Application Note

High Accuracy Wheatstone Bridge Amplifier Circuit to 4-20-mA Current Loop Transmitter

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ABSTRACT

This application note proposes a field transmitter design using a precision voltage amplifier to condition the output of a Wheatstone bridge sensor. This document also shows how the voltage output of the amplifier can be translated into a 4-20-mA signal with a current loop transmitter. All sensor and amplifier circuitry are powered by the current loop transmitter. Additionally, this application note covers the selection of the amplifier and passive components to achieve the required gain and voltage-to-current conversion. Error sources, PCB layout considerations, and measured results are also discussed.

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Trademarks

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1 Introduction

Following are the design requirements:

- Use reference voltages of the current loop transmitter to power sensor and amplifier circuitry
- Total current consumption < 3.5-mA
- Weight range = 0 to 20-lbs → output current = 4 to 20-mA
- ±0.1% accuracy

The design goals and performance are summarized in Table 1-1. The measured transfer function and completed PCB design are shown below.

Table 1-1. Design Goal versus Calculated, Simulated, and Measured Performance

	Weight	Goal	Calculated	Simulated	Measured
Iout (Min)	0lbs	4mA	4.0959mA	4.0963mA	4.0994mA
Iout (Max)	20lbs	20mA	20.1404mA	20.1397mA	20.1545mA

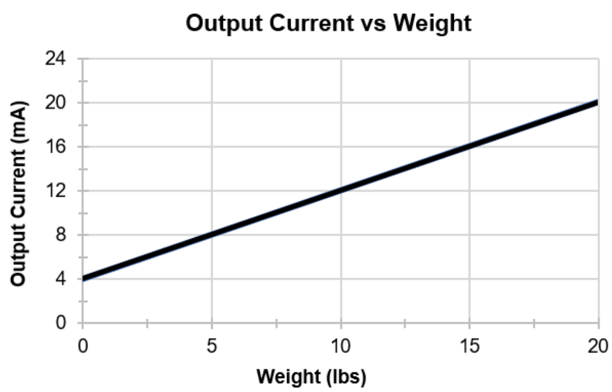

Figure 1-1. Measured Output Current vs Weight Transfer Function

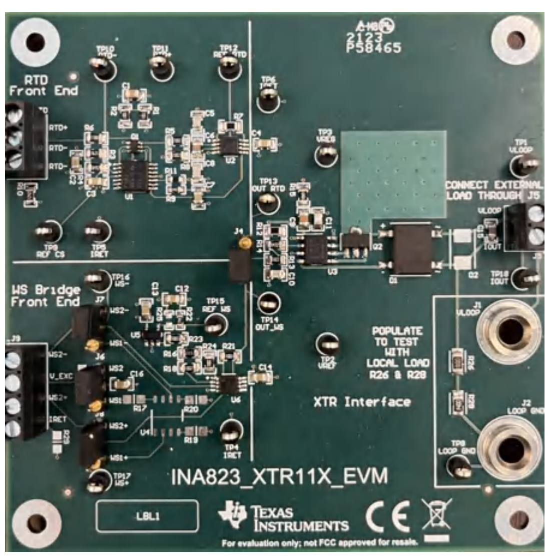

Figure 1-2. Wheatstone Bridge to 4-20-mA Current Loop Transmitter PCB Design

2 Theory of Operation

Factory automation and control systems often require the status of several processes to be monitored and communicated to a control station to ensure proper operation. It is common practice for many sensors to be dispersed on a factory floor to convert process variables such as pressure, temperature and weight into electrical signals that can be transmitted to a central location. 4-20-mA current loop transmitters are ideal for this application because they allow remote processes to be monitored with only two wires: power for the sensor or surrounding circuitry and an output current corresponding to the sensor variable of interest. A Wheatstone bridge amplifier to 4-20-mA current loop transmitter circuit is proposed as a high accuracy factory automation signal chain solution.

The circuit can be divided into three sections:

1. Wheatstone bridge sensor
2. Discrete 2-amp instrumentation amplifier (INA)
3. 4-20-mA current loop transmitter (XTR) interface

Figure 2-1 shows a simplified version of the full circuit. The reference voltages and local ground (I_{RET}) of TI's XTR116 are used to power all bridge and sensor circuitry. All current consumed by the XTR powered circuitry must return through the current loop (I_{RET}); therefore, the monitoring circuitry must consume less than 4-mA to avoid interference with the 4-20-mA output current of interest. To account for variation in device, temperature, and supply it is good practice to limit the current consumption to 3.5-mA. The XTR116 is powered by the two-wire power supply (V_{LOOP}).

The signal chain begins with a small differential voltage developed between the two outputs of the Wheatstone bridge corresponding to the variable of interest. These voltages are fed into the discrete 2-amp INA which can amplify their difference and the output voltage can be converted into a current through a resistor (R_{IN}). The current loop transmitter then takes the current at the input (I_{IN}) and returns the current multiplied by 100 at the output (I_{OUT}). The following sections provide more detail on each portion of the circuit.

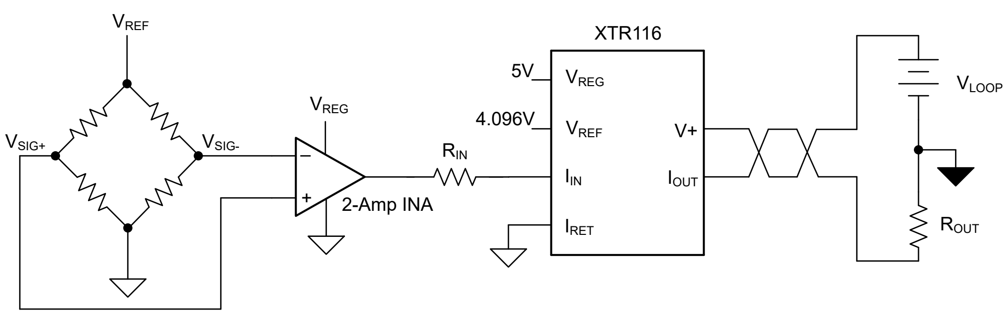

Figure 2-1. Simplified Bridge Amplification to 4-20-mA Circuit

2.1 Wheatstone Bridge Sensor

The Wheatstone bridge is a commonly used circuit configuration to achieve highly accurate sensor measurements. The bridge is composed of four resistive elements creating two voltage dividers in parallel between an excitation voltage (V_{EXC}) and ground. In the most basic form, only one of the elements can vary in resistance. This change in resistance can create a difference in voltage between the two dividers, V_{SIG+} and V_{SIG-}. A differential voltage measurement (V_{DIFF}) is taken between these two points. A large differential voltage corresponds to a large variation in resistance, and thus a large change in the sensor value being measured. Figure 2-2 depicts a classic Wheatstone bridge configuration and Equation 1 describes the relationship between V_{DIFF}, V_{EXC}, and the resistive bridge elements with respect to ground.

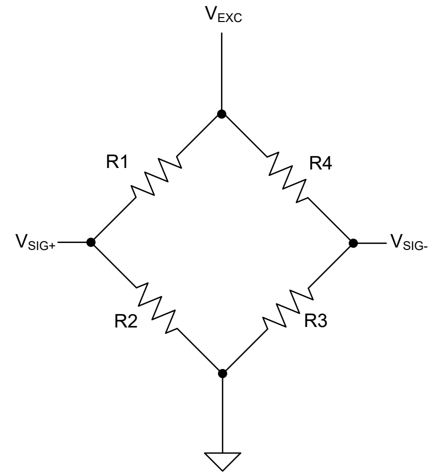

Figure 2-2. Basic Wheatstone Bridge Configuration

$$V_{DIFF} = V_{SIG+} - V_{SIG-} = V_{EXC} \times \left(\frac{R2}{R1 + R2} - \frac{R3}{R3 + R4}\right) \quad (1)$$

The input resistance of the selected sensor is approximately 1-kΩ and can consume more than 4-mA of current with a V_{EXC} of 4.096-V. Therefore, two, 500 Ω resistors were placed in series on either side of the bridge to limit the current to 2-mA while keeping the signal close to mid-supply to avoid common mode limitations in the subsequent INA stage. The current limiting resistors (R_{LIMIT}) are sized to produce an excitation voltage of 2.096-V across the Wheatstone bridge. Larger current limiting resistors can reduce the effective excitation voltage, thus decreasing bridge sensitivity. Figure 2-3, Equation 2, and Equation 3 describe the modified Wheatstone bridge and show the calculation for R_{LIMIT}.

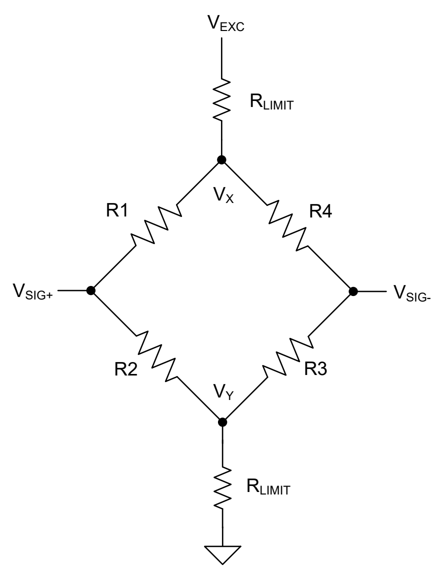

Figure 2-3. Current Limited Wheatstone Bridge Configuration

$$\frac{V_{BRIDGE}}{I_{BRIDGE}} = \frac{4.096V}{2mA} = 2R_{LIMIT} + R_{BRIDGE} = 2R_{LIMIT} + 1k\Omega \rightarrow R_{LIMIT} = 500\Omega \quad (2)$$

$$V_{EFF\_EXC} = V_X - V_Y = V_{EXC} - 2I_{BRIDGE}R_{LIMIT} = 4.096V - (2 \times 2mA \times 500\Omega) \rightarrow V_{EFF\_EXC} = 2.096V \quad (3)$$

This design uses a Wheatstone bridge load cell, however, any sensor that can be configured in Wheatstone bridge is applicable. The differential voltage developed at V_{DIFF} increases as the weight applied to the load cell increases. More detail on the selected load cell is included in the Appendix 1: Load Cell and Experimentation Setup.

2.2 2-Amp INA

A discrete 2-amp INA is selected to amplify the differential voltage developed by the bridge. A discrete solution is selected over an integrated INA because a wide gain range and zero-drift technology for high precision over temperature is required. The circuit configuration and transfer function are shown below in Figure 2-4 and Equation 4 respectively.

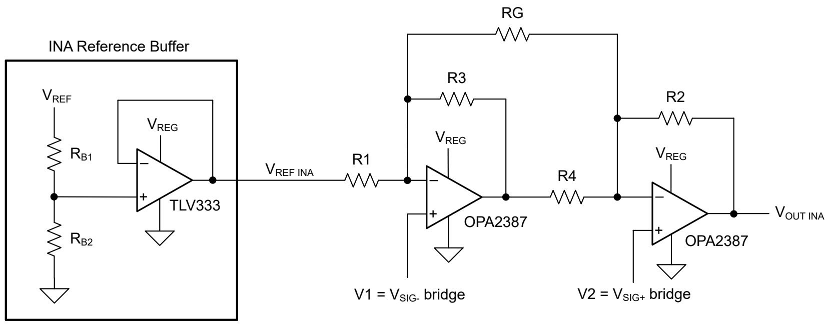

Figure 2-4. Discrete 2-Amp INA Configuration

$$V_{out\_INA} = \left(1 + \frac{R3}{R2} + \frac{2R2}{RG}\right)*(V2 - V1) + V_{REF}, \quad where\ R1 = R2\ and\ R3 = R4 \tag{4}$$

Experimentation with the load cell showed a change in V_{DIFF} of approximately 95-µV/lb. Hence, a gain stage is necessary to increase the output voltage to an appropriate range to feed into the 4-20-mA transmitter. The gain of the 2-amp INA is calculated below. The desired output voltage of the INA is 0.5-V at 0-lbs and 4.5-V at 20-lbs.

$$V_{DIFF\_MAX} = sensitivity \times max\ load = 95\mu V/lb \times 20lbs \rightarrow V_{DIFF\_MAX} = 1.9mV \tag{5}$$

$$Gain = \frac{(V_{outmax\_INA} - V_{outmin\_INA})}{V_{DIFF\_MAX}} = \frac{4.5\ V - 0.5\ V}{1.9\ mV} \rightarrow Gain = 2105\ V/V \tag{6}$$

The required gain is used to calculate the resistor values of the 2-amp INA. R1 and R2 are set to 100 kΩ and R3 and R4 are set to 10 kΩ.

$$RG = \frac{2*R2}{Gain - 1 - \frac{R3}{R2}} = \frac{2*100k\Omega}{2105V/V - 1 - \frac{100k\Omega}{10k\Omega}} = 95.511\Omega \rightarrow RG = 95.3\Omega\left(standard\ value\right) \tag{7}$$

$$Gain = \left(1 + \frac{R3}{R2} + \frac{2R2}{RG}\right), \quad where\ R1 = R2\ and\ R3 = R4 \tag{8}$$

DC precision and noise are key considerations when choosing an amplifier for bridge sensing. Low input offset voltage, drift and input bias current are vital to achieve a high accuracy output. An amplifier with low 1/f noise is important because bridge sensors are typically used with low signal frequencies. The OPA2387 with *Zero-Drift Amplifiers: Features and Benefits*, application brief is selected for the 2-amp INA. Table 2-1 summarizes the key specifications for the bridge amplifier stage and suggests other precision amplifiers that are designed for this application.

Table 2-1. Key Specifications for Bridge Amplifier Device

Device	OPAx387	OPAx333	OPAx186
Supply (V)	1.7 to 5.5	1.8 to 5.5	4.5 to 24
Vos (max, µV)	2	10	5
Vos drift (typ, nV/°C)	3	20	1
Input bias current (typ, pA)	30	70	100
Noise (0.1 to 10 Hz, nV/√Hz)	27	170	125
Iq per channel (typ, µA)	570	17	90

The output voltage of the 2-amp INA is approximately 0.345-V when no weight is applied to the load cell. Therefore, a reference of 0.155-V is implemented to boost the output voltage up to 0.5-V at 0-lbs. *TI's Analog Engineer's Calculator* can be used to calculate the standard resistor values that offer the lowest possible reference voltage error.

The reference voltage of the INA ($V_{REF\ INA}$) is set using a voltage divider between the 4.096-V XTR reference and the local ground where the series resistance must be in the 10's of kΩ to limit current consumption. $V_{REF\ INA}$ must be driven with a low-impedance source to prevent a voltage drop due to the input resistor, R1. The TLV333 was selected to buffer the reference voltage due to its low power consumption and high DC precision.

$$V_{REF\_INA} = 0.155V = V_{REF\_XTR} \times \frac{R_{B2}}{R_{B1} + R_{B2}} \rightarrow R_{B1} = 76.8k\Omega,\ R_{B2} = 3.01k\Omega \quad (9)$$

2.3 4-20-mA Current Loop Transmitter Interface

The 4-20-mA current loop transmitter is responsible for powering all bridge and INA circuitry as well as providing accurate current scaling. The device requires some external circuitry to function properly as shown in Figure 2-5.

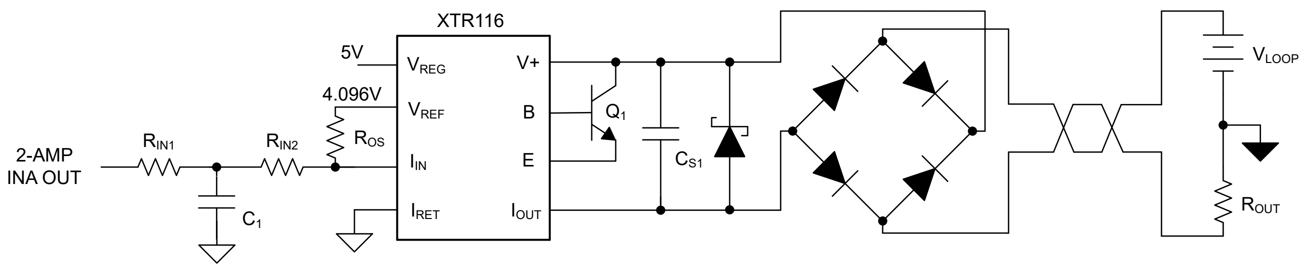

Figure 2-5. Surrounding Circuitry for Current Loop Transmitter

The XTR 5-V on chip voltage regulator (V_{REG}) powers the 2-amp INA while the 4.096-V precision reference (V_{REF}) powers the bridge and INA reference voltage divider. V_{REG} can shift hundreds of mV depending on the amount of current it is sinking or sourcing, so it is important to use V_{REF} when a precise voltage is required (see *XTR116* data sheet, Figure 6-5). Current drawn from V_{REG} or V_{REF} must be returned to the local ground pin (I_{RET}).

Resistors R_{IN1} and R_{IN2} convert the output voltage of the INA into a current that can be fed into the I_{IN} pin. The offset current resistor (R_{OS}) is used to add an additional 20-μA of current to I_{IN} to boost the input current to the desired 40-200-μA. The XTR provides a gain of 100 which is seen at the output current pin (I_{OUT} = 100*I_{IN}). Capacitor C_{IN} and R_{IN1} form a low pass filter at the output of the INA to limit noise. Calculations for these passive components are shown in the following equations.

$$R_{IN} = \frac{V_{IN\_MAX} - V_{IN\_MIN}}{I_{IN\_MAX} - I_{IN\_MIN}} = \frac{4\ V}{160\ \mu A} = 25k\Omega \quad (10)$$

$$I_{INmin} = 40\ \mu A = \frac{0.5\ V}{25\ k\Omega} + \frac{4.096\ V}{R_{os}} \rightarrow R_{os} = 204.8\ k\Omega \quad (11)$$

$$Closest\ standard\ resistor\ values:\ R_{IN1} = 10.2\ k\Omega,\ R_{IN2} = 14.7\ k\Omega,\ R_{os} = 205\ k\Omega \quad (12)$$

$$f_C = \frac{1}{2\pi \times R \times C} = \frac{1}{2\pi \times 10.2\ k\Omega \times 10nF} \rightarrow f_C = 1.56\ kHz \quad (13)$$

A 10-nF decoupling capacitor (C_{S1}) between the loop supply voltage (V+) and the output current pin (I_{OUT}) is recommended. The capacitor and output load resistor form a low pass filter that limits the bandwidth of the system. An external transistor (Q_1) is required to conduct the majority of the output current to avoid on-chip, thermal-induced errors. Power dissipation in this transistor can approach 1-W with maximum loop voltage and output current. For additional protection, a diode bridge and clamping diodes can be considered for reverse voltage and overvoltage surge protection respectively.

3 Simulation

The design was built and verified in TINA TI simulation software. The circuit uses a DC voltage source at one input of the INA to emulate the differential voltage developed across the bridge. Figure 3-1 shows the circuit schematic and DC operating point when the differential voltage corresponding to 0-lbs is applied at the input.

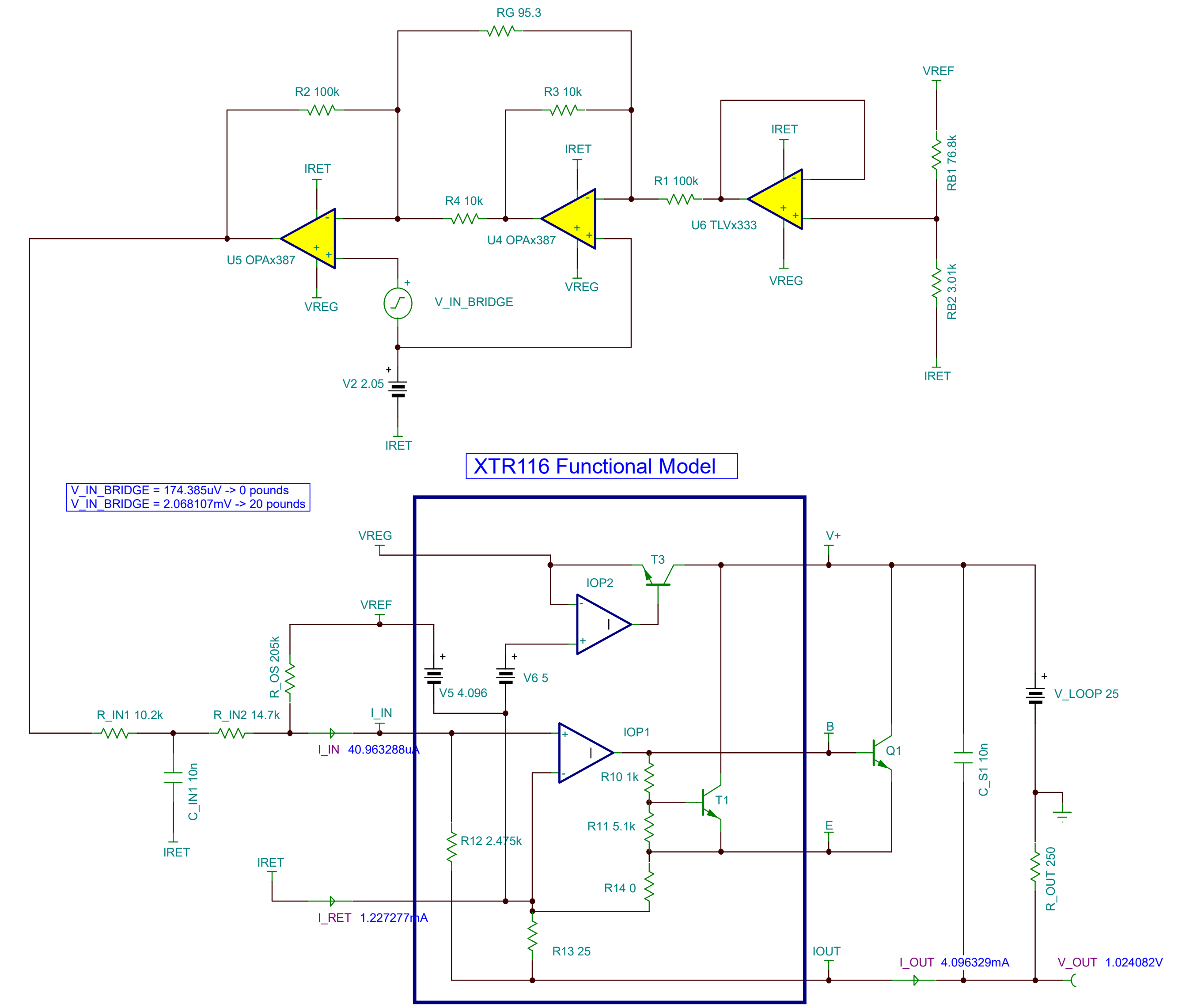

Figure 3-1. TINA TI Schematic and Simulation for 0-lbs Input

4 PCB Design

The PCB schematic, layers, and bill of materials can be found in the Appendix 2: PCB Details.

The design uses 0.1% thin film resistors and X7R ceramic bypass capacitors. Any capacitors used for filtering are C0G ceramic capacitors.

Typical layout best practices are followed in this PCB design (for example, short traces, low-impedance ground connections, nearby decoupling capacitors). An additional copper pour is placed around the external transistor (Q_1) to help dissipate heat.

5 Verification and Measured Performance

The measured output current versus weight is shown in Figure 5-1. The measured results are compared with the simulated and calculated values in Table 5-1. The measured results are ±0.1% accurate as shown in Figure 5-2. The experimentation setup with the load cell is detailed in the Appendix 1: Load Cell and Experimentation Setup. The total current consumption is calculated in Equation 14.

$$I_{TOTAL} = I_{BRIDGE} + I_{2AMP\ INA} + I_{INA\ REF} + I_{XTR} = 2mA + 1.14mA + 0.05mA + 0.2mA \rightarrow I_{TOTAL} = 3.39mA \quad (14)$$

Table 5-1. Design Goal vs Calculated, Simulated, and Measured Performance

	Weight	Goal	Calculated	Simulated	Measured
Iout (Min)	0 lbs	4 mA	4.0959 mA	4.0963 mA	4.0994 mA
Iout (Max)	20 lbs	20 mA	20.1404 mA	20.1397 mA	20.1545 mA

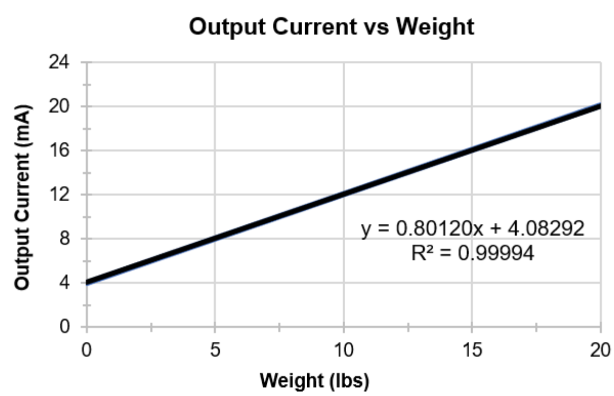

Figure 5-1. Measured Output Current vs Weight Transfer Function

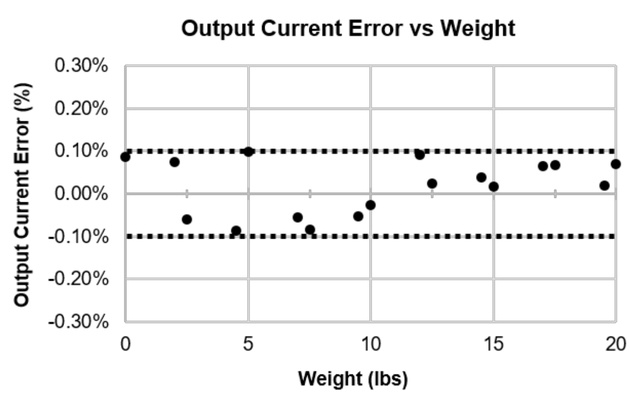

Figure 5-2. Output Current Error vs Weight

6 Summary

A high accuracy bridge amplifier to 4-20-mA current loop transmitter was successfully designed and measured. The final results are summarized in Table 6-1.

Table 6-1. Summary of Key Design Criteria and Results

Design Criteria	Results & Comments
Use XTR references (4.096-V and 5-V) to power sensor and amplifier circuitry	Design only uses XTR reference voltages
Total current consumption < 3.5-mA	Total current consumption = 3.39mA
Weight range = 0 to 20-lbs → output current = 4 to 20-mA	Weight range = 0 to 20-lbs → output current = 4.0994 to 20.1545-mA. Approximately 0.1-mA offset due to limits of standard resistor values.
±0.1% accuracy	Design is accurate to ±0.1%

7 Reference

- Texas Instruments, *A Basic Guide to Bridge Measurements*, application note.
- Texas Instruments, 2-Wire 4-20 mA Sensor Transmitters: Background and Compliance Voltage (Part 1), blog post.
- Texas Instruments, *TI's Analog Engineer's Calculator*.
- Texas Instruments, *Zero-Drift Amplifiers: Features and Benefits*, application brief.
- Texas Instruments, *XTR11x 4-20 mA Current-Loop Transmitters*, data sheet.

Appendix

Appendix 1: Load Cell and Experimentation Setup

The SparkFun Electronics SEN-13329 10kg load cell was used for the Wheatstone bridge sensor. Figure 8-1 shows the sensor where the red, black, green, and white wires correspond to the Wheatstone outputs respectively.

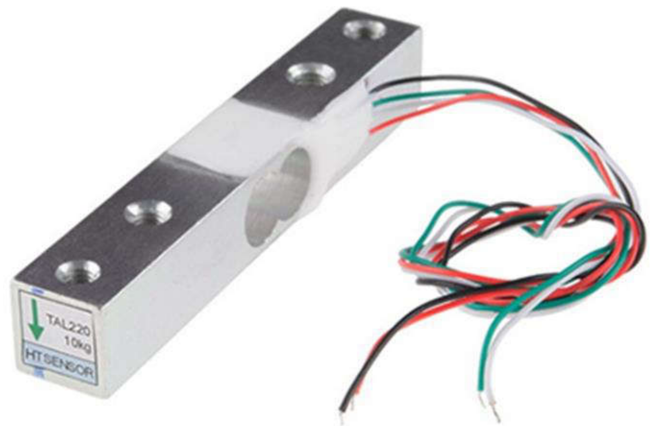

Figure 8-1. SparkFun Load Cell Selected

The load cell was secured with screws between two pieces of wood to make sure the sensor can compress freely. This process also created a stable platform to place weight plates and dumbbells. The wires of the load cell were attached to the PCB through a 4-input terminal block. Figure 8-2 shows the load cell setup.

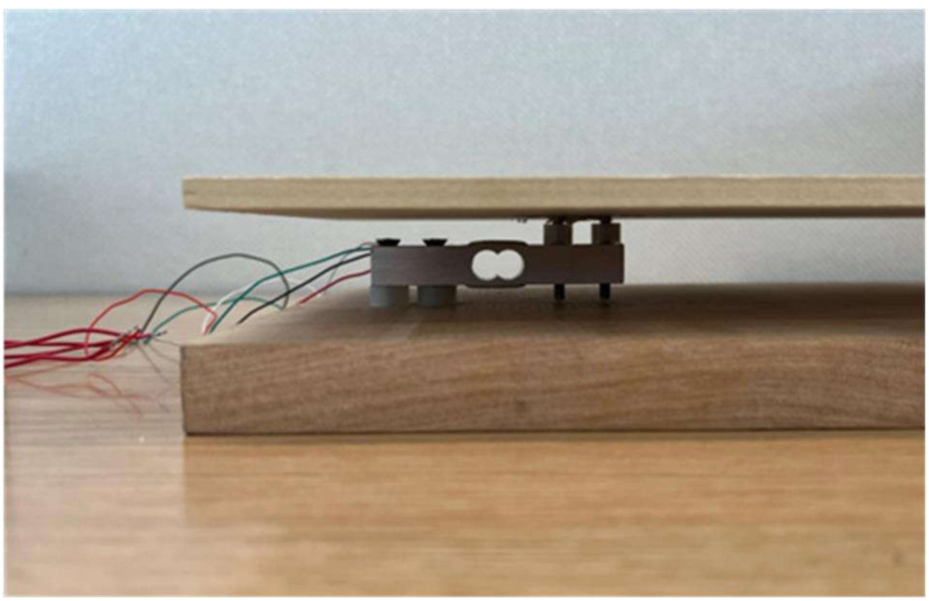

Figure 8-2. Mechanical Setup for Load Cell

When a weight was applied, a voltage measurement was taken between the two outputs of the bridge, at the INA output and at the output of the XTR. An HP 3458A multimeter was programmed to take 100 readings and the average value was used for each data point. It was vital to *reset* the load cell after each measurement by removing all weight and allowing the load cell to resettle.

Appendix 2: PCB Details

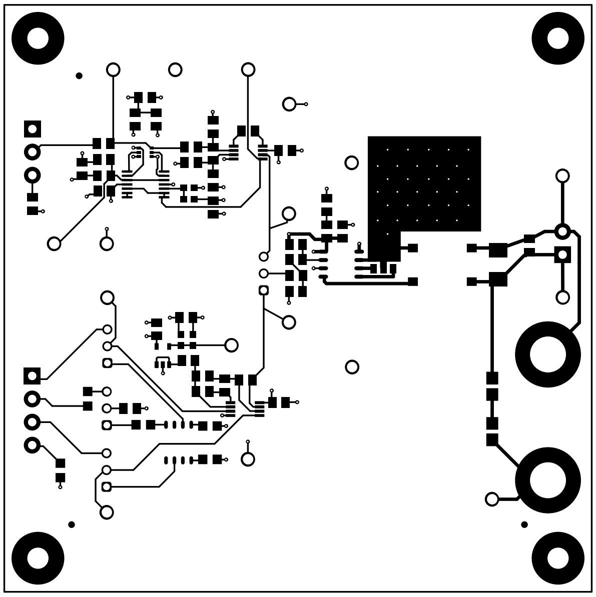

Figure 8-3. PCB Top Layer

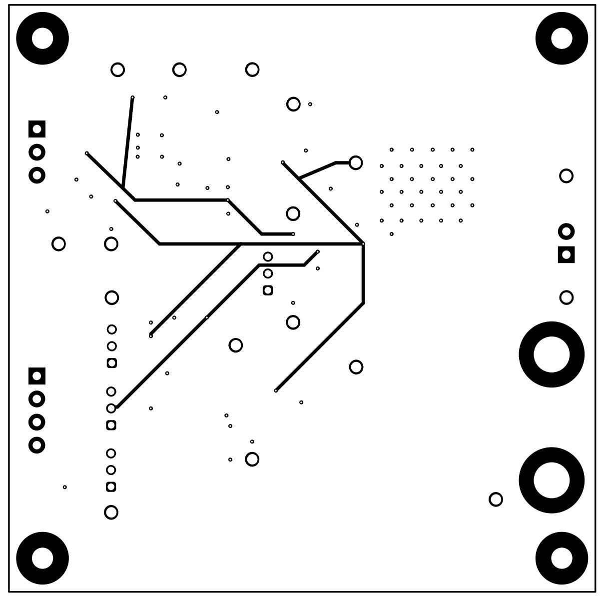

Figure 8-4. PCB Signal Layer 1

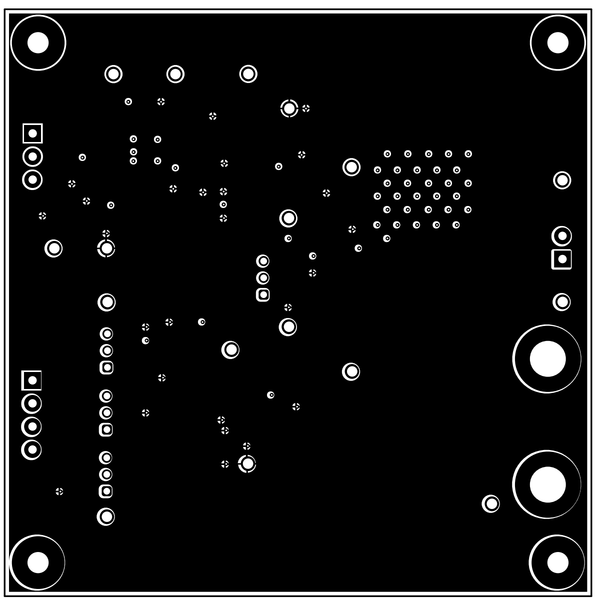

Figure 8-5. PCB Signal Layer 2

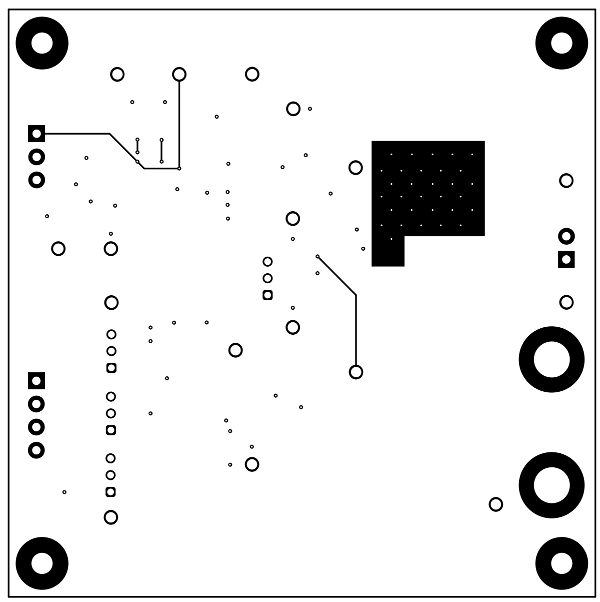

Figure 8-6. PCB Bottom Layer

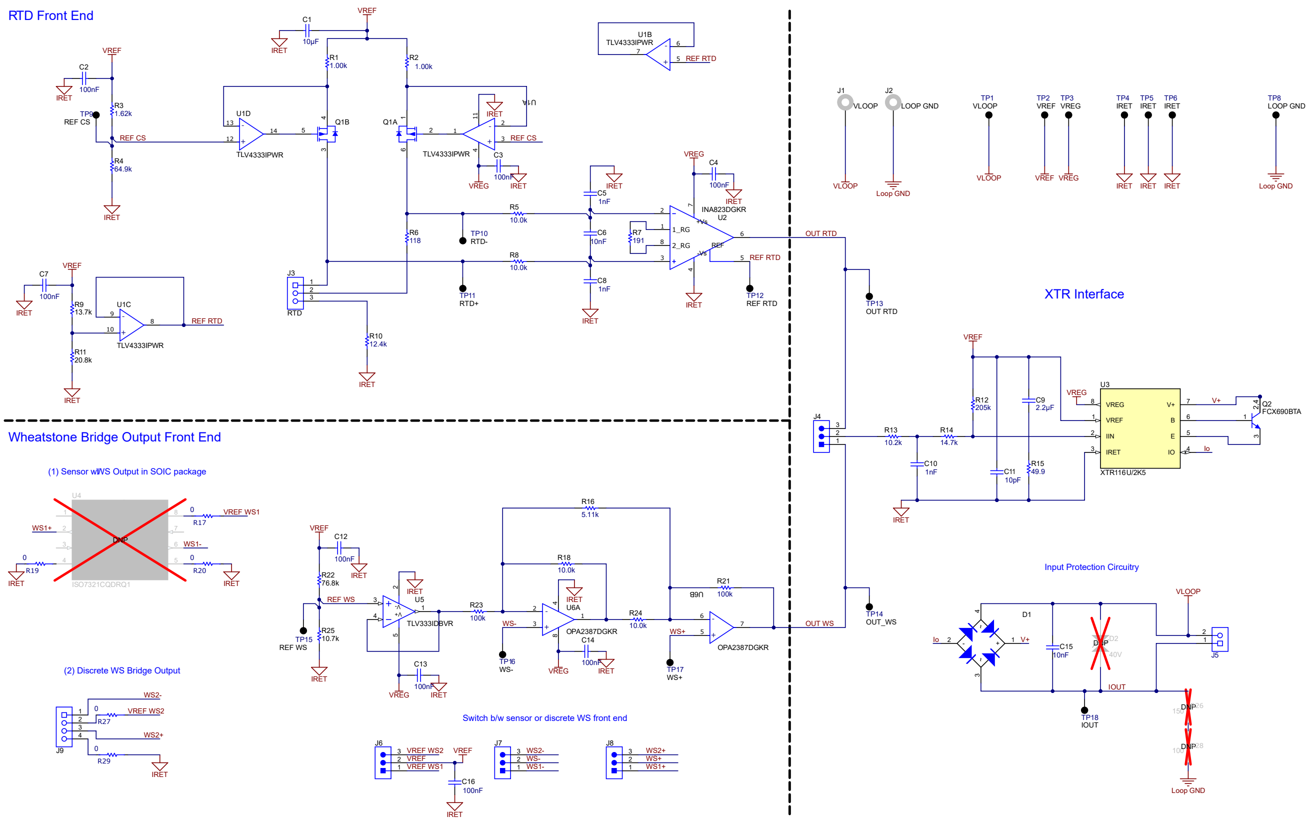

Figure 8-7. PCB Altium Schematic