not ideal, so the temperature error can be somewhat larger.

## 4.3 DATA CONDITIONING

### 4.3.1 Basic Digital Data

The firmware on the PIC microcontroller inputs data for key analog DC voltages ( $V_{AD1}$  to  $V_{AD4}$ ), then converts them to digital ( $V_{AD1}$  to  $V_{AD4}$ ), with a 12-bit representation:

#### EQUATION

$$V_{AD1} = \text{INA \#1's signal (Vad1)}$$

$$V_{AD2} = \text{INA \#1's VREF (Vad2)}$$

$$V_{AD3} = \text{INA \#2's signal (Vad3)}$$

$$V_{AD4} = \text{INA \#2's VREF (Vad4)}$$

### 4.3.2 Data Sampling

The DC analog voltages are sampled in this order:  $V_{AD1}$ ,  $V_{AD2}$ ,  $V_{AD3}$ , and  $V_{AD4}$ . Each voltage is sampled every 50 ms (a 20 SPS rate). Since the ADC samples all four voltages, it takes a total of 80 samples per second.

### 4.3.3 Data Averaging and Output Data Rate

The GUI tells the microcontroller the number of averages ( $n$ ) or whether averaging is turned off. The GUI collects the averaged data from the microcontroller at adjustable time intervals.

When averaging is off, the firmware makes the latest sample available to the GUI. The samples are updated every 50 ms.

When averaging is on, the firmware calculates an exponential moving average, which is updated every 50 ms. These samples are made available for collection by the GUI. A higher number of averages ( $n$ ) reduces noise more, but has a slower response. The following equation shows how  $V_{AD1}$ ,  $V_{AD2}$ ,  $V_{AD3}$ , and  $V_{AD4}$  (shown as  $x_k$ ) are averaged (shown as  $y_k$ ):

#### EQUATION

$$y_k = \alpha x_k + (1 - \alpha) y_{k-1}$$

Where:

$$n = 2, 4, 8, 16, 32, 64 \text{ or } 128$$

$$\alpha = 2 / (n + 1)$$

$$x_k = \text{current sample}$$

$$y_{k-1} = \text{previous average}$$

$$y_k = \text{current average}$$



## 4.4 TEMPERATURE CALCULATIONS

It would be possible to convert the measured voltages into RTD resistance, then into RTD temperature. This approach adds overhead to the PIC MCU, so it was not done on this design; the firmware converts directly from INA voltage to temperature.

The firmware gives two estimates of the same RTD temperature, based on the outputs of INA #1 and INA #2:

### EQUATION

$$T_{RTD1} = \text{RTD temperature from INA \#1 (based on } V_{AD1} - V_{AD2})$$

$$T_{RTD2} = \text{RTD temperature from INA \#2 (based on } V_{AD3} - V_{AD4})$$

### 4.4.1 Polynomial Estimate of Temperature

**Section C.3 “INA Voltage to Temperature”** discusses the conversion of  $V_{INA}$  to  $T_{RTD}$ . This section summarizes those results. To accommodate fixed point arithmetic,  $T_{RTD}$  and  $V_{INA}$  are scaled as follows:

### EQUATION

$$v = V_{INA} / (V_{DD}/2)$$

$$w = T_{RTD} / T_{S1}$$

Where:

$$V_{INA} = V_{AD1} - V_{AD2}, \quad \text{for INA \#1}$$

$$= V_{AD3} - V_{AD4}, \quad \text{for INA \#2}$$

$$V_{DD}/2 = 2.5V$$

$$T_{S1} = 256^{\circ}C$$

The firmware uses a cubic polynomial for the conversion. Its accuracy supports the 12-bit ADC we are using (1 LSB is between 0.055°C and 0.088°C, nominally).

### EQUATION

$$w = K_0 + v (K_1 + v (K_2 + v (K_3))) \pm \epsilon_W$$

$$T_{RTD} = w T_{S1} \pm \epsilon_T$$

Where:

$$K_0 = 0.00002$$

$$K_1 = 0.50417$$

$$K_2 = 0.07463$$

$$K_3 = 0.01370$$

$$\epsilon_W = \text{Error in } w$$

$$\epsilon_T = \epsilon_W T_{S1}$$

$$|\epsilon_T| \leq 0.021^{\circ}C$$

$$T_{RTD} = T_{RTD1}, \quad \text{INA \#1}$$

$$T_{RTD2}, \quad \text{INA \#2}$$

The GUI collects 10 temperature estimates per second for each INA.

## 4.5 RESISTANCE CALCULATIONS

For convenience of the user, the firmware gives two estimates of the RTD resistance. We do not need these estimates, since we convert directly from voltage to temperature. They are useful, however, to a user that wants to change the firmware or hardware.

The firmware gives two estimates of the same RTD resistance, based on the previously calculated of  $T_{RTD1}$  and  $T_{RTD2}$ ; see **Appendix C. “Conversion Polynomials”**.

### EQUATION

$$R_{RTD1} = \text{RTD resistance from INA \#1 (based on } T_{RTD1}\text{)}$$
$$R_{RTD2} = \text{RTD resistance from INA \#2 (based on } T_{RTD2}\text{)}$$

To accommodate fixed point arithmetic,  $T_{RTD}$  and  $R_{RTD}$  are scaled as follows:

### EQUATION

$$p = T_{RTD} / T_{S1}$$
$$q = (R_{RTD} - R_{S0}) / R_{S1}$$

Where:

$$T_{S1} = +256^{\circ}\text{C}$$
$$R_{S0} = 120 \Omega$$
$$R_{S1} = 64 \Omega$$

The RTD's resistance is estimated with this polynomial approximation (with scaling):

### EQUATION

$$q = A_0 + p (A_1 + p (A_2)) \pm \varepsilon_Q$$
$$R_{RTD} = R_{S0} + q R_{S1} \pm \varepsilon_R$$

Where:

$$A_0 = -0.31251$$
$$A_1 = 1.56353$$
$$A_2 = -0.05946$$
$$\varepsilon_Q = \text{Error in } q$$
$$\varepsilon_R = \varepsilon_Q R_{S1},$$
$$|\varepsilon_R| \leq 0.0053 \Omega$$
$$R_{RTD} = R_{RTD1}, \text{ INA \#1}$$
$$= R_{RTD2}, \text{ INA \#2}$$
$$\varepsilon_T = \varepsilon_R / (dR_{RTD}/dT_{RTD})$$

The GUI collects 10 resistance estimates per second for each INA.

## 4.6 CALIBRATING THE MCP6N11

When JP3 is set to position #1, the PIC MCU can send an `mCal` signal to the MCP6N11 device. This happens when the GUI sends a signal to the PIC MCU (via USB) to start an `mCal` event. The effect of this signal is to internally re-calibrate the MCP6N11 devices' input offset voltage; its output is high-impedance while this re-calibration is in progress.

## 4.7 TEMPERATURE CALIBRATION

### 4.7.1 Single Point Calibration

One of the user options available in our Thermal Management GUI (see **Chapter 5. “Software GUI”**) is a single-point (offset) calibration (usually at 50°C); it helps to correct for both circuit and RTD errors.

The GUI calculates the errors and sends calibration coefficients to the USB PIC MCU, which correct all subsequent temperature values. These corrections are simple subtractions.

- Note 1:** The demo board initially has the calibration coefficient set to zero.  
**2:** Only a single point calibration will be provided for our demo board.

### 4.7.2 Higher Order Calibrations

Higher order calibrations are potentially more accurate. With two temperature measurements (e.g., at 0°C and +100°C), it is possible to do a linear correction (offset and gain). With three temperature measurements (e.g., at 0°C, +50°C, and +100°C), it is possible to do a quadratic correction (offset, gain, and bow). These corrections require firmware modifications by the user.

### 4.7.3 Circuit Calibration

Separating the circuit calibration from the temperature calibration gives more insight into error sources, but not more accuracy.

It is possible to do a separate circuit calibration by inserting a resistance in R2's place. For example, use the 0°C value of 100Ω (±0.01%).

## 4.8 PWM OUTPUT

The firmware sets the Vpwm output (pin 13) to produce a square wave with 5 V<sub>P-P</sub>, 25 kHz and 50% duty cycle. It runs continuously.

The manually set options on JP1 allow different coupling methods to the Wheatstone bridge, including no connection.

## 4.9 USB COMMUNICATIONS

The USB PIC MCU device's clock runs on a 20 MHz ceramic resonator, which supports the microcontroller's firmware overhead and USB communications (see **Section 3.5 “PIC Microcontroller”**).

The GUI provides a means for sending the following configuration information to the board via the USB:

- Temperature calibration coefficient
- Number of averages
- Strobe signal to trigger a V<sub>OS</sub> calibration event (mCa1) in INA #1

The firmware will send the following data to the GUI (in this order): V<sub>AD1</sub>, V<sub>AD2</sub>, V<sub>AD3</sub>, V<sub>AD4</sub>, T<sub>RTD1</sub>, T<sub>RTD2</sub>, R<sub>RTD1</sub>, and R<sub>RTD2</sub>.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

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## **Chapter 5. Software GUI**

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### **5.1 INTRODUCTION**

This chapter discusses the PC's GUI. Items discussed in this chapter include:

- Platform Requirements
- USB Communications
- Display Data
- Calibrate Temperature
- Calibrate the MCP6N11
- Configuration Options
- Export Data to a File

The GUI is Microchip's "Thermal Management Utility" software. It downloads data from the USB PIC MCU, calculates one point calibration coefficients for  $T_{RTD1}$  and  $T_{RTD2}$ , sends them to the PIC MCU, sends an  $mCal$  event trigger signal, sends the number of averages, displays the data on a strip chart and exports data in different file formats, including text.

### **5.2 PLATFORM REQUIREMENTS**

The "Thermal Management Utility" software used for many of our thermal demo boards runs on Microsoft Windows (XP SP3, Vista, and 7 (64 and 32 bit)). It also needs the .NET2 framework package; the installer package will install it, if it is not on your machine.

### **5.3 USB COMMUNICATIONS**

The GUI sends configuration information to the firmware, via the USB. This includes: temperature calibration coefficient, number of averages and a strobe signal to trigger a  $V_{OS}$  calibration event ( $mCal$ ) in INA #1.

The GUI collects the following (averaged) data from the firmware:  $V_{AD1}$ ,  $V_{AD2}$ ,  $V_{AD3}$ ,  $V_{AD4}$ ,  $T_{RTD1}$ ,  $T_{RTD2}$ ,  $R_{RTD1}$  and  $R_{RTD2}$ . This data is collected at adjustable time intervals, with a default value of 200 ms (5 SPS per variable).

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## 5.4 DISPLAY DATA

The GUI uses a standard interface to display the temperature calibration coefficient and number of averages.

Displays the four voltages ( $V_{AD1}$  through  $V_{AD4}$ ) on a strip chart. Also displays the RTD temperature estimates ( $T_{RTD1}$  and  $T_{RTD2}$ ) on a strip chart, with a different y-axis. The RTD resistance estimates ( $R_{RTD1}$  and  $R_{RTD2}$ ) are not displayed on the strip chart.

The user will select the data to display on the strip chart. The vectors in bold blue font in Figure 5-1 can be displayed when their check boxes are checked (the ADC & F/W block represents the ADC internal to the PIC MCU and the firmware stored in its memory). The GUI requests the latest data from the microcontroller, after each sampling interval period has passed, and uses that data to perform the plotting and data calculations. Data between collection requests are not sent to the GUI.

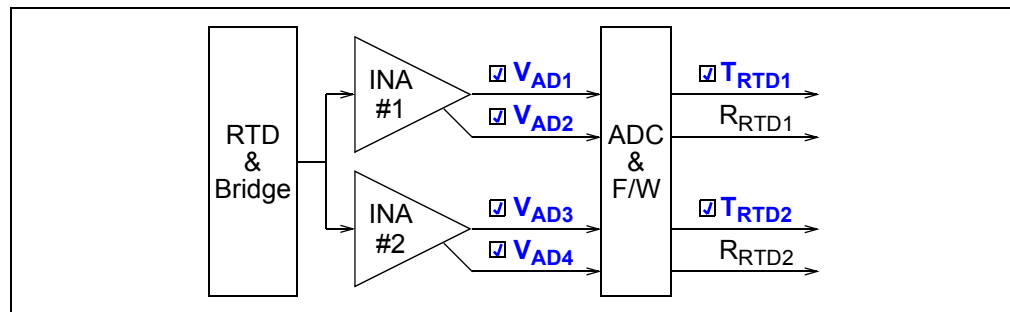


FIGURE 5-1: Selecting Vectors to Display on Strip Chart.

## 5.5 CALIBRATE TEMPERATURE

Supports a single-point calibration of  $T_{RTD1}$  and  $T_{RTD2}$ , at a temperature selected by the user. The GUI sends these calibration coefficients to the USB PIC microcontroller, which does the actual corrections.

## 5.6 CALIBRATE THE MCP6N11

The MCP6N11 MCU internally re-calibrates its input offset voltage when any one of these three events occurs:

- Power up
- The user clicks the `mCal` push button in the GUI (which sends an `mCal` event signal to the PIC microcontroller)
- The user presses the `mCalSw` switch (SW1)

## 5.7 CONFIGURATION OPTIONS

The GUI provides a means for sending the following configuration information to the firmware, via the USB bus:

- Temperature calibration coefficient
- Number of averages (n)
- Strobe signal to trigger a  $V_{OS}$  calibration event (`mCal`) in INA #1

## 5.8 EXPORT DATA TO A FILE

Export all of the data ( $V_{AD1}$ ,  $V_{AD2}$ ,  $V_{AD3}$ ,  $V_{AD4}$ ,  $T_{RTD1}$ ,  $T_{RTD2}$ ,  $R_{RTD1}$  and  $R_{RTD2}$ ) to a user-selected text file. The GUI either sends the displayed data (limited to 500 time points) to the file, or sends “recorded” data over a selected time period (which has no time point limit).

Export the strip chart to a user-selected file, in one of several formats.

## 5.9 SCREEN CAPTURES

All of the figures in this section have circled numbers that point to important features. These numbers correspond to the associated numbered list. Cross references to these numbers are displayed in the text as follows: (#1).

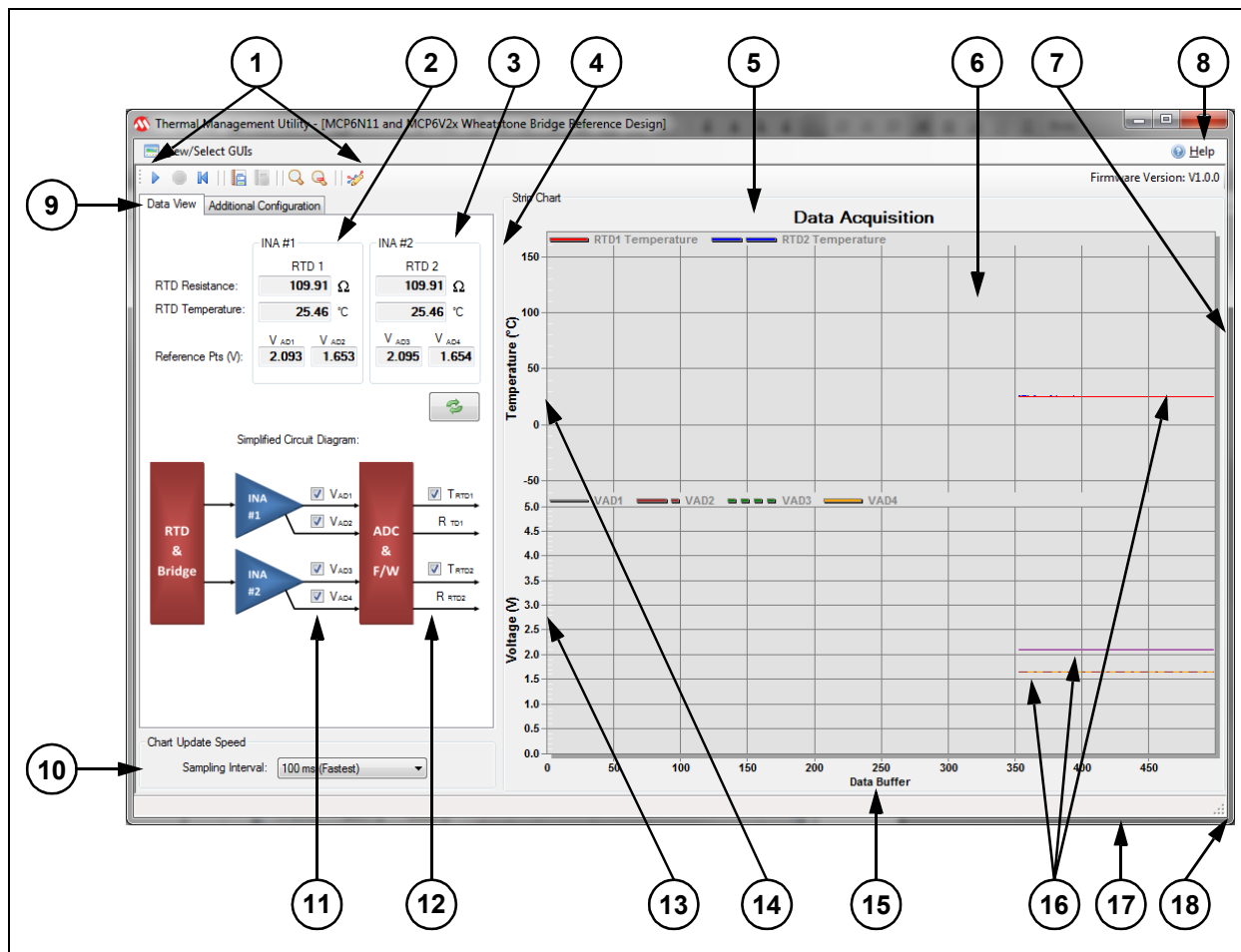
Some useful features, that may be hard to find, include:

- Resize Right Edge of Information Box (#4)
- Export Strip Chart
  - See **Section 5.9.4.8 “Exporting Data Acquisition Box”**
  - Data File
  - Graphic File
- Maximize Strip Chart
  - See **Section 5.9.4.9 “Maximized Strip Chart Display”**
  - Maximizes Strip Chart only
- Chart Menu (more chart options)
  - See **Section 5.9.4.10 “Right Mouse Click (inside the Strip Chart Area)”**

### 5.9.1 Data View Tab

Figure 5-2 shows the default screen. On the left, the **Data View** tab (#9) is selected, and the Strip Chart is displayed.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design



**FIGURE 5-2:** Data View Tab, with Strip Chart.

The indicated features for Figure 5-2 are:

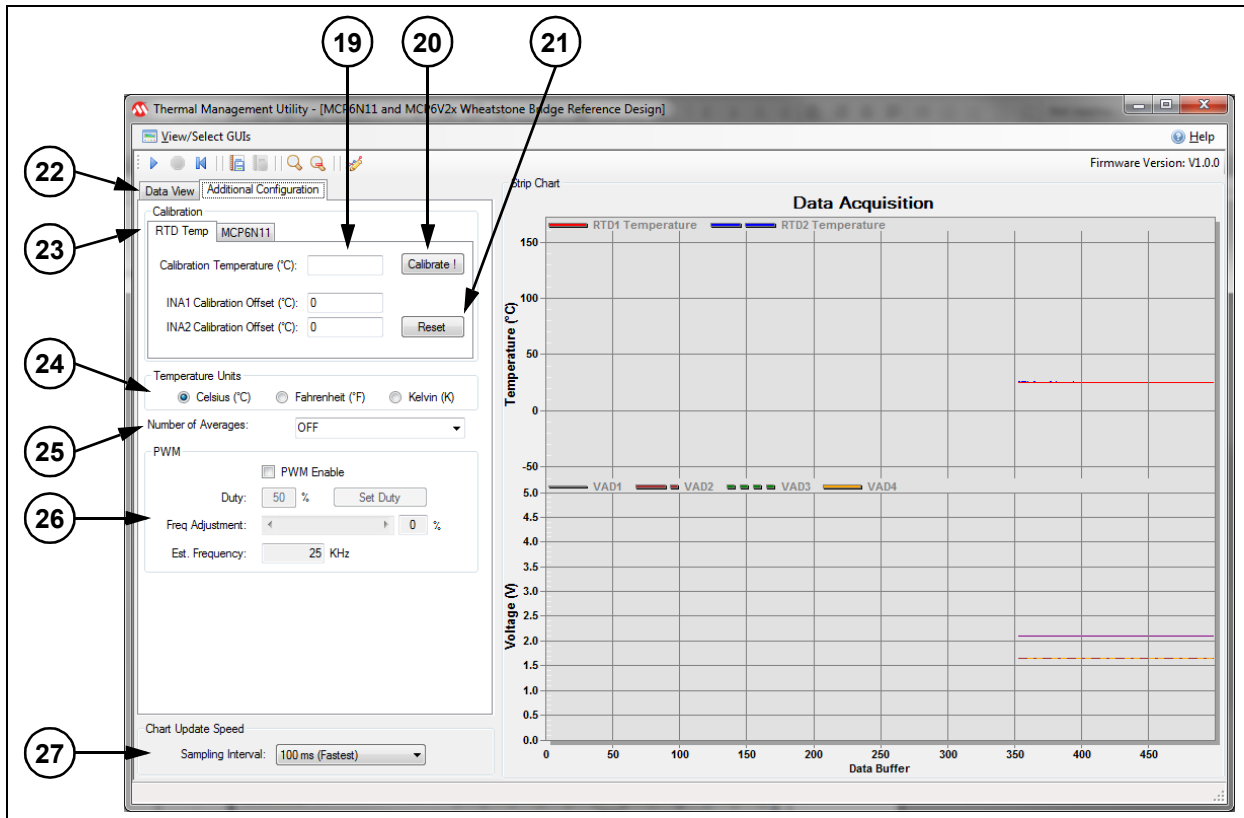
1. **Data Collection** buttons:
  - a) **Data Acquisition** Buttons (standard data collection).
    - Start Acquisition**
    - Stop Acquisition**
    - Reset Chart Buffer**
  - b) **Record Acquisition** Buttons (data sent to a file, with user selected length).
    - Record Acquisition**
    - Stop Record Acquisition**
  - c) **Zoom** Buttons (resize Strip Chart).
    - Zoom Information (click and drag inside Strip Chart)
    - Zoom Out
  - d) **Chart Customization** Button.
    - Open chart customization dialog
2. Current measured values for INA #1:
  - a) RTD Resistance
  - b) RTD Temperature
  - c)  $V_{AD1}$  Reference Point (voltage which changes with temperature)
  - d)  $V_{AD2}$  Reference Point (voltage based on VREF)



3. Current measured values for INA #2:
  - a) RTD Resistance
  - b) RTD Temperature
  - c)  $V_{AD3}$  Reference Point (voltage which changes with temperature)
  - d)  $V_{AD4}$  Reference Point (voltage based on VREF)
4. Right edge of Information Box. To resize this box, Left Click this edge with the mouse and Drag.
5. Strip Chart area.
  - a) Double-click in this area to open the Strip Chart Dialog Box.
  - b) Right-click in this area to open another chart menu.
6. Strip Chart.
  - a) To zoom in on a smaller area, click on one corner and drag to the other corner (the magnifier icon appears).
  - b) To zoom out to the full Strip Chart area, click on the **Zoom Out** button (#1).
7. Right edge of GUI window. To resize this window, click this edge and drag.
8. **Help** button
9. **Data View** tab is selected
10. Sampling Interval drop-down menu (interval between stored and displayed points).
11. Data display boxes for ADC input voltages ( $V_{AD1}$  to  $V_{AD4}$ ).
12. Data display boxes for calculated temperatures ( $T_{RTD1}$  and  $T_{RTD2}$ ).
13. Y-axis for ADC input voltages ( $V_{AD1}$  to  $V_{AD4}$ ).
14. Y-axis for calculated temperatures ( $T_{RTD1}$  and  $T_{RTD2}$ ).
15. X-axis for collected data.
16. Strip Chart curves.
17. Bottom edge of GUI window. To resize this window, click this edge and drag.
18. Bottom Right corner of GUI window. To resize this window, click and drag.

## 5.9.2 Additional Configuration and RTD Temp Tabs

Figure 5-3 shows that the **Additional Configuration** tab (#22) and **RTD Temp** sub-tab (#23) are selected, and the Strip Chart is displayed (Figure 5-2 has more information).

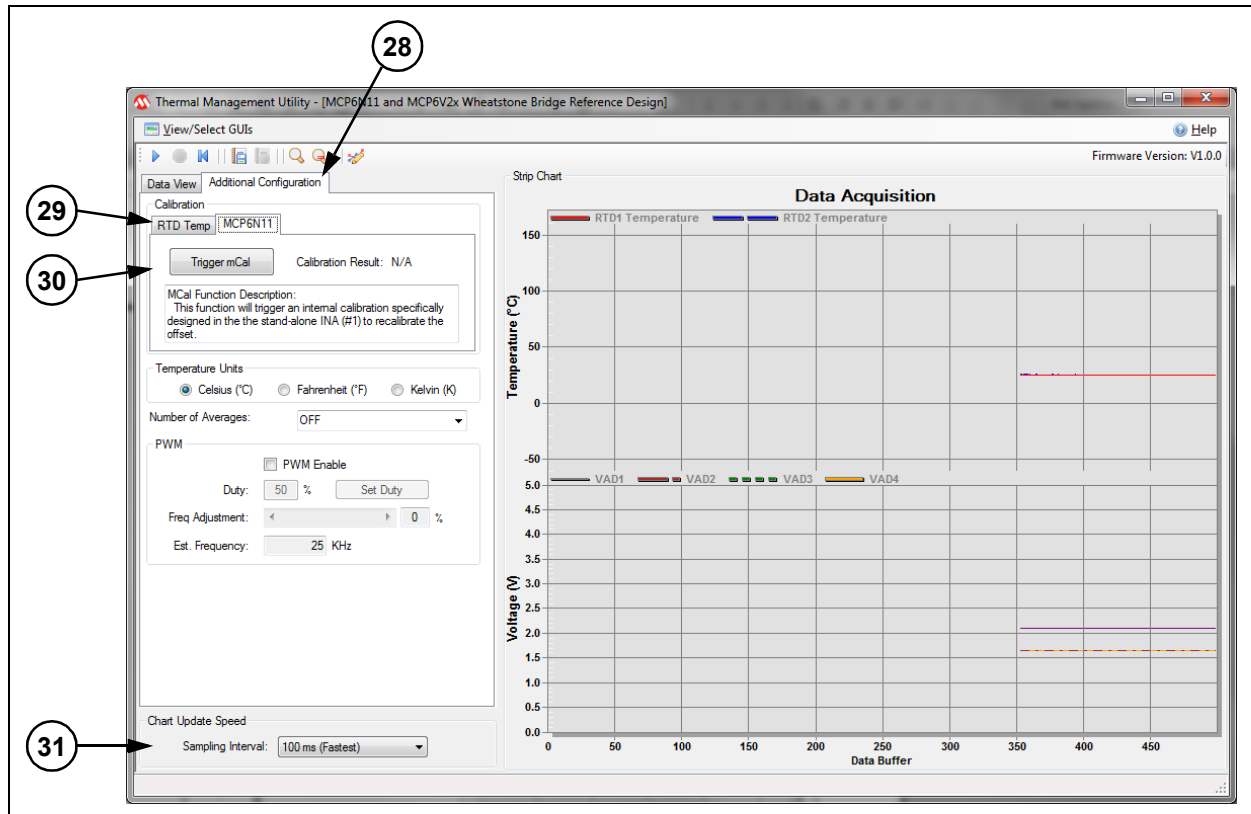


**FIGURE 5-3:** Additional Configuration and RTD Temp Tabs, with Strip Chart.

19. Calibration input boxes:
  - a) Calibration Temperature (press the Calibrate ! button (#20) when ready).
  - b) INA1 Calibration Offset (input temperature correction for INA1).
  - c) INA2 Calibration Offset (input temperature correction for INA2).
20. **Calibrate !** button (enter Calibration Temperature (#19), then press when ready).
21. **Reset** button (resets Calibration inputs (#19) to 0).
22. **Additional Configuration** tab is selected.
23. **RTD Temp** sub-tab is selected.
24. **Temperature Units** selection radio buttons.
25. Number of Averages drop-down menu.
26. PWM inputs:
  - a) Enabled check box (turns on PWM output from PIC microcontroller and activates other features in the PWM box).
  - b) Duty input box (inputs duty cycle).
  - c) **Set Duty** button (sends updated value to the microcontroller).
  - d) Frequency Adjustment slider (changes the PWM frequency).
  - e) Approximate Frequency input box (adjusts PWM frequency; 25 kHz is preferred).
27. Sampling Interval drop-down menu (shown at 100 ms per sample).

### 5.9.3 Additional Configuration and MCP6N11 Tabs

Figure 5-4 shows that the **Additional Configuration** tab (#29) and **MCP6N11** sub-tab (#30) are selected, and the Strip Chart is displayed (Figure 5-2 has more information).



**FIGURE 5-4:** Additional Configuration and MCP6N11 Tabs, with Strip Chart.

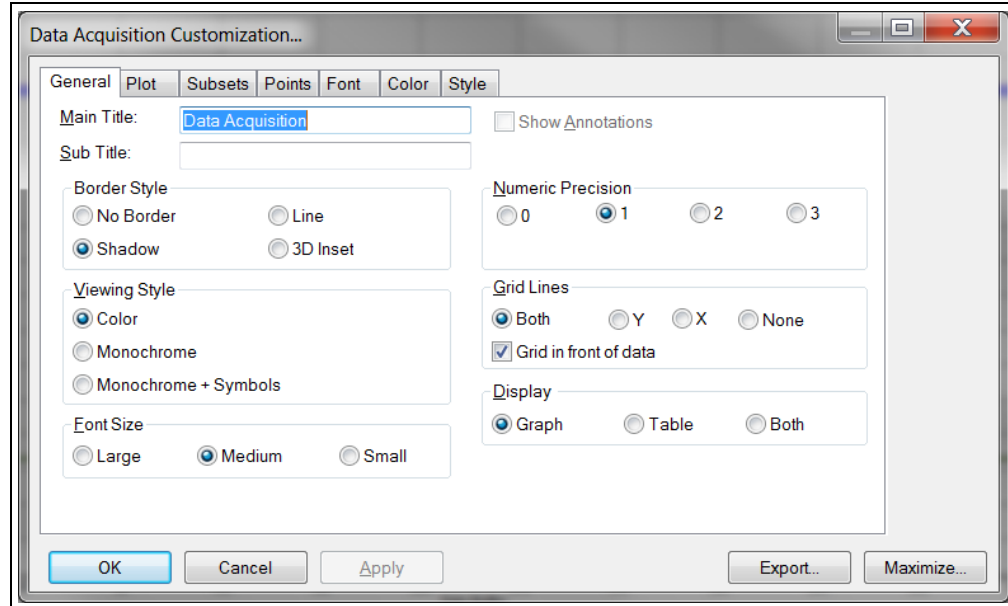
The indicated features for Figure 5-4 are:

28. **Additional Configuration** tab is selected.
29. **MCP6N11** sub-tab is selected.
30. **Trigger mCal** button; sends a trigger to INA #1 to recalibrate its offset.
31. Sampling Interval pull-down menu (shown at 100 ms per sample)

## 5.9.4 Strip Chart Customization

### 5.9.4.1 DATA ACQUISITION CUSTOMIZATION – GENERAL TAB

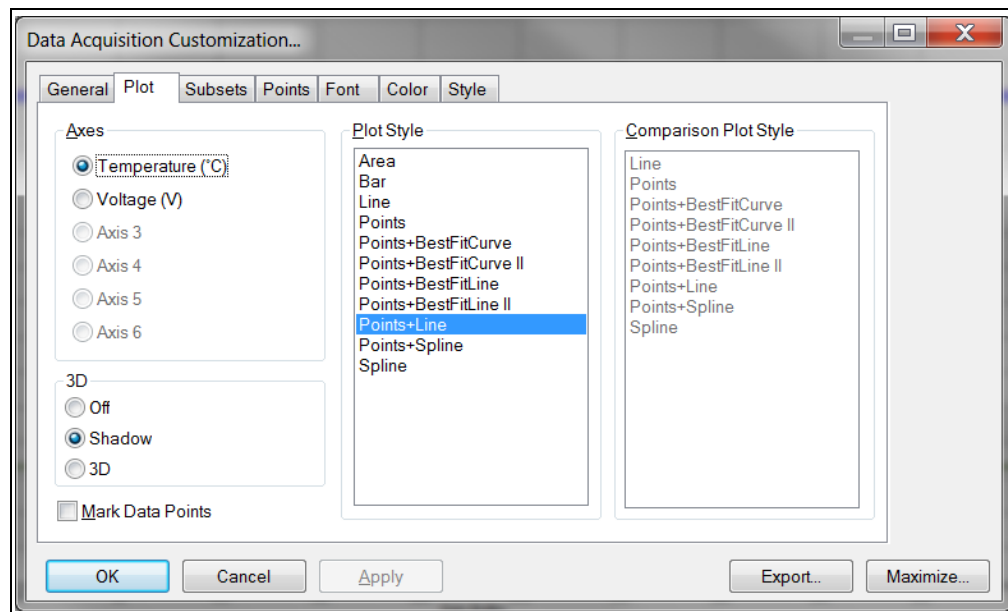
Figure 5-5 shows the dialog box, with the **General** tab selected. To open this box, double-click inside the Strip Chart area (#5). The overall look and feel of the Strip Chart area can be changed here.



**FIGURE 5-5:** Data Acquisition Customization – General Tab.

### 5.9.4.2 DATA ACQUISITION CUSTOMIZATION – PLOT TAB

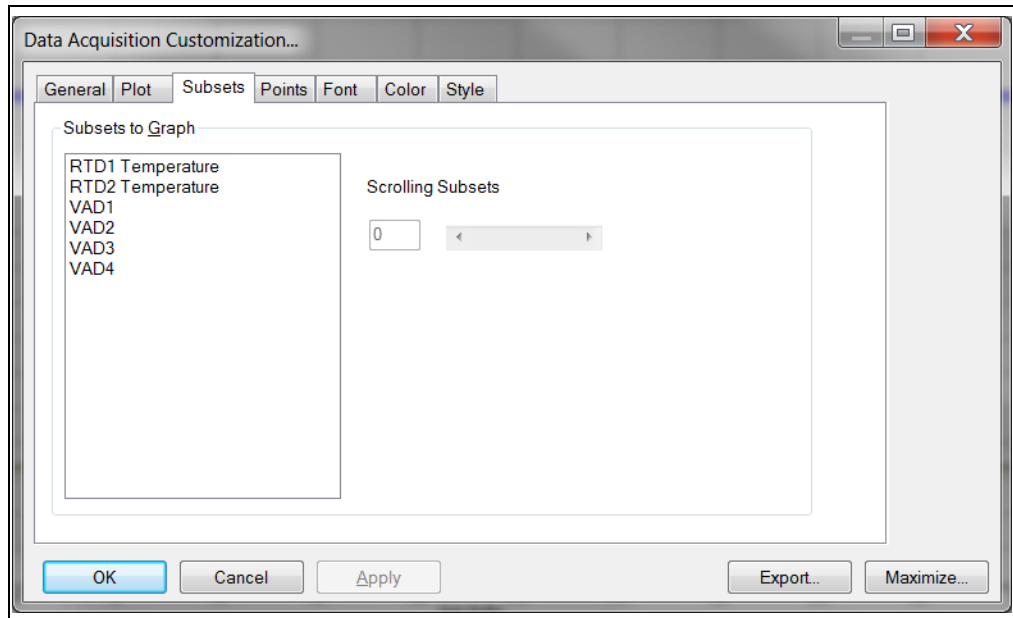
Figure 5-6 shows the Data Acquisition dialog box, with the **Plot** tab selected. To open this box, double-click inside the Strip Chart area (#5). The Strip Chart curve's axes and display types can be changed here.



**FIGURE 5-6:** Data Acquisition Customization – Plot Tab.

5.9.4.3 DATA ACQUISITION CUSTOMIZATION – SUBSETS TAB

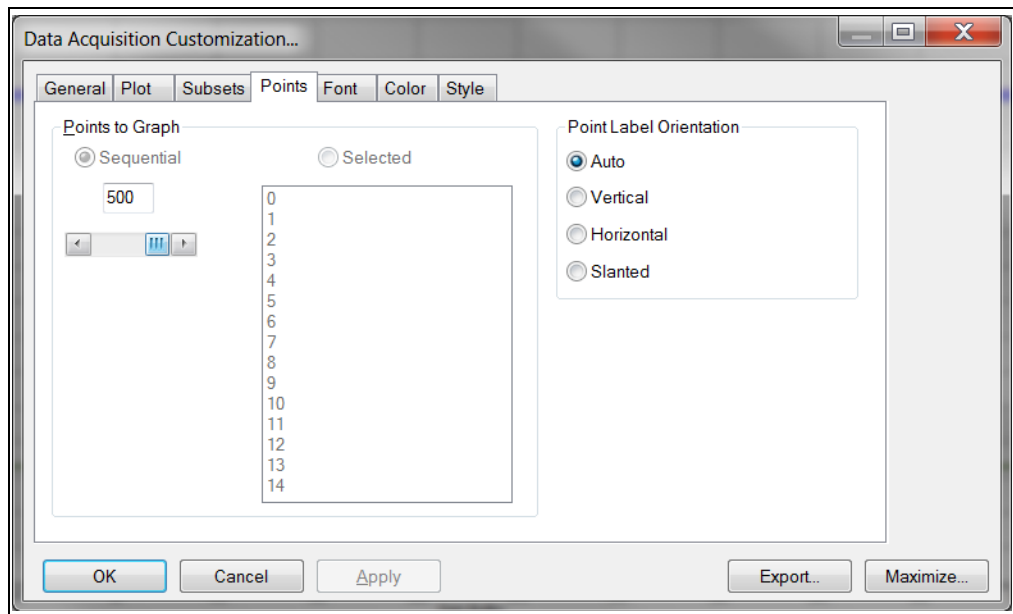
Figure 5-7 shows that the Data Acquisition Dialog box, with the **Subsets** tab selected. To open this box, double-click inside the Strip Chart area (#5). The Strip Chart curves can be selected, or de-selected, here.



**FIGURE 5-7:** Data Acquisition Customization – Subsets Tab.

5.9.4.4 DATA ACQUISITION CUSTOMIZATION – POINTS TAB

Figure 5-8 shows that the Data Acquisition dialog box, with the **Points** tab selected. To open this box, double-click inside the Strip Chart area (#5). The number of points displayed on the Strip Chart's x-axis is changed here.

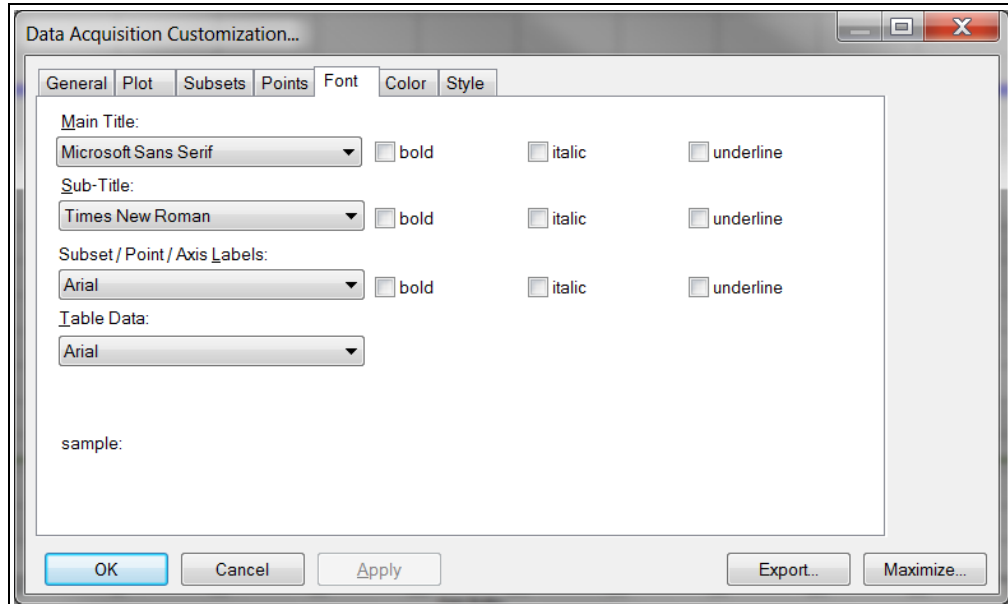


**FIGURE 5-8:** Data Acquisition Customization – Points Tab.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## 5.9.4.5 DATA ACQUISITION CUSTOMIZATION – FONT TAB

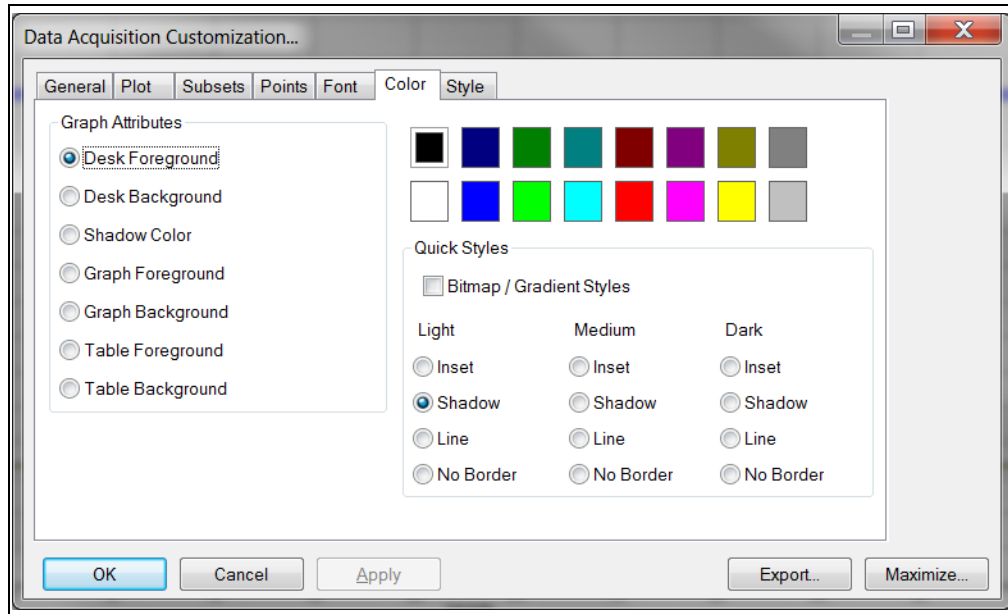
Figure 5-9 shows that the Data Acquisition dialog box, with the **Font** tab selected. To open this box, double-click inside the Strip Chart area (#5). The Strip Chart's font types and sizes are changed here.



**FIGURE 5-9:** Data Acquisition Customization – Font Tab.

## 5.9.4.6 DATA ACQUISITION CUSTOMIZATION – COLOR TAB

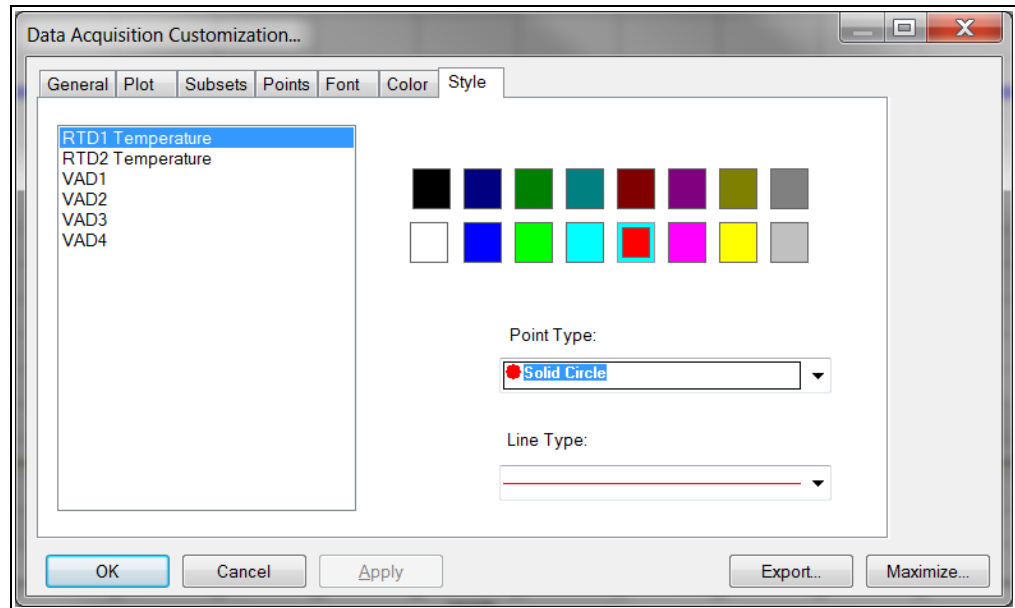
Figure 5-10 shows that the Data Acquisition dialog box, with the **Color** tab selected. To open this box, double-click inside the Strip Chart area (#5). The font and object colors are changed here.



**FIGURE 5-10:** Data Acquisition Customization – Color Tab.

5.9.4.7 DATA ACQUISITION CUSTOMIZATION – STYLE TAB

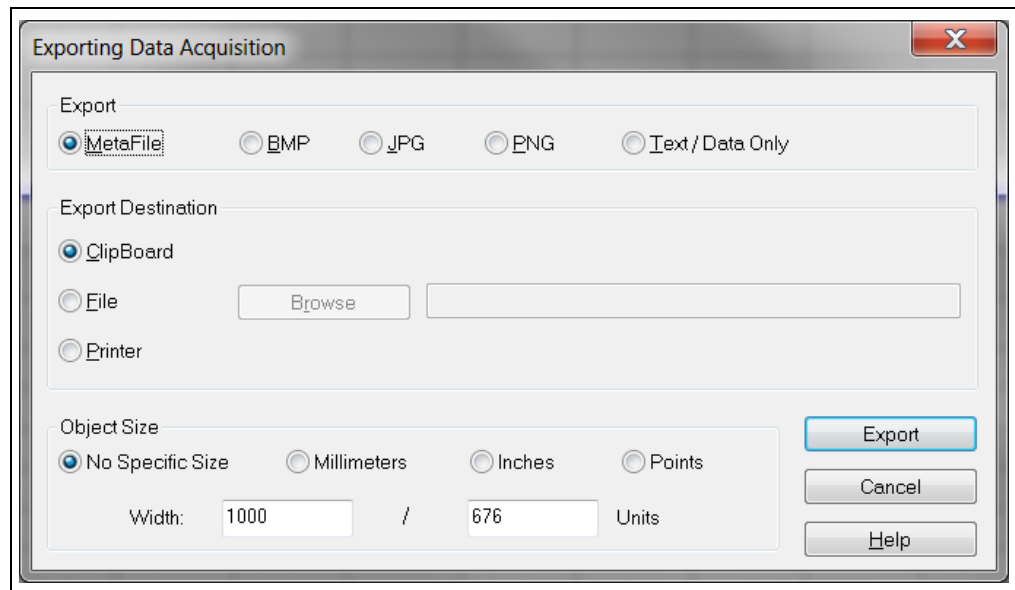
Figure 5-11 shows that the Data Acquisition dialog box, with the Style tab selected. To open this box, double-click inside the Strip Chart area (#5). The Strip Chart’s curve colors are changed here.



**FIGURE 5-11:** Data Acquisition Customization – Style Tab.

5.9.4.8 EXPORTING DATA ACQUISITION BOX

Figure 5-12 shows the Exporting Data Acquisition box. To open this dialog, double-click inside the Strip Chart area (#5), then press the **Export** button on the bottom right (e.g., see Figure 5-11). When the data is exported as a picture, its destination and size can be selected. When the data is exported as text, only its destination can be selected.

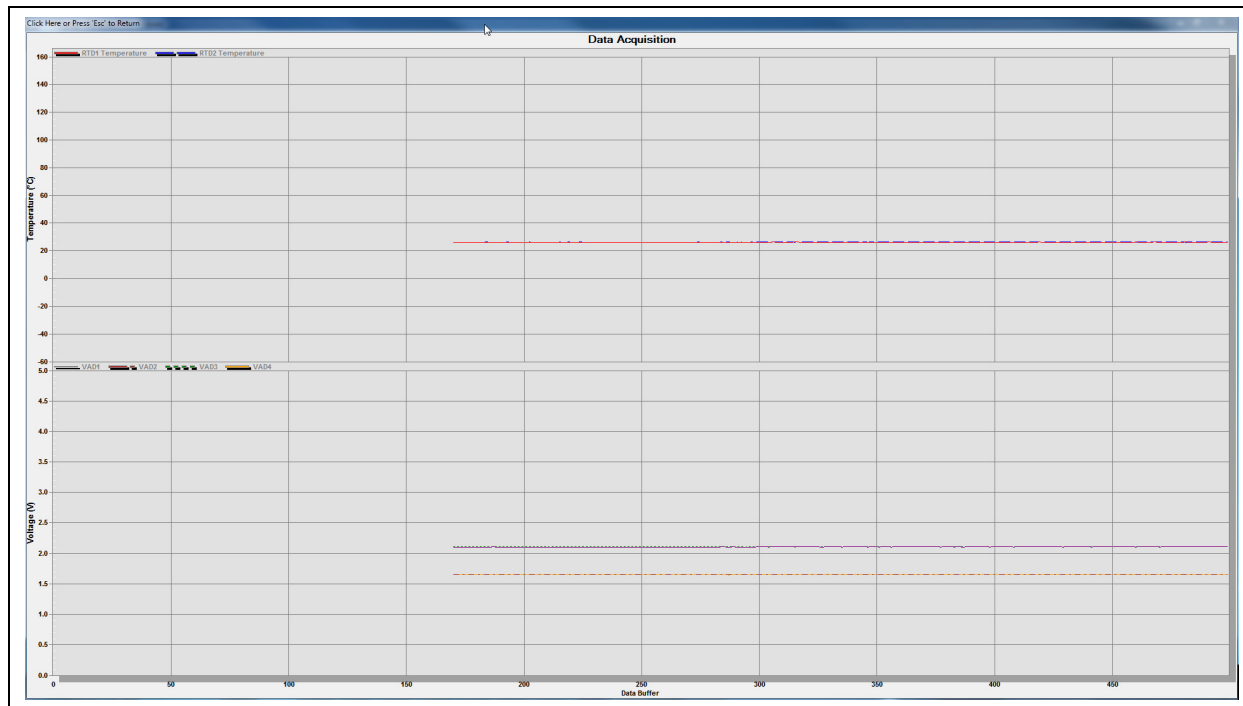


**FIGURE 5-12:** Exporting Data Acquisition Box.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## 5.9.4.9 MAXIMIZED STRIP CHART DISPLAY

Figure 5-13 shows the maximized strip chart display. To open this window (on the PC's main display), double-click inside the Strip Chart area (#5), then press the **Maximize ...** button on the bottom right (e.g., see Figure 5-11). To exit this screen, click on the top banner or press the "Esc" key on your keyboard.

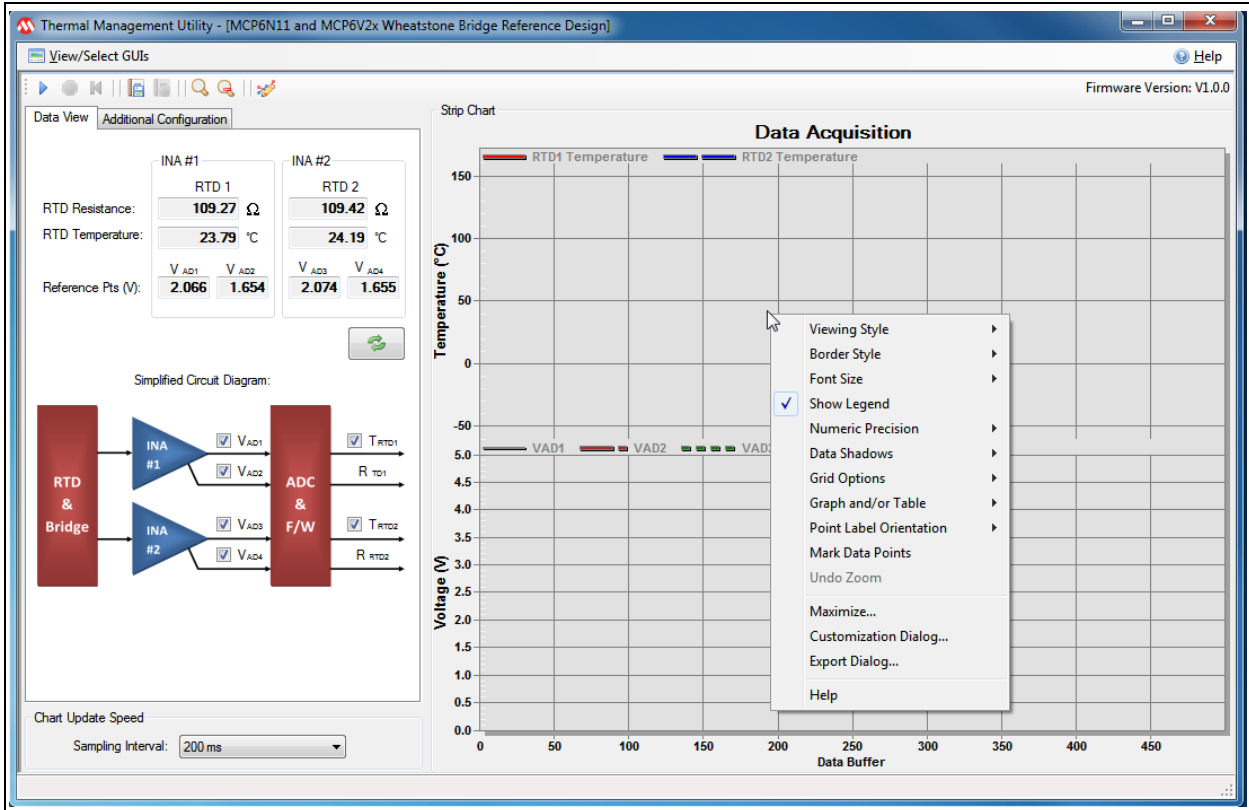


**FIGURE 5-13:** Maximized Strip Chart Display (under the Strip Chart Dialog Box).



5.9.4.10 RIGHT MOUSE CLICK (INSIDE THE STRIP CHART AREA)

Figure 5-14 shows a chart menu with more chart options. This window is opened (on the PC's main display) by right-clicking inside the Strip Chart area (#5).

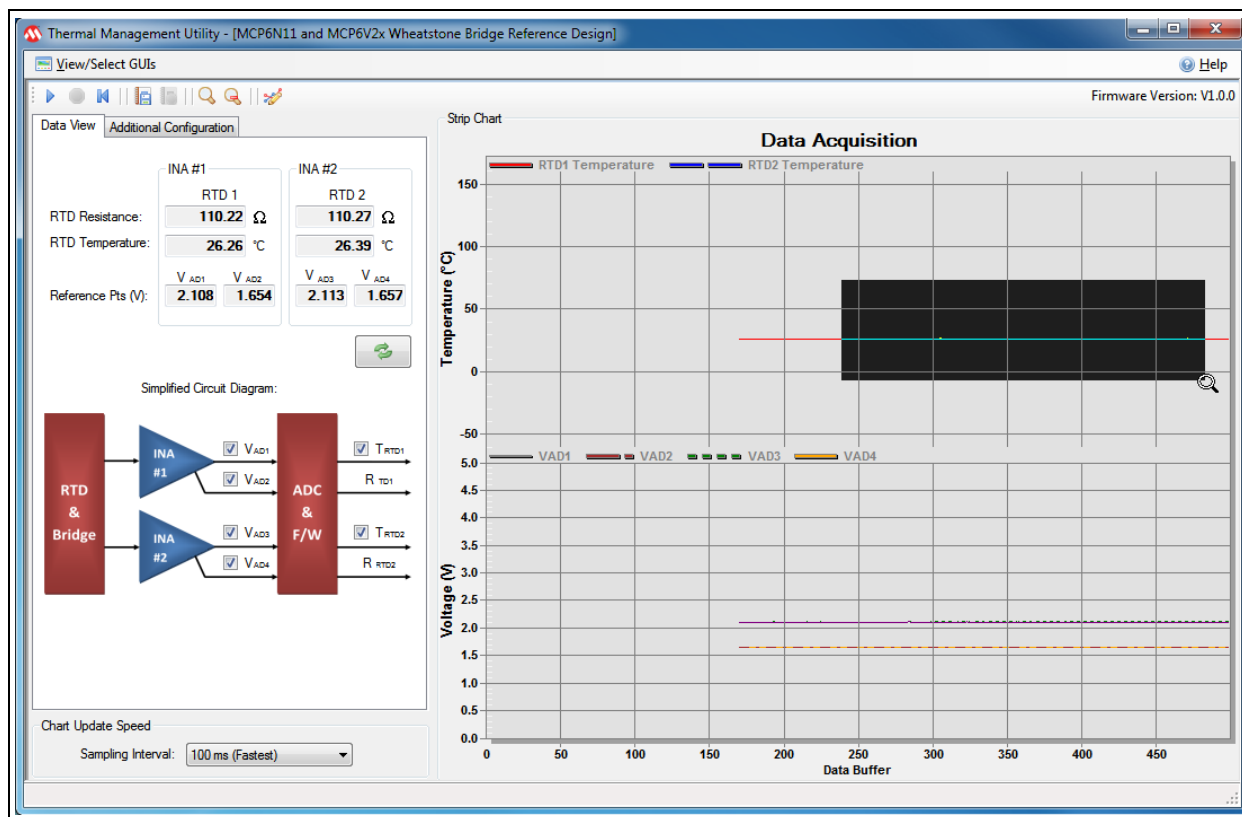


**FIGURE 5-14:** Chart Menu With More Chart Options (Right Click inside the Strip Chart Area).

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## 5.9.4.11 ZOOMING IN AND OUT

Figure 5-15 shows the result of clicking and dragging inside the Chart Area; this will cause the Strip Chart to display the selected area only. To zoom out to full view, click the Zoom out button (second from right button under arrows #1 in Figure 5-2).



**FIGURE 5-15:** Zoom In area in Strip Chart.



# MCP6N11 AND MCP6V2X WHEATSTONE BRIDGE REFERENCE DESIGN USER'S GUIDE

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## Appendix A. Schematics and Layouts

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### A.1 INTRODUCTION

This appendix contains the following schematics and layouts for the MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design:

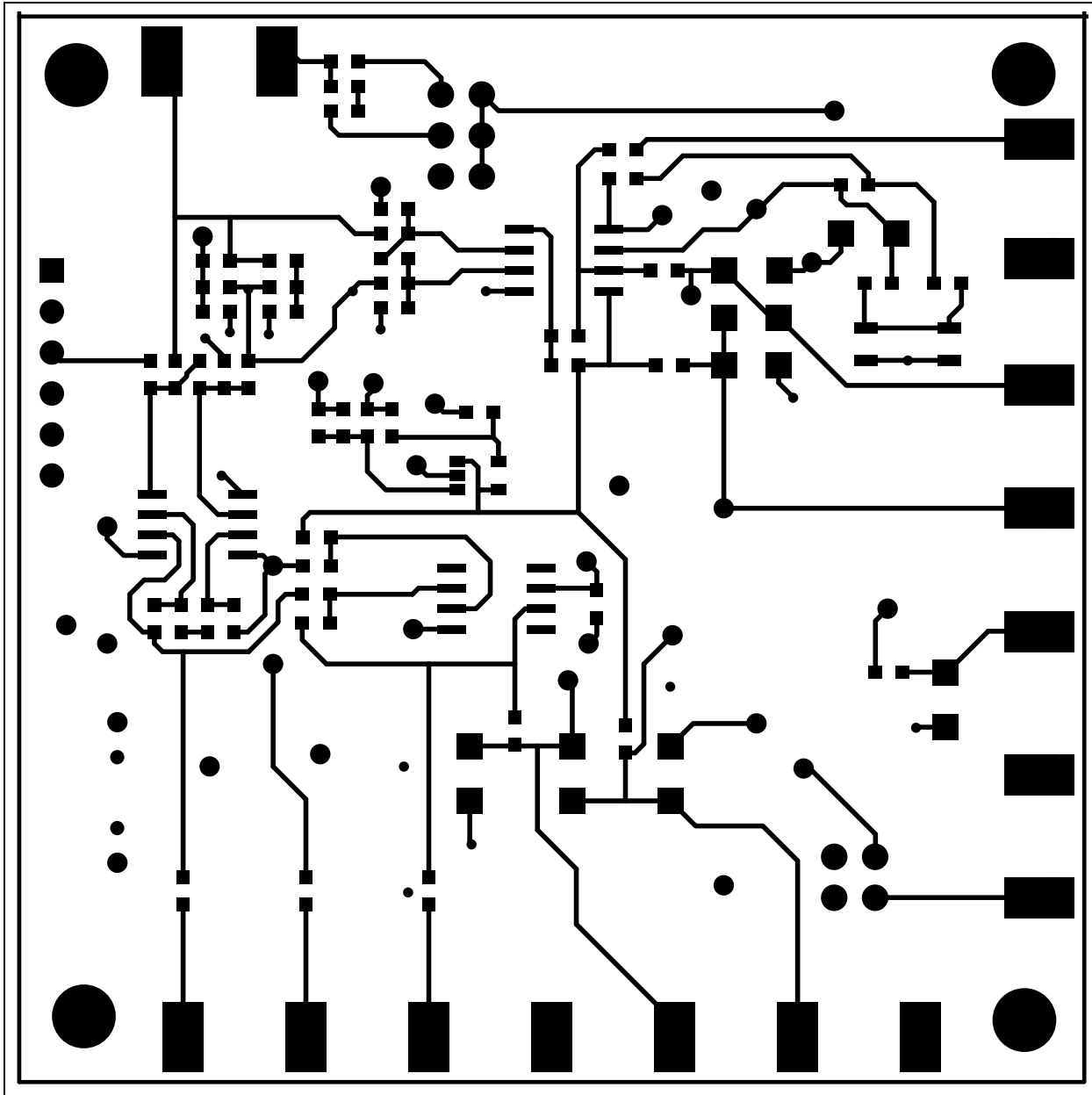
- Board – Schematic
- Board – Top Silk Screen and Pads
- Board – Top Metal Layer
- Board – Ground Plane (Second layer)
- Board – Power Plane (Third layer)
- Board – Bottom Metal Layer (top view)
- Board – Bottom Silk and Pads (top view)

The Gerber files for this board are available on the Microchip website, ([www.microchip.com](http://www.microchip.com)) and are contained in the zip file *00354R3\_Gerbers.zip*. This is a four-layer PCB.

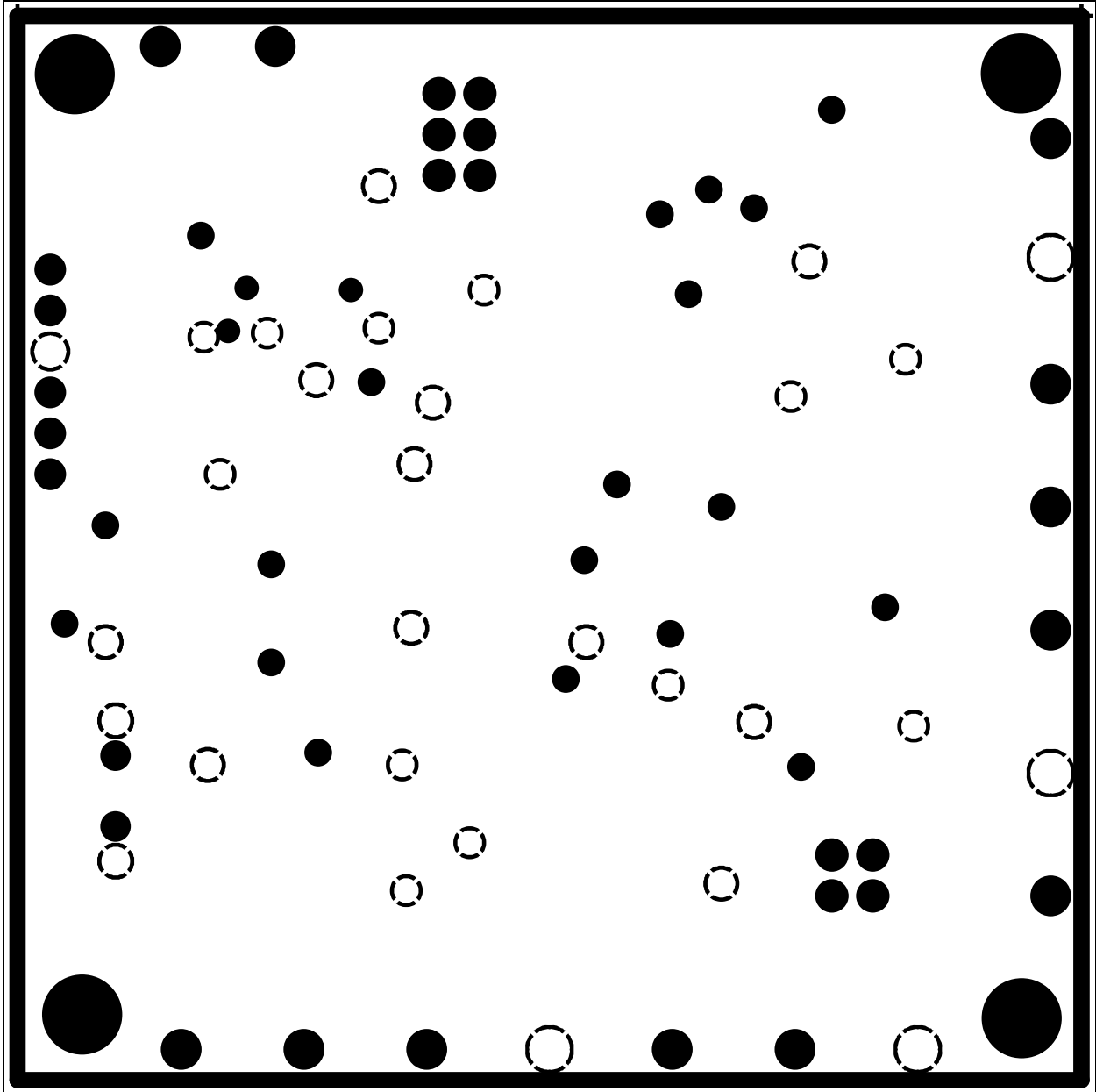




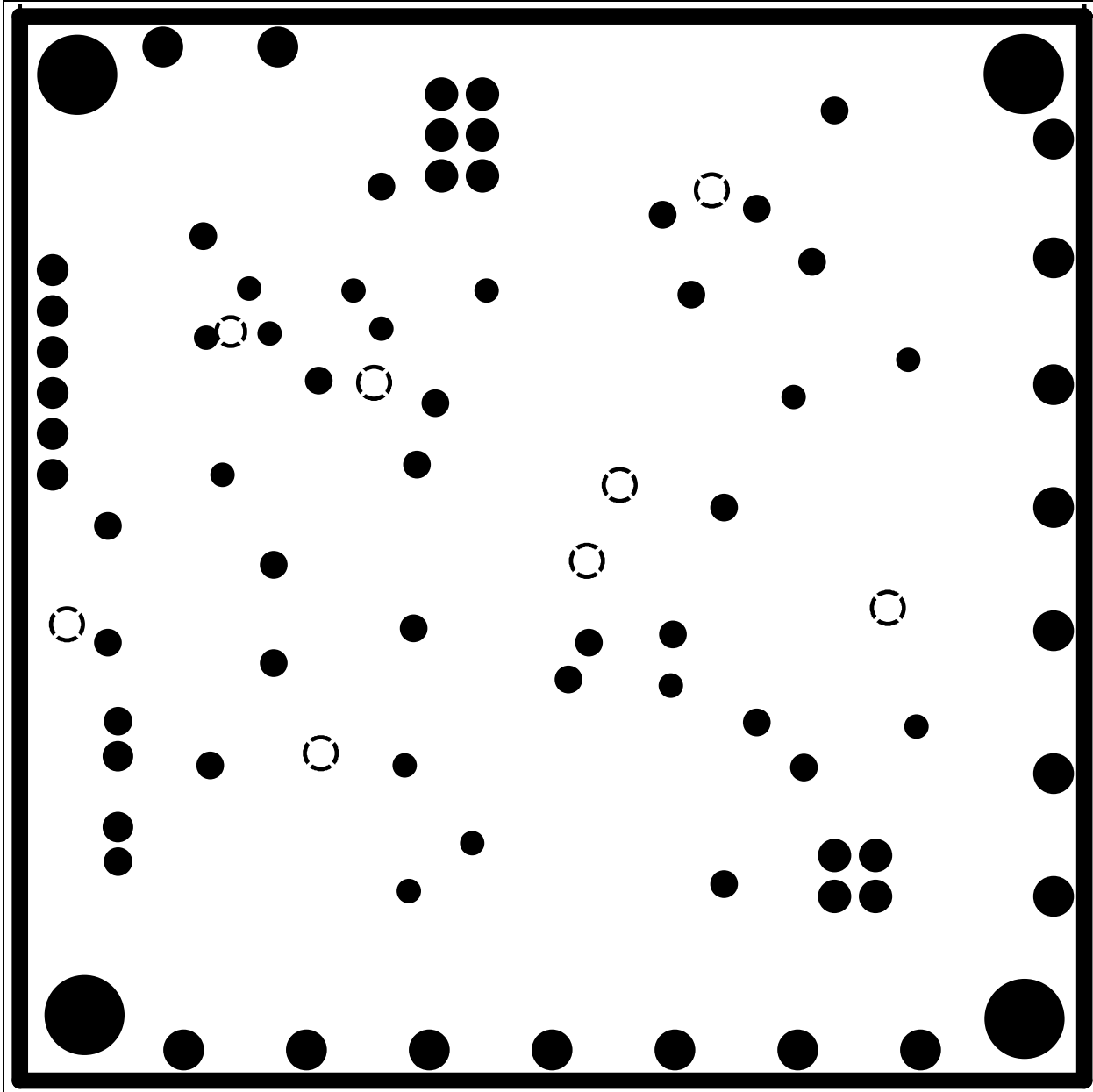
## A.4 BOARD – TOP METAL LAYER



A.5 BOARD – GROUND PLANE (SECOND LAYER)

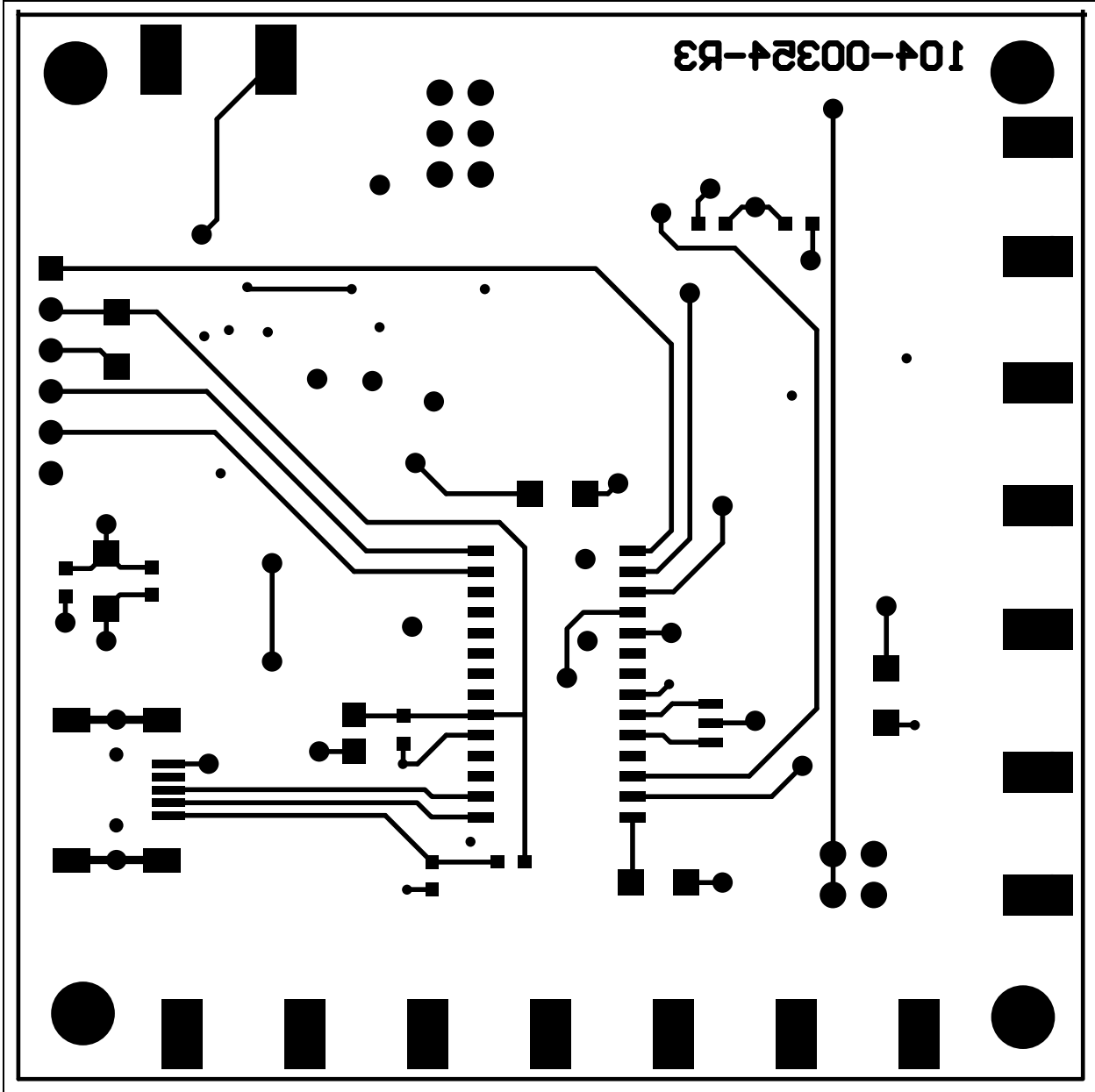


## A.6 BOARD – POWER PLANE (THIRD LAYER)





A.7 BOARD – BOTTOM METAL LAYER (TOP VIEW)





## Appendix B. Bill Of Materials (BOM)

**TABLE B-1: BILL OF MATERIALS – ASSEMBLED PCB**

Qty	Reference Designator	Description	Manufacturer	Part Number
1	C1	220 pF, 0603 SMD, Ceramic, NP0, 50V, 5%	AVX Corporation	06035A221JAT2A
10	C2-C4, C6, C9, C10, C18, C21, C23, C28	100 nF, 0603 SMD, Ceramic, X7R, 50V, 10%	AVX Corporation	06035C104KAT2A
4	C5, C7, C17, C19	10 nF, 0603 SMD, Ceramic, X7R, 50V, 10%	AVX Corporation	06035C103KAT2A
11	C8, C11-C14, C20, C22, C24-C27	1.0 $\mu$ F, 1206 SMD, Ceramic, X7R, 25V, 10%	AVX Corporation	12063C105KAT2A
2	C15, C16	10 $\mu$ F, 1206 SMD, Ceramic, X7R, 16V, 10%	AVX Corporation	1206YC106KAT2A
1	J2	Header, Mini USB	Tyco Electronics	1734035-2
1	JP1	Header, 3 $\times$ 2, 100 mil	Molex <sup>®</sup>	10-89-7062
1	JP2	Header, 2 $\times$ 2, 100 mil	Molex <sup>®</sup>	10-89-7042
1	L1	10 $\mu$ H, 100 mA, 0805 SMD, 20%	Murata Electronics	LQM21FN100M70L
1	PCB	MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design, 4 layer PCB (2.60 in $\times$ 2.60 in)	—	—
2	R1, R6	2.49 k $\Omega$ , 0603 SMD, 0.1%, 1/10W	SUSUMU	RG1608P-2491-B-T5
1	R2	100 $\Omega$ RTD, 0603 SMD, 1%	Vishay/Beyschlag	PTS060301B100RP100
3	R3-R5	100 $\Omega$ , 0603 SMD, 0.1%, 1/10W	SUSUMU	RG1608P-101-B-T5
1	R7	30.1 k $\Omega$ , 0603 SMD, 0.1%, 1/10W	SUSUMU	RG1608P-3012-B-T5
1	R8	121 k $\Omega$ , 0603 SMD, 1%, 1/10W	Yageo	RC0603FR-07121KL
1	R9	68.1 k $\Omega$ , 0603 SMD, 1%, 1/10W	Yageo	RC0603FR-0768K1L
1	R10	200 $\Omega$ , 0603 SMD, 5%, 1/10W	Yageo	RC0603JR-07200RL
8	R11, R12, R19, R20, R24, R25, R35, R36	20.0 k $\Omega$ , 0603 SMD, 1%, 1/10W	Yageo	RC0603FR-0720KL
2	R13, R26	10.0 $\Omega$ , 0603 SMD, 1%, 1/10W	Yageo	RC0603FR-0710RL
2	R14, R16	10 k $\Omega$ , 0603 SMD, 5%, 1/10W	Yageo	RC0603JR-0710KL
2	R15, R23	100 k $\Omega$ , 0603 SMD, 5%, 1/10W	Yageo	RC0603JR-07100KL
3	R17, R27, R30	100 k $\Omega$ , 0603 SMD, 0.1%, 1/10W	SUSUMU	RG1608P-104-B-T5
3	R18, R28, R29	499 $\Omega$ , 0603 SMD, 0.1%, 1/10W	SUSUMU	RG1608P-4990-B-T5
2	R21, R22	10 $\Omega$ , 0603 SMD, 5%, 1/10W	Yageo	RC0603JR-0710KL

**Note 1:** The components listed in this Bill of Materials are representative of the PCB assembly. The released BOM used in manufacturing uses all RoHS-compliant components.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

**TABLE B-1: BILL OF MATERIALS – ASSEMBLED PCB (CONTINUED)**

Qty	Reference Designator	Description	Manufacturer	Part Number
4	R31-R34	10.0 kΩ, 0603 SMD, 0.1%, 1/10W	SUSUMU	RG1608P-103-B-T5
4	R37-R40	1.00 kΩ, 0603 SMD, 1%, 1/10W	Yageo	RC0603FR-071KL
2	SH1, SH2	Shunt, 100 mil Thru-Hole, 2 Pos., 30 μm Au	Tyco Electronics Corp.	881545-2
1	SW1	SMD, Switch, Push Button, 1 Pos., SPST-NO	Panasonic-ECG	EVQ-P2R02M
1	U1	MCP6001, SOT-23-5, Single Op Amp	Microchip Technology Inc.	<b>MCP6001T-E/OT</b>
1	U2	MCP6N11, SOIC-8, Single INA, GMIN = 100	Microchip Technology Inc.	<b>MCP6N11-100U/SN</b>
1	U3	MCP6V27, SOIC-8, Dual Auto-Zeroed Op Amp	Microchip Technology Inc.	<b>MCP6V27-E/SN</b>
1	U4	MCP6V26, SOIC-8, Single Auto-Zeroed Op Amp	Microchip Technology Inc.	<b>MCP6V26-E/SN</b>
1	U5	PIC18F2553, SOIC-28 (300 mil), USB PIC MCU	Microchip Technology Inc.	<b>PIC18F2553-I/SO</b>
1	Y1	20 MHz Ceramic Resonator, SMT, E-temp	Murata Electronics	CSTCE20M0V53Z-R0

**Note 1:** The components listed in this Bill of Materials are representative of the PCB assembly. The released BOM used in manufacturing uses all RoHS-compliant components.

**TABLE B-2: BILL OF MATERIALS – OTHER PARTS IN KIT**

Qty	Reference Designator	Description	Manufacturer	Part Number
1	—	USB 2.0 Cable, A to Mini B, 1 m	Molex <sup>®</sup>	88732-8600

**Note 1:** The components listed in this Bill of Materials are representative of the other parts in the kit. The released BOM used in manufacturing uses all RoHS-compliant components.

**TABLE B-3: BILL OF MATERIALS – ALTERNATE COMPONENTS**

Qty	Reference Designator	Description	Manufacturer	Part Number
1	C27	470 nF, 1206 SMD, Ceramic, X7R, 25V, 10%	AVX Corporation	12063C474KAT2A
4	R31-R34	10.0 kΩ, 0603 SMD, 0.01%, 1/16W	Stackpole Electronics Inc.	RNCF0603TKY10K0
1	U3	MCP6V07, SOIC-8, Dual Auto-Zeroed Op Amp	Microchip Technology Inc.	MCP6V07-E/SN
		MCP6V02, SOIC-8, Dual Auto-Zeroed Op Amp	Microchip Technology Inc.	MCP6V02-E/SN
1	U4	MCP6V06, SOIC-8, Single Auto-Zeroed Op Amp	Microchip Technology Inc.	MCP6V06-E/SN
		MCP6V01, SOIC-8, Single Auto-Zeroed Op Amp	Microchip Technology Inc.	MCP6V01-E/SN

**Note 1:** The components listed in this Bill of Materials are representative of the alternate components used for modifications. The released BOM used in manufacturing uses all RoHS-compliant components.

**TABLE B-4: BILL OF MATERIALS – OPTIONAL PARTS**

Qty	Reference Designator	Description	Manufacturer	Part Number
1	J1	Header, 1×6, 100 mil	Molex®	22-28-4060
16	TP1-TP16	SMD, Test Point	Keystone Electronics	5016
4	(for PCB mounting)	Hemispherical Bumpon™ Standoff, 0.44 in × 0.20 in	3M™	SJ-5003 (BLACK)
4	(for PCB mounting)	Stand-off, Hex, 0.500", 4 × 40 Thread, Nylon, 0.285" max. O.D.	Keystone Electronics	1902C
4	(for PCB mounting)	Machine Screw, Phillips, 4 × 40 Thread, 1/4" long, Nylon	Building Fasteners	NY PMS 440 0025 PH
2	(for External RTD)	24 AWG wires, twisted strands, 2 m	n/a	n/a

**Note 1:** The components listed in this Bill of Materials are representative of the optional parts that the user may wish to acquire and install. The released BOM used in manufacturing uses all RoHS-compliant components.

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

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NOTES:

## Appendix C. Conversion Polynomials

### C.1 CIRCUIT RESPONSE

Table C-1 shows the nominal performance of critical circuit parameters used in this appendix.  $V_{\text{BRIDGE}}$  is the differential output voltage of the Wheatstone bridge.  $V_{\text{INA\_OUT}}$  is the output voltage of the INAs.  $V_{\text{REF}}$  shifts the INAs' output above ground (about 1.80V).  $V_{\text{INA}}$  is  $V_{\text{INA\_OUT}} - V_{\text{REF}}$ , which corrects the measured voltages for  $V_{\text{REF}}$  errors (about  $\pm 0.03\text{V}$ ).

**TABLE C-1: NOMINAL VALUES**

$T_{\text{RTD}}$ (°C)	$R_{\text{RTD}}$ ( $\Omega$ )	$V_{\text{BRIDGE}}$ (V)	$V_{\text{INA\_OUT}}$ (V)	$V_{\text{INA}}$ (V)
-55	78.32	-0.00565	0.665	-1.136
-50	80.31	-0.00510	0.774	-1.026
-45	82.29	-0.00456	0.883	-0.918
-40	84.27	-0.00403	0.989	-0.811
-35	86.25	-0.00351	1.095	-0.706
-30	88.22	-0.00299	1.199	-0.601
-25	90.19	-0.00248	1.303	-0.498
-20	92.16	-0.00197	1.404	-0.396
-15	94.12	-0.00147	1.505	-0.295
-10	96.04	-0.00097	1.605	-0.196
-5	98.04	-0.00048	1.703	-0.097
0	100.00	0.00000	1.801	0.000
5	101.95	0.00048	1.897	0.096
10	103.90	0.00095	1.992	0.191
15	105.85	0.00142	2.086	0.285
20	107.79	0.00188	2.179	0.378
25	109.74	0.00234	2.271	0.470
30	111.67	0.00279	2.362	0.561
35	113.61	0.00324	2.452	0.651
40	115.54	0.00368	2.541	0.740
45	117.47	0.00412	2.629	0.828
50	119.40	0.00455	2.716	0.915
55	121.32	0.00498	2.802	1.001
60	123.24	0.00540	2.887	1.086
65	125.16	0.00582	2.971	1.171
70	127.08	0.00623	3.055	1.254
75	128.99	0.00664	3.137	1.336
80	130.90	0.00705	3.219	1.418
85	132.80	0.00745	3.299	1.499
90	134.71	0.00785	3.379	1.579
95	136.61	0.00824	3.458	1.658

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

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TABLE C-1: NOMINAL VALUES (CONTINUED)

$T_{RTD}$ (°C)	$R_{RTD}$ ( $\Omega$ )	$V_{BRIDGE}$ (V)	$V_{INA\_OUT}$ (V)	$V_{INA}$ (V)
100	138.51	0.00863	3.537	1.736
105	140.40	0.00901	3.614	1.813
110	142.29	0.00939	3.691	1.890
115	144.18	0.00977	3.767	1.966
120	146.07	0.01014	3.842	2.041
125	147.95	0.01051	3.916	2.115
130	149.83	0.01088	3.990	2.189
135	151.71	0.01124	4.063	2.262
140	153.58	0.01160	4.135	2.334
145	155.46	0.01196	4.206	2.405
150	157.33	0.01231	4.277	2.476
155	159.19	0.01266	4.347	2.546



## C.2 RTD TEMPERATURE AND RESISTANCE

The RTD's temperature error is Class F0.3:

### EQUATION

$$T_{Tot} = \pm(0.30^{\circ}\text{C} + 0.005 |T_{RTD}|), \quad \text{Class F0.3}$$

To accommodate fixed point arithmetic,  $R_{RTD}$  and  $T_{RTD}$  are scaled as follows:

### EQUATION

$$p = T_{RTD} / T_{S1}$$

$$q = (R_{RTD} - R_{S0}) / R_{S1}$$

Where:

$$T_{S1} = +256^{\circ}\text{C}$$

$$R_{S0} = 120 \Omega$$

$$R_{S1} = 64 \Omega$$

The RTD's resistance is estimated with this polynomial approximation (with scaling):

### EQUATION

$$q = A_0 + p (A_1 + p (A_2)) \pm \epsilon_Q$$

$$R_{RTD} = R_{S0} + q R_{S1} \pm \epsilon_R$$

Where:

$$A_0 = -0.31251$$

$$A_1 = 1.56353$$

$$A_2 = -0.05946$$

$$\epsilon_R = \epsilon_Q R_{S1}, \quad |\epsilon_R| \leq 0.0053 \Omega$$

$$\epsilon_T = \epsilon_R / (dR_{RTD}/dT_{RTD}), \quad |\epsilon_T| \leq 0.013^{\circ}\text{C}$$

The RTD's temperature is estimated with this polynomial approximation (with scaling):

### EQUATION

$$p = B_0 + q (B_1 + q (B_2 + q (B_3 + q (B_4)))) \pm \epsilon_P$$

$$T_{RTD} = p T_{S1} \pm \epsilon_T$$

Where:

$$B_0 = 0.201424$$

$$B_1 = 0.649547$$

$$B_2 = 0.016232$$

$$B_3 = 0.000768$$

$$B_4 = 0.000163$$

$$\epsilon_T = \epsilon_P T_{S1}, \quad |\epsilon_T| \leq 0.013^{\circ}\text{C}$$

$$\epsilon_R = \epsilon_T (dR_{RTD}/dT_{RTD}), \quad |\epsilon_R| \leq 0.0049 \Omega$$

# MCP6N11 and MCP6V2x Wheatstone Bridge Reference Design

## C.3 INA VOLTAGE TO TEMPERATURE

Preliminary work was done in an Excel<sup>®</sup> spreadsheet to fit polynomials to the  $T_{RTD}$  using  $V_{INA}$  (see Table C-1). Different order approximations were produced for different purposes: hand estimates, firmware algorithm and spreadsheet calculations.

To accommodate fixed point arithmetic,  $T_{RTD}$  is scaled as before and  $V_{INA}$  is scaled based on its binary representation:

### EQUATION

$$v = V_{INA} / (V_{DD}/2)$$

$$w = T_{RTD} / T_{SI}$$

Where:

$$V_{INA} = V_{AD1} - V_{AD2} \quad \text{for INA \#1}$$

$$= V_{AD3} - V_{AD4}, \quad \text{for INA \#2}$$

$$V_{DD}/2 = 2.5V$$

$$T_{SI} = +256^{\circ}C$$

The reason  $V_{INA}$  subtracts  $V_{REF}$  ( $V_{AD2}$  or  $V_{AD4}$ ) is to correct the  $V_{REF}$ 's inaccuracy (about  $\pm 0.03V$ ).

Since the PIC MCU's ADC uses the supply as its reference voltage,  $v$  is easy to produce in firmware. Simply use the most significant bit (MSb) as the sign bit, and the other bits to produce the magnitude.

The fitted polynomials are based on the average of the two nominal INA gains ( $G_{INA} = 201.2 V/V$ ); the resulting nominal error is only  $\pm 0.1\%$ , which is well within the circuit's error budget.

### EQUATION

$$w = K_0 + v (K_1 + v (K_2 + v (K_3 + v (K_4)))) \pm \epsilon_W$$

$$T_{RTD} = w T_{SI}$$

$$\epsilon_T = \epsilon_W T_{SI}$$

Where several polynomials are of use:

Parameters	Polynomials			
	n = 1	n = 2	n = 3	n = 4
$K_0$	0.01453	-0.00130	0.00002	0.00001
$K_1$	0.55695	0.50628	0.50417	0.50465
$K_2$	0	0.08652	0.07463	0.07452
$K_3$		0	0.01370	0.01116
$K_4$			0	0.00221
$\epsilon_T (^{\circ}C)$	6.1	0.35	0.021	0.0013

**Note 1:** n = 1 and 2 are useful for hand calculations, n = 3 for the firmware algorithm and n = 4 for spreadsheet design calculations.

**2:** Other RTDs will use different coefficients.

## Appendix D. Board Validation Summary

This appendix summarizes the data collected during validation of two Rev. 1 boards.

### D.1 THERMAL STEADY STATE RESPONSE

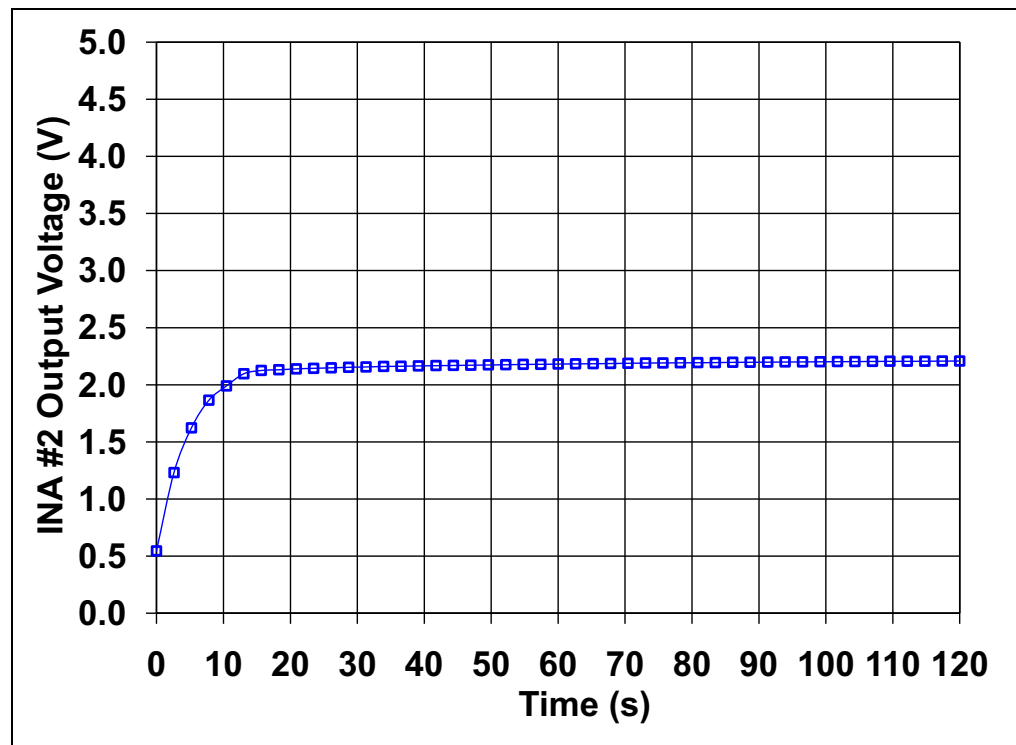
The boards' bias voltages were within expected ranges. The difference between the two INA outputs on each board was less than  $\pm 0.2^{\circ}\text{C}$  (caused by resistor tolerances). The difference between the two boards was less than  $\pm 1.4^{\circ}\text{C}$  (caused by RTD tolerances).

The first board's steady state temperature was  $23.4^{\circ}\text{C}$  ( $74.1^{\circ}\text{F}$ ).

### D.2 THERMAL IMPULSE RESPONSE

A quick blast from a freeze spray can onto the RTD (on the first board) cooled it rapidly, giving the thermal impulse response of the RTD and PCB. The following plots are from the second INA on that board.

Figure D-1 shows  $V_{AD3}$ , which is in range.



**FIGURE D-1:** INA #2's Output Voltage.

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Figure D-2 shows the RTD's temperature as it changes over a two minute period of time. It starts out of range for this RTD sensor (-55°C is the specified minimum).

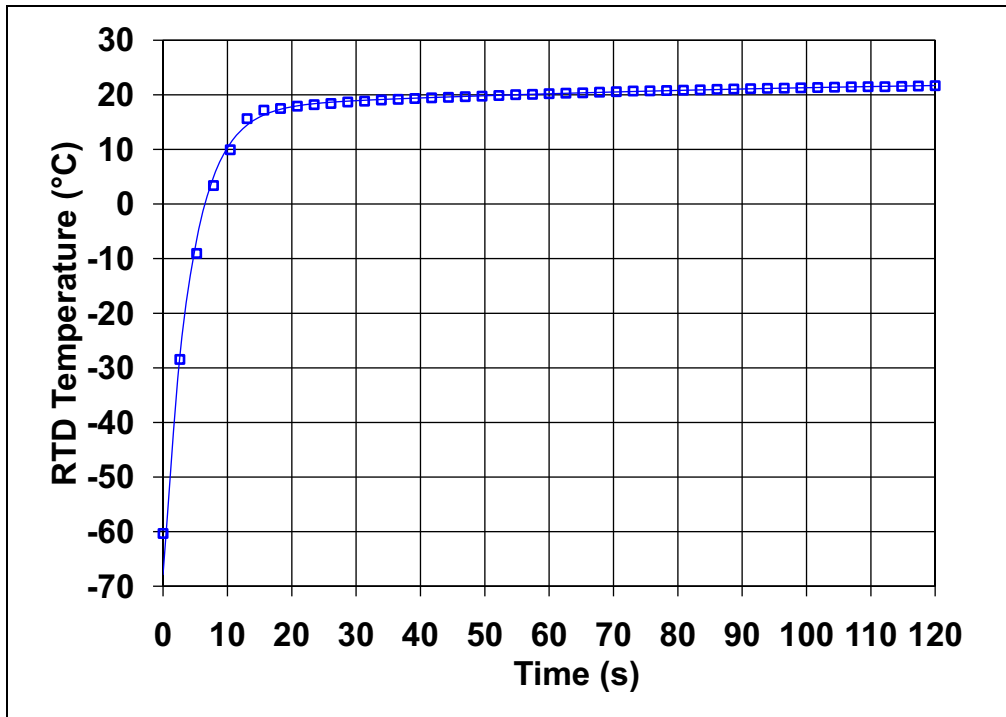


FIGURE D-2: RTD Temperature.

Figure D-3 shows the difference between the steady state temperature (23.4°C) and the temperature at each time point. Initially, the RTD's thermal settling dominates, with  $\tau = 4.2$  s ( $f_p = 38$  MHz). Later on, the PCB's thermal settling (with still air, laying flat on the bench) dominates, with  $\tau = 94$  s ( $f_p = 1.7$  MHz).

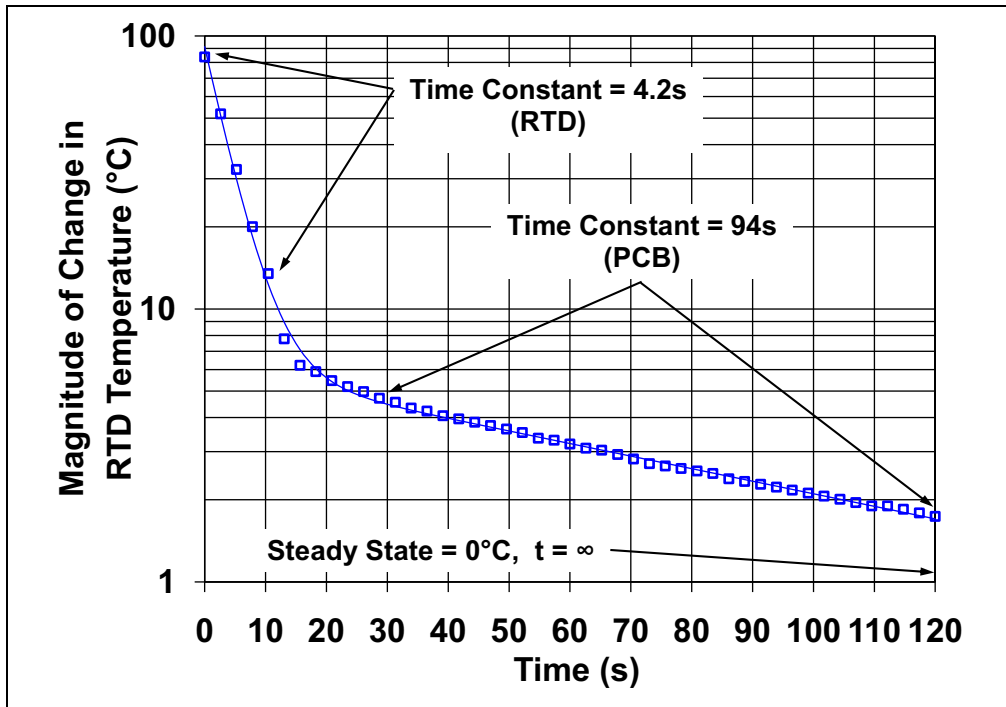


FIGURE D-3: Exponential Settling of Temperature vs. Time.



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