Design Guide: TIDA-010197

Versatile Satellite Health Monitoring and Control Platform Reference Design With < 1% Accuracy

TEXAS INSTRUMENTS

Description

This reference design features a highly modular solution for radiation-hardened satellite telemetry systems that utilizes the versatility of the LMP7704-SP to accurately monitor temperature, voltage, and current to provide feedback to the host board. It also provides controlled analog outputs to provide protection and optimal efficiency. The majority of space applications require monitoring of these three key measurables in multiple sub-systems of the satellite.

Resources

TIDA-010197	Design Folder
LMP7704-SP	Product Folder
TMP461-SP	Product Folder
INA901-SP	Product Folder
MSP430FR5969-SP	Product Folder
ADC128S102QML-SP	Product Folder
DAC121S101QML-SP	Product Folder
TPS7H2201-SP	Product Folder
TPS7A4501-SP	Product Folder

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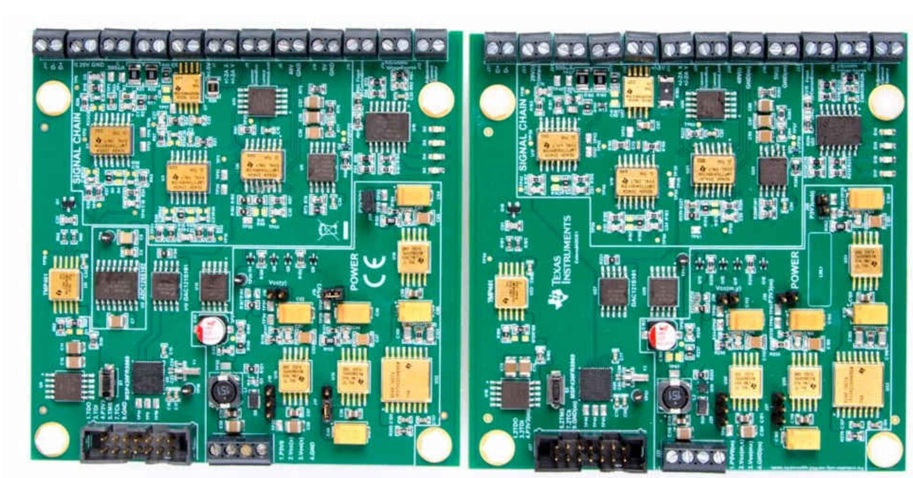
Features

- Nine analog inputs (1% accuracy)
  - Voltage monitoring: 5-, 20-, and 40-V inputs
  - Current sensing: 500 µA, 0.25 A–1 A, and ±2 A
  - Temperature sensing: NTC thermistor and thermal diode
- Three analog outputs
  - 1% Adjustable voltage source
  - 5% Fixed current source
  - 1% Adjustable current source
- External ADC or MCU integrated ADC options

Applications

- Command and data handling (C and DH)
- Communications payload
- Satellite electrical power system (EPS)



1 System Description

As Figure 2-1 and Figure 2-2 illustrate, the TIDA-010197 reference design is comprised of numerous subsystems including:

- An MCU for system control and data processing
- An analog front end (AFE) for signal conditioning for voltage, current, temperature measurements
- Three analog outputs for sensor excitation, biasing networks, temperature sensing
- System power management and sequencing

The ability to monitor voltage, current, and temperature has multiple value propositions, and is critical for maintaining reliable system operation in many applications. From a system health perspective, the ability to have accurate voltage, current, and temperature data for a board is an effective and relatively simple approach to get a relative metric on the health of a board. Changes in current, voltage, and temperature over time could indicate failure, or potential for failure, of some components. Another use case is operation with sensitive components such as many power amplifiers or thermoelectric coolers. The MCU monitors the current, voltage, or temperature (or all of these) of the power amplifier or thermoelectric cooler and triggers a recalibration if there is a deviation over a preset threshold at which a calibration was performed.

There are two variations of the signal chain. Details on the differences are found in the systems overview (Section 2.1).

1. External ADC variation
   - Includes an external 12-bit SAR ADC, ADC128S102QML-SP, that offers a higher accuracy and higher speeds with a full scale range (FSR) of 5 V
2. Integrated ADC variation
   - Utilizes the 12-bit SAR ADC integrated in the MSP430FR5969-SP for a more compact design with an FSR of 2.5 V

To power the TIDA-010197 reference design, there are two methods. The first method provides 5 V and 12 V from an external power supply. The other option supplies a single 5-V rail and utilizes the unregulated boost with LDO.

2 System Overview

Table 2-1 details the system specifications.

Table 2-1. System Specification

PARAMETER			FS ACCURACY
Input Power Supply	Voltage	5 V or 12 V	N/A
Eight Monitored Analog Inputs	Voltage	0 to 5 V	1% + 8 LSD
		0 to 20 V	1% + 5 LSD
		0 to 40 V	1% + 1 LSD
		–5 to 5 V	1% + 2 LSD
	Current	0.25 to 1 A	1% + 5 LSD
		–2 to 2 A	1% + 4 LSD
		0 to 500 µA	1%
Outputs	Voltage	0 to 10 V	1%
	Current	4 mA (fixed)	5%
		4 mA (adjustable)	1%

For more information, see the *TI Space Products Selection Guide* on space grade products, radiation, and ECCN qualification.

Radiation reports for all the listed TI devices in Table 2-2 are found on their TI.com product folder.

Table 2-2. Radiation Qualification

PART NUMBER	TOTAL IONIZATION DOSAGE HDR (kRAD)	TOTAL IONIZATION DOSAGE LDR (kRAD)	Single Event Latch-Up Immune (MeV-cm^2/mg)
ADC128S102QML-SP	100	100	120
DAC121S101QML-SP	100	100	120
MSP430FR5969-SP	50	50	72
LMP7704-SP	100	100	85
INA901-SP	50	50	93
LM4050QML-SP	100	100	SEL Immune (Bipolar process)
LM158QML-SP	100	100	SEL Immune (Bipolar process)
LM139AQML-SP	100	100	SEL Immune (Bipolar process)
TPS7A4501-SP	100	100	86
TMP461-SP	100	100	76

2.1 Block Diagram

Figure 2-1 and Figure 2-2 illustrate system block diagrams of the external and internal ADC configurations.

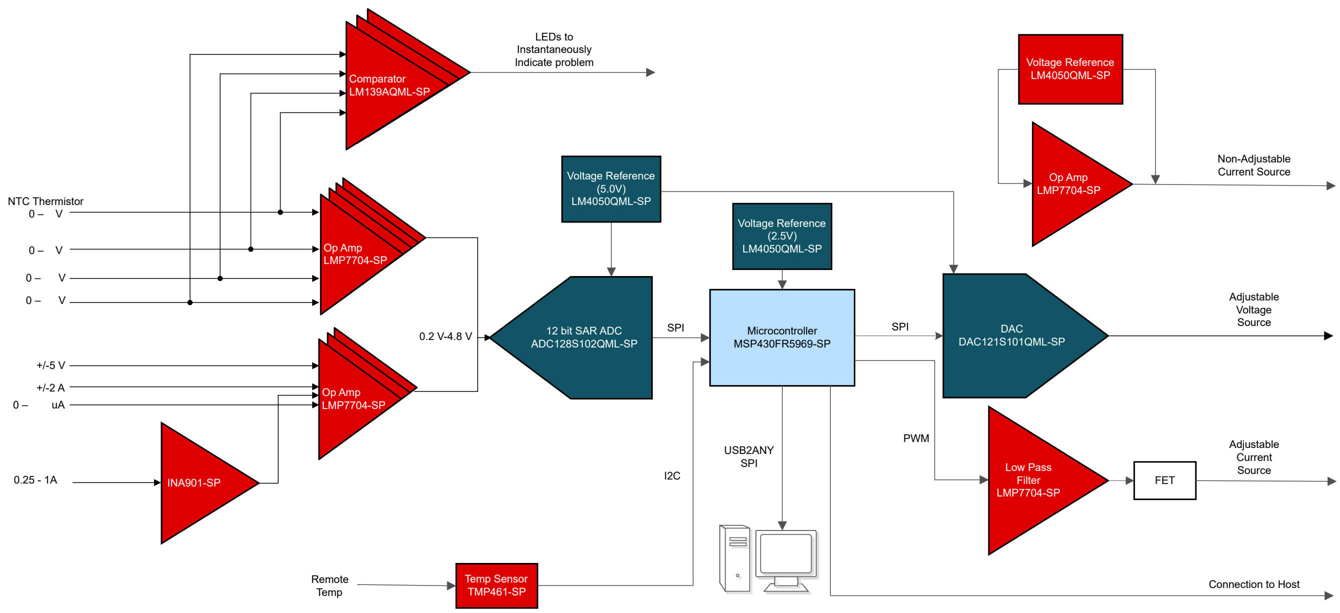


Figure 2-1. System Block Diagram (External ADC Configuration)

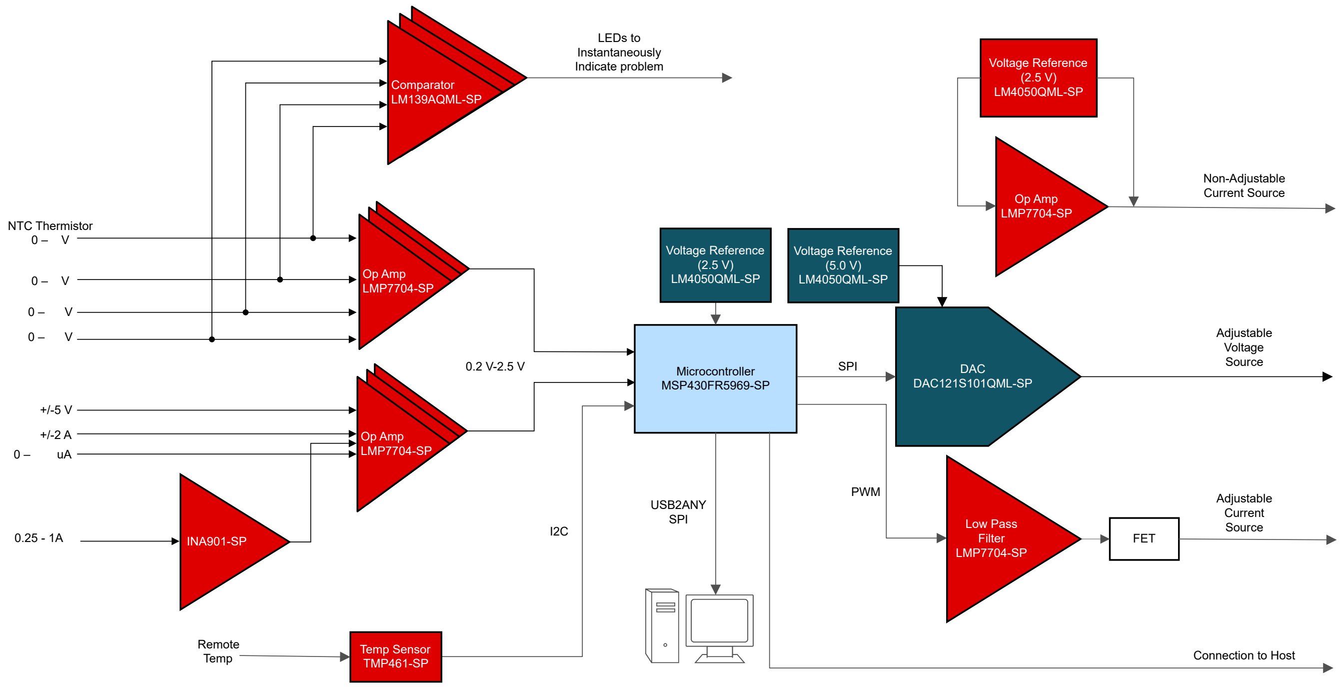


Figure 2-2. System Block Diagram (Internal ADC Configuration)

2.2 Design Considerations

The following sections describe the fundamental subsystems of the reference design for the system control, processing, and the analog front end sensing.

2.2.1 System Control and Processing

The TIDA-010197 system control and processing is based on the significant feature set and capabilities of the MSP430FR5969-SP MCU. The MSP430FR5969-SP provides the communication protocol to interface with the main FPGA, while measuring key telemetry and adjusting system functionality based on the measurements.

The MSP430FR5969-SP is also used to provide the logic and timing for the power sequencing while providing the PWM switching signal for an unregulated boost controller circuit.

2.2.2 Analog Front End

The TIDA-010197 demonstrates two different approaches for the analog front end (AFE). The first option is to use an external ADC paired with the MSP430FR5969-SP. The second option is to use the integrated ADC in the MSP430FR5969-SP allowing for a smaller solution size.

The first option uses the 12-bit SAR ADC, ADC128S102QML-SP, which offers a high accuracy and speeds with a FSR of 5 V. The second option uses the integrated ADC, which is a 12-bit SAR ADC FSR of 2.5 V.

Selecting a low-power 12-bit SAR ADC like the ADC128S102QML-SP helps to achieve the resolutions and speed needed to meet design goals. Both the external and integrated solutions have the same signal conditioning architecture leading up to the ADC. This includes the components and circuitry associated with the voltage and current measurements, voltage range scaling, current-voltage conversion, signal conditioning, and reference voltage generation. The AFE outputs the resulting voltage and current signals for input to the buffer, gain stage, and ADC, which is interfaced with the MSP430FR5969-SP through an SPI.

2.2.3 Input Voltage Monitoring: 5 V, 20 V, 40 V, and ±5 V

There are 4 main voltage rails that are monitored: 5 V, 20 V, 40 V, and ±5 V. Each rail is measured using the same architecture; starting with a voltage divider to scale the voltage down to within the input limitation of the operational amplifier (op amp), followed by a buffer stage allowing for high input impedance on the sensor side and a low impedance on the ADC side to ensure fast settling time.

There are two options to effectively measure the lower limit of the circuits and remain within the input voltage limitations of the op amp which is approximately 200 mV greater than the negative voltage supply rail.

For the external ADC variation and internal ADC variation, the voltage reference for the offset voltage is the same as the voltage reference for their respective ADC (external, 5 V or internal, 2.5 V). This negates any noise and inaccuracies created by the offset voltage. The second option includes an external negative bias on the negative voltage supply pin of the op amp to decrease the lower input limitation of the op amp.

To help with calculations of the circuit, the Analog Engineer's Calculator was used to calculate resistor and capacitor values. Table 2-3 and Table 2-4 show the calculated values of R_a, R_b, and R_c determined from the gain and voltage output range of the circuit. The calculated resistor values results with a 0-V input having a 0.2-V output, and the maximum voltage input resulting in a 4.8-V output and 2.5-V output for the external ADC or internal ADC configuration, respectively.

R_{CB} and C_{CB} are charge bucket circuits that help with the settling time of the output signal to drive the ADC128S102QML-SP. Due to the MUXed input of the ADC128S102QML-SP the acquisition and conversion time has to be properly calculated. In this design, the desired bandwidth is 5 kHz per channel. This results in 40 kHz of accumulated bandwidth. Finally, to fulfill the Nyquist Theorem, the resulting sampling rate is double the needed bandwidth, resulting in a final sample rate of 80 kHz or 12.5 µs per sample which leads to a minimum conversion time of 10.156 µs and an acquisition time of 2.3437 µs. To help with calculations of the circuit, the Analog Engineer's Calculator was used to calculate R_{CB} and C_{CB}.

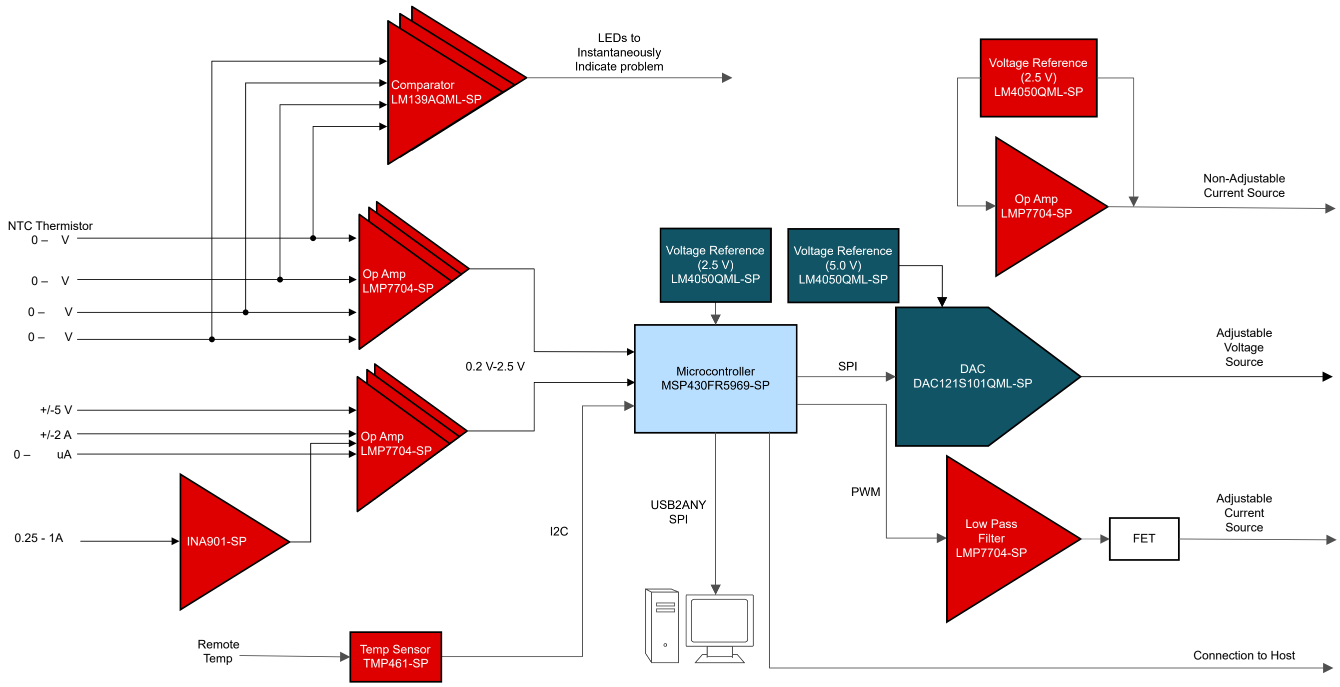


Figure 2-3. Voltage Monitoring - Internal ADC Configuration

Table 2-3. Resistor Values for External Configuration With 5-V Reference

VOLTAGE INPUT (V)	R_a (kΩ)	R_b (kΩ)	R_c (kΩ)	GAIN
±5	10	115	9.09	0.46
5	10	232	232	0.92
20	100	31.6	576	0.23
40	100	13.7	287	0.115

Table 2-4. Resistor Values for MSP430™ Configuration With 2.5-V Reference

VOLTAGE INPUT (V)	R_a (kΩ)	R_b (kΩ)	R_c (kΩ)	GAIN
±5	10	9.76	4.22	0.23
5	100	97.6	576	0.46
20	100	14.3	143	0.115
40	100	6.65	71.5	0.0575

2.2.4 Bidirectional Current Sense: ±2 A

The current sense circuit is used to measure a current range over ±2 A at an accuracy range of 1%, similar to current requirements typically seen in the thermoelectric cooler. The bidirectional circuit configuration shown in Figure 2-4 converts an input current source into an output voltage. The circuit can be used on either the high side or low side of a circuit. If low-side sensing, then there are no V_{cm} limitations, but should not be used in applications where the system load cannot withstand small ground disturbances or in applications that need to detect load shorts. High-side sensing requires a high CMRR to reject any changes in V_{bus} and should not be used when common mode might exceed amplifier supply ($V_{cm} = V_{bus}$). For more information, see the Analog Engineer's Circuit: Low-side bidirectional current sensing circuit.

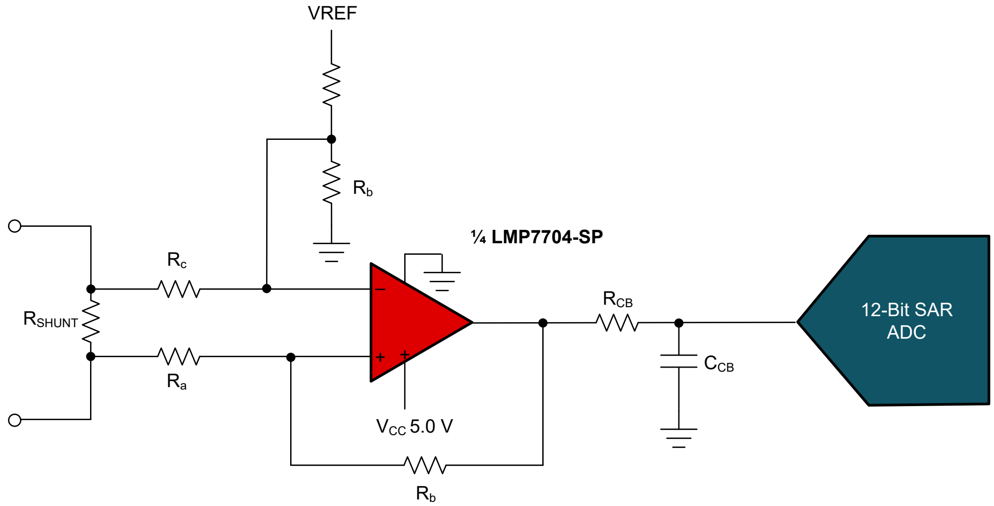


Figure 2-4. Bidirectional Current Sense Circuit

2.2.5 Unipolar Current Sense: 0.25 A to 1 A

The INA901-SP is used to measure a current over a range of 0.25 to 1 A at an accuracy of 1%. In Figure 2-5, the INA901-SP is paired with a buffer circuit to drive the ADC while also allowing low impedance on the ADC side to ensure fast settling time. The INA901-SP has a built in gain of 20 V/V allowing for a smaller current sense resistor minimizing the drop and loss across the sense resistor. The external LMP7704-SP buffer stage provides an additional charge bucket circuit to help with the settling time when interfacing with the ADC.

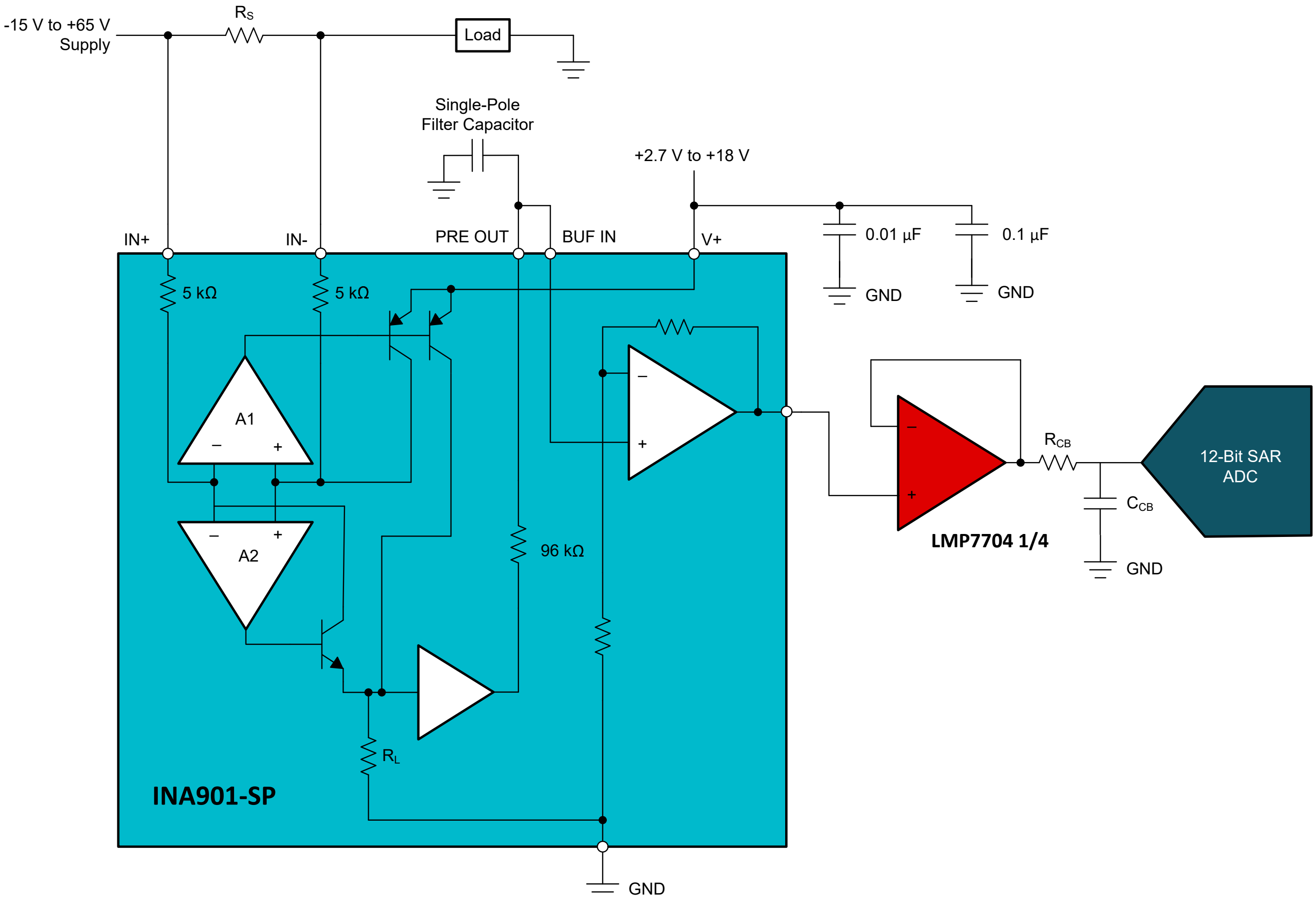


Figure 2-5. Unipolar Current Sense Circuit

2.2.6 TMP461-SP: Local and Remote Temperature Sensing

Temperature sensing is important to monitor for the lifetime and proper operation of the system. The TMP461 is used to measure temperature locally from –55 to 105°C with a target accuracy of 1.5% (approximately ±2°C) and remotely from –55 to 125°C (approximately ±1.5°C). The temperature measurement is represented as a 12-bit digital code for both local and remote sensors. For remote temperature sensing, an example transistor, Q4, is used and are typically low-cost discrete NPN or PNP transistors, or substrate thermal transistors or diodes that are integral parts of microprocessors, analog-to-digital converters (ADC), digital-to-analog converters (DAC), microcontrollers, or field-programmable gate arrays (FPGA).

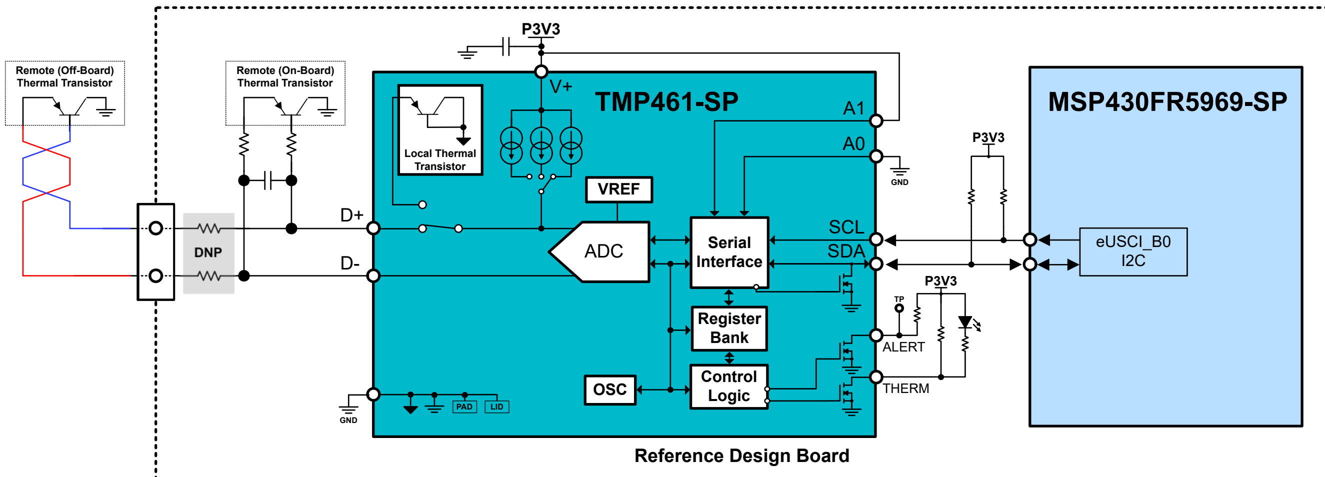


Figure 2-6. TMP461-SP - Local and Remote Temperature Sensing

2.2.7 NTC Thermistor Temperature Sensing

The target of this circuit is to measure a local temperature range of –55 to 105°C at an accuracy of 0.25%. There is a default NTC thermistor, but there is an option to externally connect a different thermistor. The thermistor network is powered by the voltage reference utilized by the corresponding ADC (5 V for external ADC, 2.5 V for internal ADC). This results in the design being ratiometric and thus the measurement accuracy does not depend on the accuracy of the reference voltage. A buffer op amp is utilized to provide high input impedance on the sensor size and a low-impedance to the ADC to ensure a fast settling time.

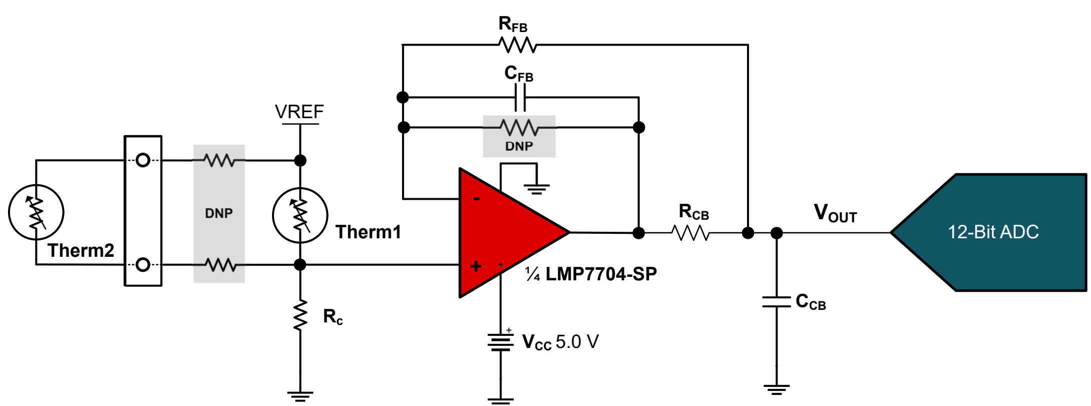


Figure 2-7. Thermistor Temperature Sensing

2.2.8 Adjustable Voltage Source

Figure 2-8 shows the adjustable voltage source circuit utilizing the DAC121S101QML-SP 12-bit output capability. The circuit is capable of supplying an output voltage of 0–5 V at 1% accuracy. The MSP430FR5969-SP communicates with the DAC121S101QML-SP via a 3-wire SPI. The DAC121S101QML-SP and the LMP7704-SP output voltage is dependent on the supply voltage to both. To default output voltage range is 0–5 V; however, the output voltage range can be adjusted via the LMP7704-SP non-inverting amplifier stage.

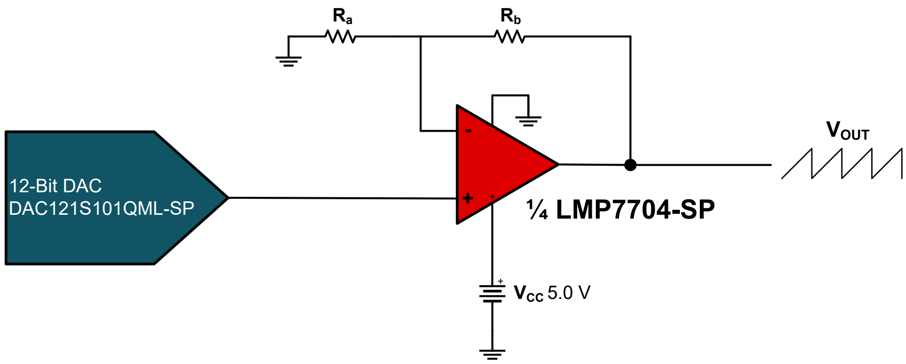


Figure 2-8. Adjustable Voltage Source

2.2.9 Fixed Output Current Source

Figure 2-9 shows the fixed output current source which is capable supplying 4 mA with a full scale accuracy of 1.5%. The circuit is dependent on the applied supply voltage to the LMP7704-SP and the LM4050QML-SP 2.5-V reference. The supply voltage for this circuit is 12 V, which results in an output voltage of 12 V. With the voltage reference being a fixed 2.5 V, it results in a fixed voltage at the inverting input of the LMP7704-SP. This results in an equivalent voltage at the non-inverting pin. This creates a voltage drop across R_a which results in a fixed current output. To choose the output current, R_a and R_b are calculated using the following equations.

$$V_{out\_opampmax} = 12V,\ V_{ref} = 2.5V,\ I_Q = 9.5mA \tag{1}$$

$$R_b = \frac{V_{out\_opampmax} - V_{ref}}{I_Q} \tag{2}$$

$$R_b = \frac{12V - 2.5V}{9.5mA} = 1k\Omega \tag{3}$$

$$R_a = \frac{V_{ref}}{I_{out}} = \frac{2.5V}{4mA} = 625\Omega\left(Actual\ Resistor\ Value = 626\Omega\right) \tag{4}$$

Equation 1 through Equation 4 are for an ideal reference; however, the DC accuracy of the reference can impact the current output. As seen in the test results, the output current resulted in 3.83 mA instead of the 4 mA because of the DC accuracy of the LM4050QML-SP. Therefore, to get the desired current output, R_a should be recalculated with the desired current and the measured voltage drop across the reference, instead of the ideal reference voltage.

R_c is an optional resistor to help with no load scenarios. When the load is disconnected, the output saturates but is offset by R_c; however, the trade off is that there are larger current droops at higher loads at the output.

R_d is another optimal resistor connected to the output and positive supply of the op amp to ensure that the circuit turns on and that the output rail is pulled high to the positive supply of the op amp.

Figure 2-9 shows the fixed output current source circuit.

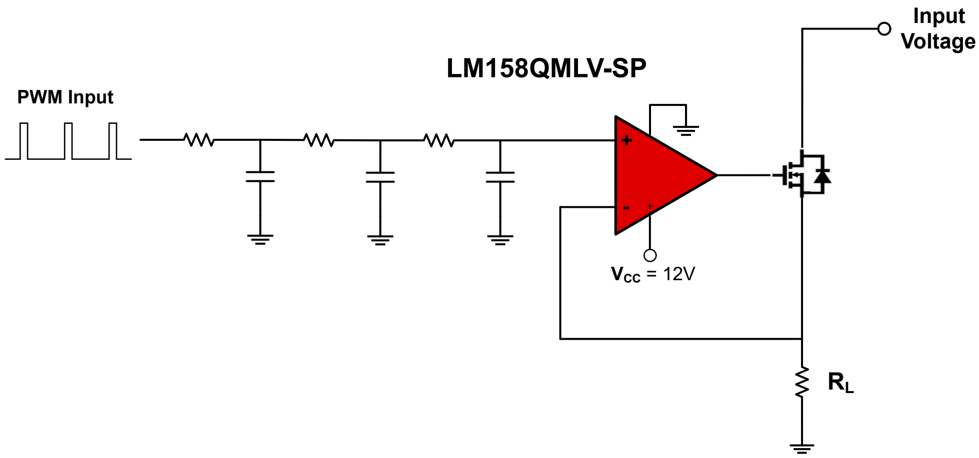


Figure 2-9. Fixed Output Current Source

2.2.10 Adjustable 4-mA Current Source

The adjustable current source provides up to 4 mA with a full scale accuracy of 1.5%. The circuit is adjusted by utilizing the MSP430FR5969-SP PWM output going into a passive low-pass filter that converts the PWM into a DC voltage. The DC voltage is the input to the LMP7704-SP that is configured as a voltage follower op amp that changes the gain until the voltage on the source of the transistor is equal to the DC voltage created by the low-pass filter.

Figure 2-10 shows the adjustable current source circuit.

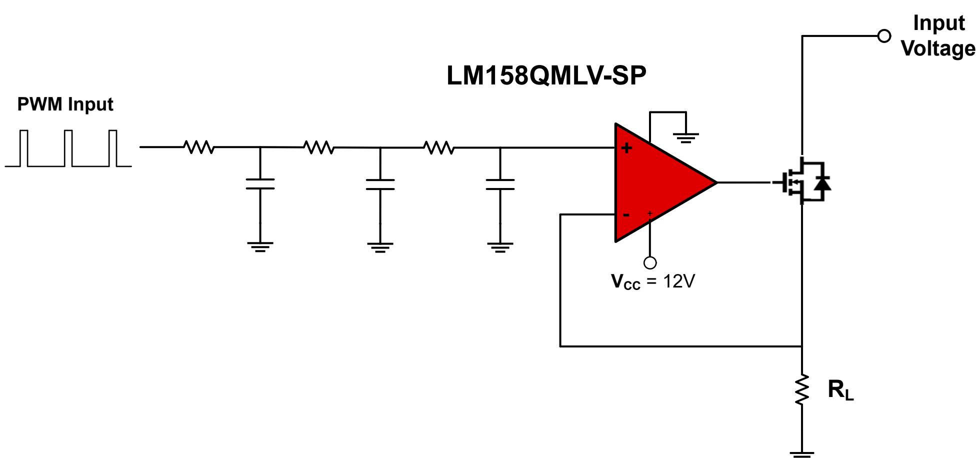


Figure 2-10. Adjustable Current Source Circuit

2.2.11 Power Tree and Power Sequencing

Figure 2-11 shows the power tree consisting of four main power components: the TS7A4501-SP, LMP4050QML-SP, TPS7H2201, and boost circuit.

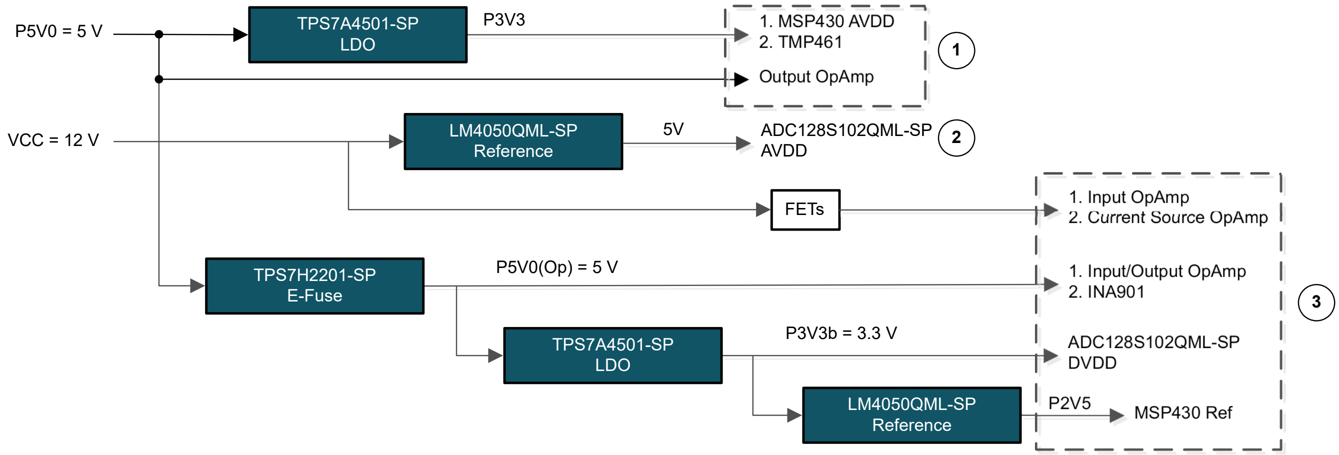


Figure 2-11. Power Tree and Sequencing

The TPS7A4501-SP is selected to power these rails because of its low noise output to ensure no performance degradation due to injected power noise. There are three TPS7A4501-SP used to power this design. The first TPS7A4501-SP provides a 3.3-V rail used to power the MSP430FR5969-SP. The second TPS7A4501-SP is used to provide the 3.3-V digital voltage rail for the ADC128S102QML-SP. The third device is used to regulate the output of the discrete boost controller to 12 V. The 12 V supplied by the TPS7A4501-SP is optional to the operation of this reference design and an external 12 V can be provided to bypass the boost and LDO circuit.

The LMP4050QML-SP are voltage references to provide a stable voltage at two places in the power tree. The first is the 5-V analog voltage rail for the ADC128S102QML-SP. The second rail is the 2.5-V reference for the integrated ADC in the MSP430FR5969-SP. It is important that this is a clean stable signal, or else it can cause inaccuracies in the measurements taken from the ADC.

The TPS7H2201-SP is a load switch that is used for sequencing and ramp up power safely for the op amps. The main power sequencing in this design is to make sure that the ADC128S102QML-SP analog voltage rail has ramped up first before the digital voltage rails ramps up as Figure 2-12 shows. It is important that the analog voltage rail of the ADC128S102QML-SP is stable at 5 V, because the digital rail must stay at least 0.3 V below the analog voltage rail or else it could cause damage to the ADC128S102QML-SP.

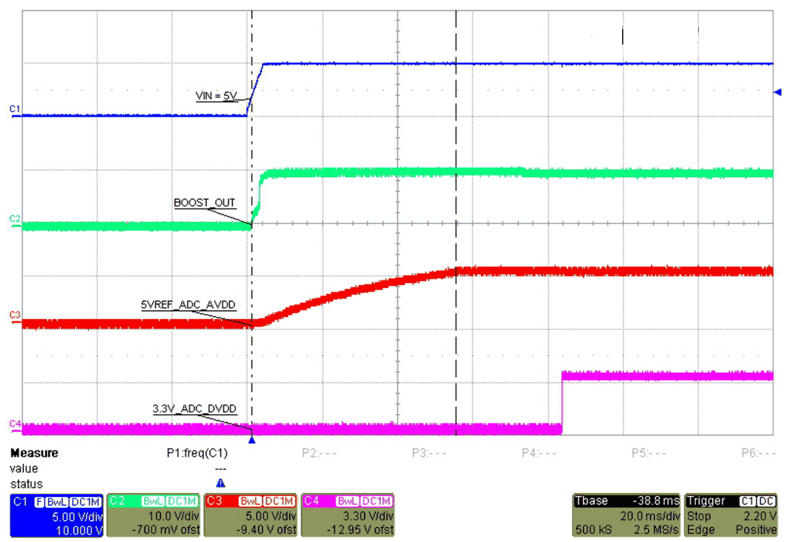


Figure 2-12. ADC128S102-SP Start-up Power Sequence

2.3 Highlighted Products

The following sections describe the highlighted products used in the reference design for the system control, processing, and the analog front end sensing.

2.3.1 MSP430FR5969-SP

The MSP430™ ultra-low-power (ULP) FRAM platform combines uniquely embedded FRAM and a holistic ultralow-power system architecture, allowing innovators to increase performance at lowered energy budgets. FRAM technology combines the speed, flexibility, and endurance of SRAM with the stability and reliability of flash at much lower power. The ultra low-power architecture of the MSP430FR5969-SP showcases seven low-power modes, optimized to achieve power efficient distributed telemetry/housekeeping systems. The integrated mixedsignal features of the MSP430FR5969-SP make it ideally suited for distributed telemetry applications in nextgeneration spacecraft. The strong immunity to single-event latchup and total ionizing dose, enable the device to be used in a variety of space and radiation environments.

2.3.2 ADC128S102QML-SP

The ADC128S102 device is a low-power, eight channel CMOS 12-bit analog-to-digital converter specified for conversion throughput rates of 50 kSPS to 1 MSPS. The converter is based on successive approximation register architecture with an internal track-and-hold circuit. The device can be configured to accept up to eight input signals at inputs IN0 through IN7. The output serial data is straight binary and is compatible with several standards, such as SPI, QSPI, MICROWIRE, and many common DSP serial interfaces. The ADC128S102 may be operated with independent analog and digital supplies. The analog supply (VA) can range from 2.7 V to 5.25V, and the digital supply (VD) can range from 2.7 V to VA. Normal power consumption using a 3-V or 5-V supply is 2.3 mW and 10.7 mW, respectively. The power-down feature reduces the power consumption to 0.06 μW using a 3-V supply and 0.25 μW using a 5-V supply

2.3.3 DAC121S101QML-SP

The DAC121S101QML-SP device is a full-featured, general-purpose, 12-bit voltage-output digital-to-analog converter (DAC) that can operate from a single 2.7-V to 5.5-V supply and consumes just 177 μA of current at 3.6V. The on-chip output amplifier allows rail-to-rail output swing and the three wire serial interface operates at clock rates up to 20 MHz over the specified supply voltage range and is compatible with standard SPI, QSPI, MICROWIRE, and DSP interfaces. The supply voltage for the DAC121S101QML-SP serves as its voltage reference, providing the widest possible output dynamic range. A power-on reset circuit ensures that the DAC output powers up to zero volts and remains there until there is a valid write to the device. A power-down feature reduces power consumption to less than a microWatt. The low power consumption and small packages of the DAC121S101QML-SP make it an excellent choice for use in battery-operated equipment.

2.3.4 LMP7704-SP

The LMP7704-SP is a precision amplifier with low input bias, low offset voltage, 2.5-MHz gain bandwidth product, and a wide supply voltage. The device is radiation hardened and operates in the military temperature range of −55°C to +125°C. The high dc precision of this amplifier, specifically the low offset voltage of ±37 μV and ultra low input bias of ±200 fA, make this device an excellent choice for interfacing with precision sensors with high output impedances. This amplifier can be configured for transducer, bridge, strain gauge, and transduce amplification.

2.3.5 INA901-SP

The INA901-SP is a voltage-output, current-sense amplifier that can sense drops across shunt resistors at common-mode voltages from –15 V to 65 V, independent of the supply voltage. The INA901-SP operates from a single 2.7-V to 16-V supply, drawing 700 μA (typical) of supply current. The gain of the INA901-SP is 20 V/V. The 130-kHz bandwidth simplifies use in current-control loops. The pinouts readily enable filtering. The device is specified over the extended operating temperature range of –55 °C to 125 °C and is offered in an 8-pin CFP package

2.3.6 LM4050QML-SP

The LM4050QML precision voltage reference eliminates the need for an external stabilizing capacitor. All while ensuring stability with a capacitive load making it easy to use. There are two different reference voltages the LM4050QML comes in. The first is a 2.5V reference operating at 60uA minimum to 15mA maximum. The second is a 5V reference operating at a minimum of 74uA and 15mA maximum. The LM4050QML utilizes fuse and zener-zap reverse breakdown voltage trim during wafer sort to ensure that the prime parts have an accuracy of better than +/- 0.1% at 25C. Band gap reference temperature drift curvature correlation and low dynamic impedance ensure stable reverse breakdown voltage accuracy over a wide range of operating temperature and currents.

2.3.7 LM158QML-SP

The LM158QML-SP series consist of two independent, high gain, and internally frequency compensated operational amplifiers which were designed specfically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

2.3.8 LM139QML-SP

The LM139QML-SP series consist of four independent precision voltage comparators with an offset voltage specification as low as 2 mV max for all four comparators. These were designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage. These comparators also have a unique characteristic in that the input common-mode voltage range includes ground, even though operated from a single power supply voltage.

2.3.9 TMP461-SP

The TMP461-SP device is a radiation-hardened, high-accuracy, low-power remote temperature sensor monitor with a built-in local temperature sensor. The remote temperature sensors are typically low-cost discrete NPN or PNP transistors, or substrate thermal transistors or diodes that are integral parts of microprocessors, analog-todigital converters (ADC), digital-to-analog converters (DAC), microcontrollers, or field-programmable gate arrays (FPGA). Temperature is represented as a 12-bit digital code for both local and remote sensors, giving a resolution of 0.0625°C. The two-wire serial interface accepts the SMBus communication protocol with up to nine different pin-programmable addresses. Advanced features such as series resistance cancellation, programmable nonideality factor (ηfactor), programmable offset, programmable temperature limits, and a programmable digital filter, are combined to provide a robust thermal monitoring solution with improved accuracy and noise immunity. The TMP461-SP is ideal for multi-location, high accuracy temperature measurements in a variety of distributed telemetry applications. The integrated local and remote temperature sensors simplify spacecraft housekeeping activities by providing an easy way of measuring temperature gradients. The device is specified for operation over a supply voltage range of 1.7 V to 3.6 V, and a temperature range of –55°C to 125°C

2.3.10 TPS7A4501-SP

TPS7A4501-SP is a low-dropout (LDO) regulator optimized for fast-transient response. The TPS7A4501-SP can supply 750mA of output current with a dropout voltage of 300mV. The TPS7A4501-SP can supply 1.5A of output current with a dropout voltage of 320mV. Quiescent current is well controlled; it does not rise in dropout, as with many other regulators. In addition to fast transient response, the TPS7A4501-SP regulator has very-low output noise, which makes it ideal for sensitive RF supply applications.

2.3.11 TPS7H2201-SP

The TPS7H2201-SP is a single channel load switch that provides configurable rise time to minimize inrush current and reverse current protection. The device contains a P-channel MOSFET that can operate over an input voltage range of 1.5 V to 7 V and can support a maximum continuous current of 6 A. The switch is controlled by an on and off input (EN), which is capable of interfacing directly with low-voltage control signals. The TPS7H2201-SP is available in a ceramic package with integrated thermal pad allowing for high power dissipation. The device is characterized for operation over the free-air temperature range of –55°C to 125°C.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware and Software

3.1.1 Hardware

The TIDA-010197 hardware includes two variations: an external ADC version utilizing the ADC128S102-SP, and an internal ADC version using the internal ADC of the MSP430. Both variations include the same power tree, sequencing, outputs and measures the same parameters (voltage, current, and temperature).

To power up the board, an external 12-V and 5-V power supply is required and is connected via J15 for the external ADC version and J35 for the MSP430 version.

3.1.2 Software

Solution-specific and device-independent files are provided as .c/.h files. The main.c file provides the initialization of the GPIOs, I2C and SPI communication, ADC or DAC setup, PWM setup for the nonsynchronous boost, and power sequencing. The software is required to power up the board properly as well as read the ADC data.

To program the MSP430FR5969-SP independently, make sure no other jumpers are installed and provide an external 3.3 V to J16 (for the external ADC circuit) and J36 (for the integrated ADC solution). This only powers on the MSP430FR5969-SP so that adjustments to the power sequencing are done without damaging the ADC128S102QML-SP.

In main.c the variable "ext_int" is set to either 0 or 1 to run two different functions. When "ext_int" is set to 0, it runs the code to read all the channels from the external ADC via SPI. If "ext_int" is set to 1, the code reads all inputs from the integrated ADC. The ADC reads are done via low power interrupts to save on processing power of the MSP430. The values are then stored in the FRAM and are accessed when the software is paused. Each ADC channel corresponds to a specific point in memory with a memory word length default of 1000 and can be changed via the variable WRITE_SIZE.

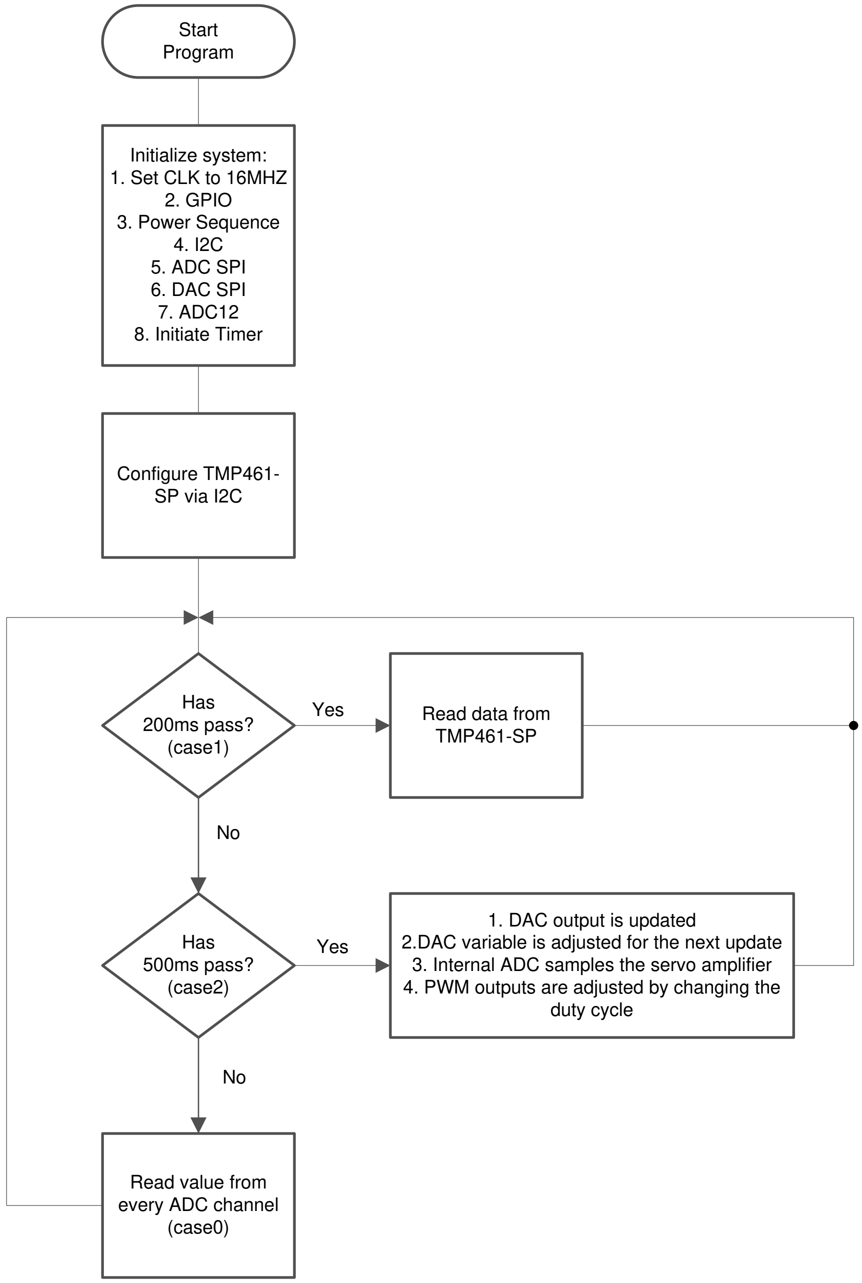


Figure 3-1. Software Flow

To access the data in FRAM from Code Composer Studio (CCS), open the memory browser (View → Memory Browser) and type the starting address outlined in Table 3-1 and Table 3-2. Select save memory and save it as a .dat file (this file type can be opened with Microsoft® Excel®). The save memory function allows saving of the data in different formats for different processing requirements. After selecting the file location to save the file, enter the start address and specify the length of the array (default is 1000). Opening the .dat file shows the raw ADC data in column one. To convert the integer values, use the ADC equation (Equation 5) in a column next to the data captured to convert the integer values to voltage, where n is the number of bits used for the measurement.

$$ADC\ conversion\ equation = \frac{Digital\ Output \times V_{ref}}{2^n} \tag{5}$$

Table 3-1. Memory Location and Variable Name: External ADC Configuration

ADC BUFFER	ADC128S102-SP ADC CHANNEL	MEASURED RAIL	MEMORY LOCATION
adc_buffer_0	IN0	500 µA	x004400
adc_buffer_1	IN1	±2 A	x0047E8
adc_buffer_2	IN2	20 V	x004BD0
adc_buffer_3	IN3	Temperature voltage	x004FB8
adc_buffer_4	IN4	±5 V	x0053A0
adc_buffer_5	IN5	40 V	x005788
adc_buffer_6	IN6	0.25 A–1 A	x005B70
adc_buffer_7	IN7	5 V	x005F58

Table 3-2. Memory Location and Variable Name: MSP430™ Configuration

ADC BUFFER	MSP430 ADC12 CHANNEL	MEASURED RAIL	MEMORY LOCATION
adc_buffer_0	A0	500 µA	x004400
adc_buffer_1	A8	40 V	x0047E8
adc_buffer_2	A9	0.25 A–1 A	x004BD0
adc_buffer_3	A10	5 V	x004FB8
adc_buffer_4	A12	±2 A	x0053A0
adc_buffer_5	A13	20 V	x005788
adc_buffer_6	A14	Temperature voltage	x005B70
adc_buffer_7	A15	±5 V	x005F58

3.2 Test Setup

This section provides the voltage monitor and current monitor test setup instructions.

3.2.1 Voltage Monitor Test Setup

Figure 3-2 illustrates the voltage monitor test setup.

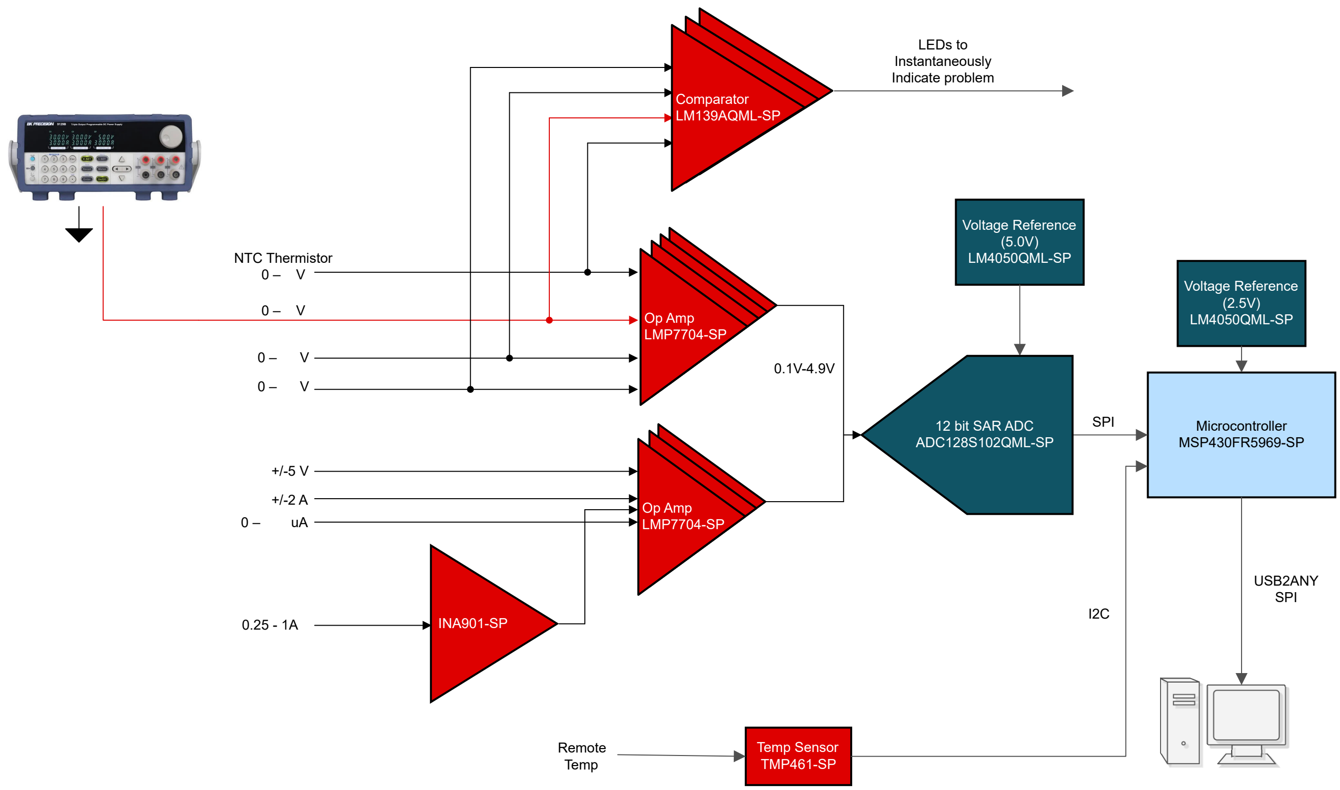


Figure 3-2. Voltage Monitor Test Setup

To test the voltage monitoring circuits, a power supply is required for the testing. For each of the voltage rails, tie the positive output rail of the power supply to the input of the terminal block for the ±5-V, 5-V, 20-V, and 40-V rails. Two tests are performed for each of the voltage rails: Noise floor and Linearity. All tests were done at an ambient temperature of 25°C.

The following list provides the test procedure for Noise floor:

1. Short the voltage input on the terminal block, to ground.
2. Open Code Composer Studio (CCS) to run the MSP430 software.
3. Configure the MSP430 software for either internal or external ADC, and set the desired ADC channel.
4. Capture and plot 1000 plots by using memory export and Microsoft Excel to convert the digital data to the ADC voltage reading using the ADC conversion equation.
5. Calculate the actual voltage reading by solving the linear equation

$$Input\ Voltage\ (Actual) = \frac{ADC\ Voltage\ Reading - 0.2V}{Gain} \tag{6}$$

6. Repeat for the rest of other the voltage inputs

The following list provides the test procedure for Linearity:

1. Connect the power supply to the desired terminal block as shown in Figure 3-2.
2. Open CCS to run the MSP430 software.
3. Configure the MSP430 software for either internal or external ADC, and set the desired ADC channel.
4. Capture and export 1000 measurements by using the memory export and Microsoft Excel to convert the digital data to the voltage reading using the ADC conversion equation.
5. Calculate the actual voltage reading by solving the linear equation

$$Input\ Voltage\ (Actual) = \frac{ADC\ Voltage\ Reading - 0.2V}{Gain} \quad (7)$$

6. Repeat over the rest of the voltage range.

3.2.2 Current Monitor Test Setup

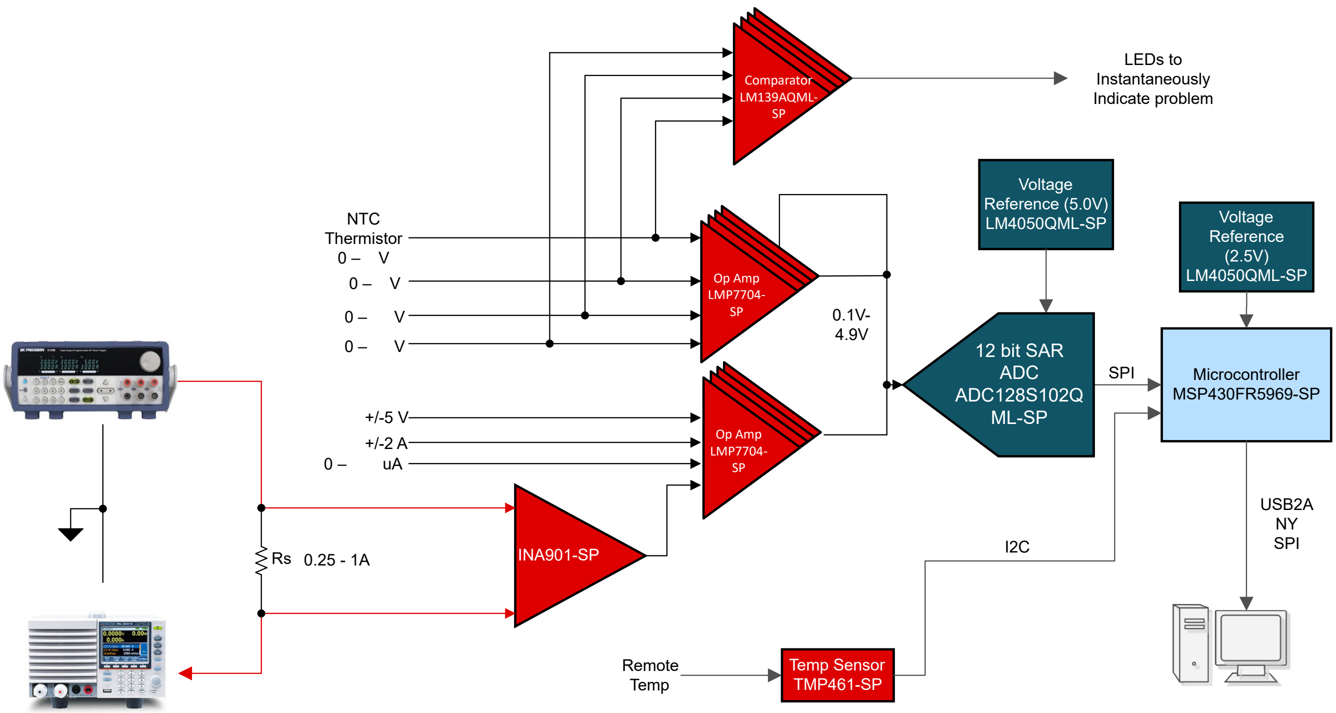


Figure 3-3. Current Monitor Test Setup

To test the current monitoring circuits, a power supply and electronic load are required. The power supply provides a voltage on one side of the sense resistor, and the other side of the sense resistor is connected to the electronic load. For the ±2 A and 0.25–1 A monitoring, two tests are performed for each rail. All tests were done at an ambient temperature of 25°C.

The following list provides the test procedure for Noise floor:

1. Short both sides of the sense resistor to ground.
2. Open Code Composer Studio (CCS) to run the MSP430 software.
3. Configure the MSP430 software for either internal or external ADC, and set the desired ADC channel.
4. Capture and plot 1000 plots by using memory export and Microsoft Excel to convert the digital data to the ADC voltage reading using the ADC conversion equation.
5. Calculate the actual current reading by solving the linear equation

$$Input\ Current\ (Actual) = \frac{ADC\ Voltage\ Reading - 0.2V}{Gain \times Sense\ Resistor} \quad (8)$$

6. Repeat for the rest of the other current inputs.

The following list provides the test procedure for Linearity

1. Connect the power supply to the desired terminal block as shown in Figure 3-3.
2. Open CCS to run the MSP430 software.
3. Configure the MSP430 software for either internal or external ADC, and set the desired ADC channel.
4. Capture and export 1000 measurements by using the memory export and Microsoft Excel to convert the digital data to the voltage reading using the ADC conversion equation.
5. Calculate the actual current reading by solving the linear equation:

$$Input\ Current\ (Actual) = \frac{ADC\ Voltage\ Reading - 0.2V}{Gain \times Sense\ Resistor} \tag{9}$$

6. Repeat over the rest of the current range.

3.3 Test Results

3.3.1 Voltage Measurement - Noise Floor Results

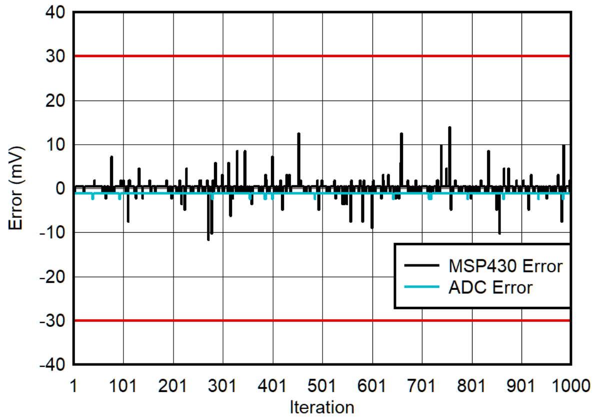


Figure 3-4. Noise Floor (5-V Range, 0-V Input)

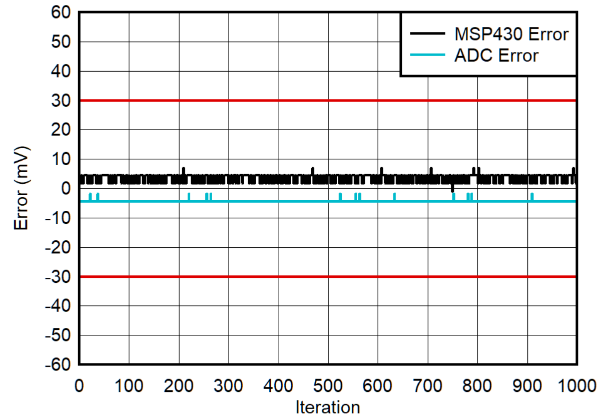


Figure 3-5. Noise Floor (±5-V Range, 0-V Input)

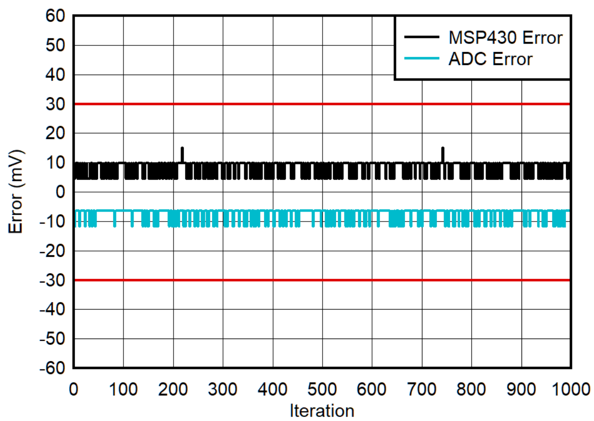


Figure 3-6. Noise Floor (20-V Range, 0-V Input)

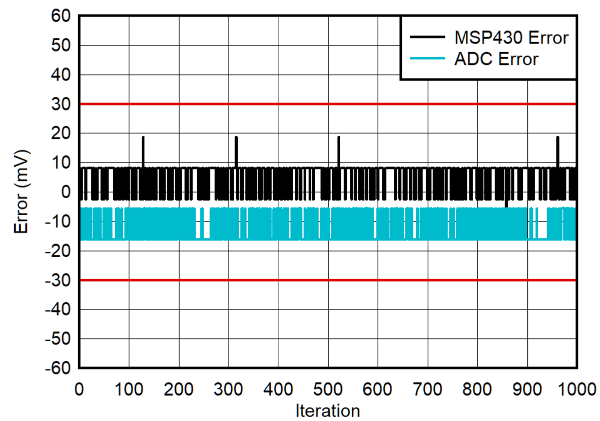


Figure 3-7. Noise Floor (40-V Range, 0-V Input)

3.3.2 Voltage Measurement - Linearity Results

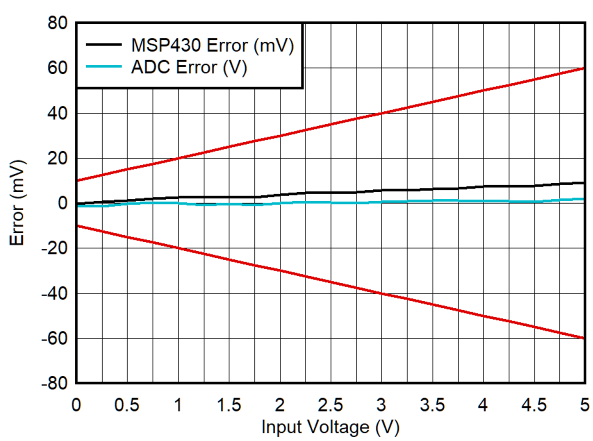


Figure 3-8. Linearity Plot (5-V Range)

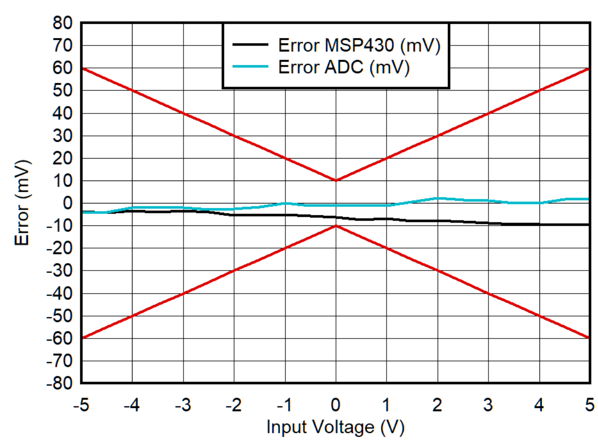


Figure 3-9. Linearity Plot (±5-V Range)

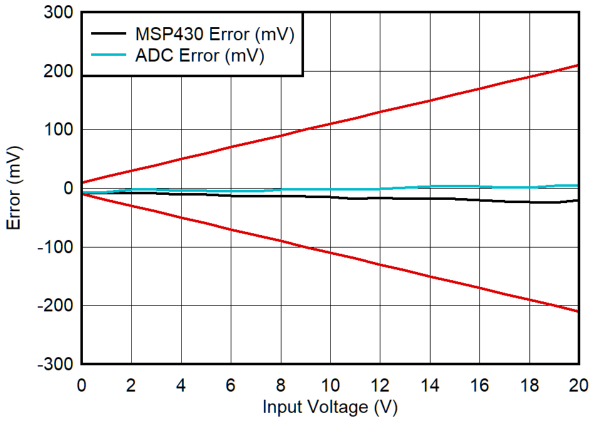


Figure 3-10. Linearity Plot (20-V Range)

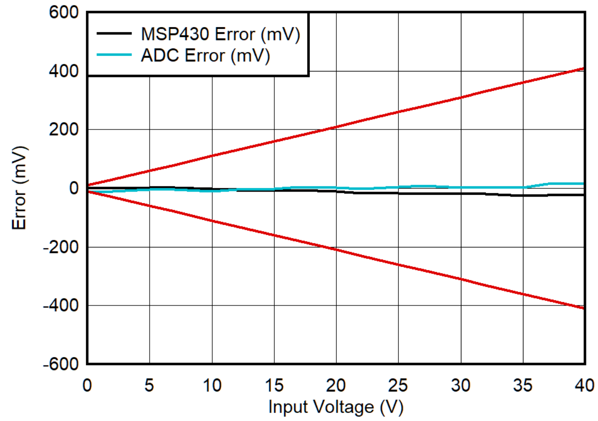


Figure 3-11. Linearity Plot (40-V Range)

3.3.3 Current Measurement - Noise Floor Results

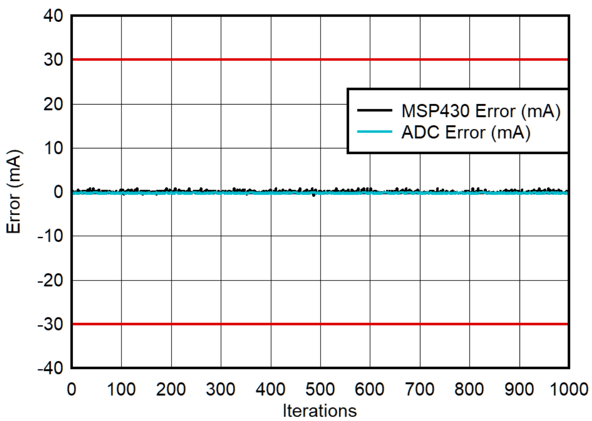


Figure 3-12. Noise Floor (0.25- to 1-A Range, 0 A, 5-V Input)

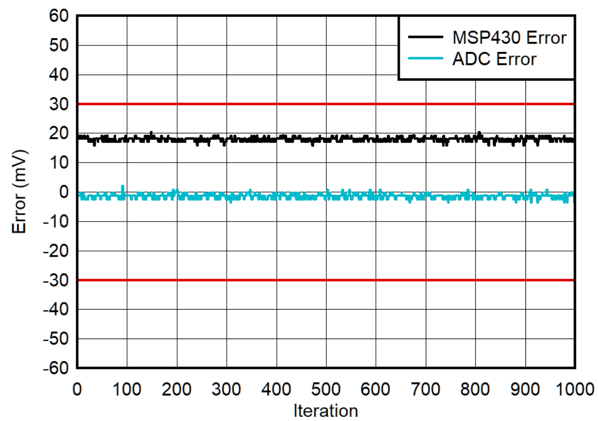


Figure 3-13. Noise Floor (±2-A Range, –2 A, 1-V Input)

3.3.4 Current Measurement - Linearity Results

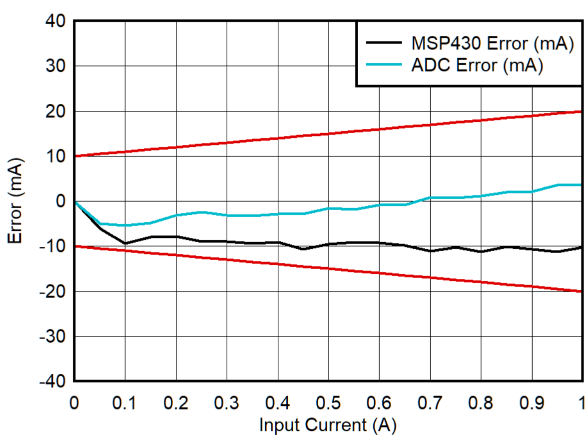


Figure 3-14. Linearity Plot (0.25- to 1-A Range)

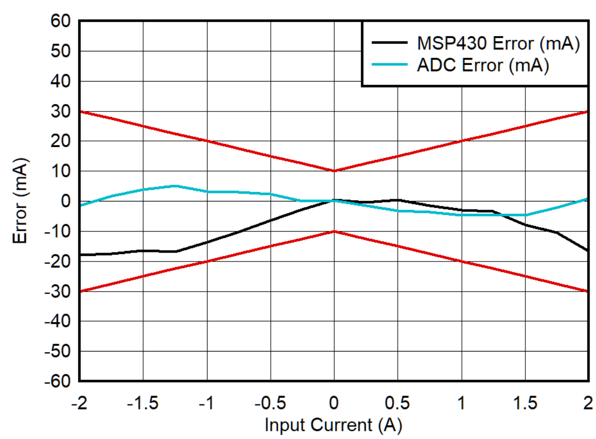


Figure 3-15. Linearity Plot (±2-A Range)

3.3.5 Analog Outputs

By default the software is setup to sweep the voltage from 0 to max resulting in the scope shot in Figure 3-16. The output of the DAC121S101QML-SP goes from 0–2.5 V, and the LMP7704-SP is setup to have a gain of 2 V/V which results in a 0- to 5-V output.

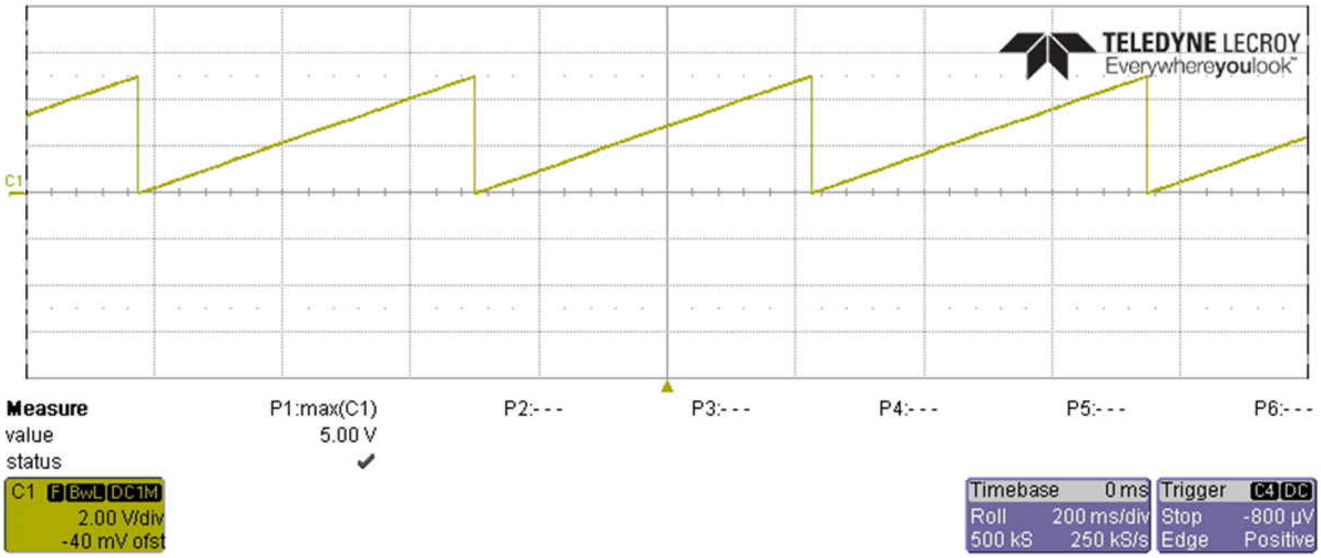


Figure 3-16. Adjustable Voltage Source

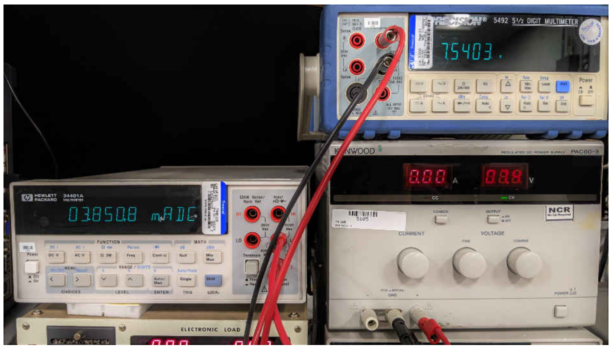


Figure 3-17. Constant Current Output Test Setup (7.5 V Applied)

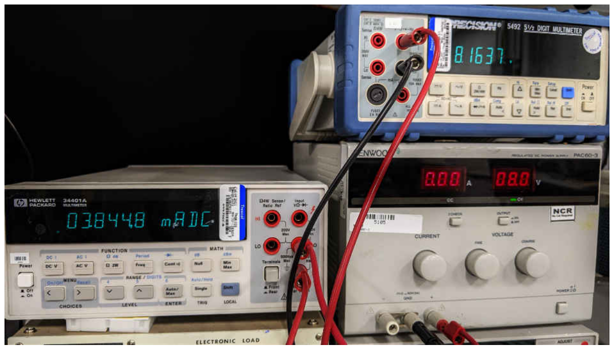


Figure 3-18. Constant Current Output Test Setup (8 V Applied)

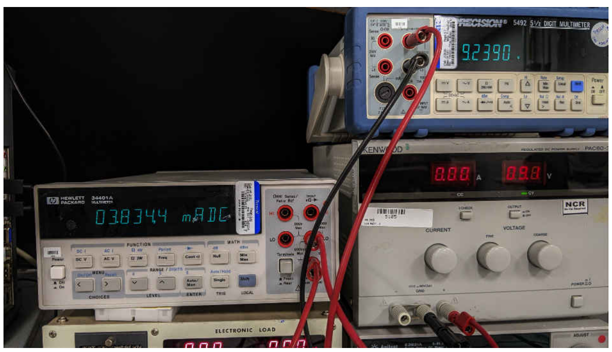


Figure 3-19. Constant Current Output Test Setup (9 V Applied)

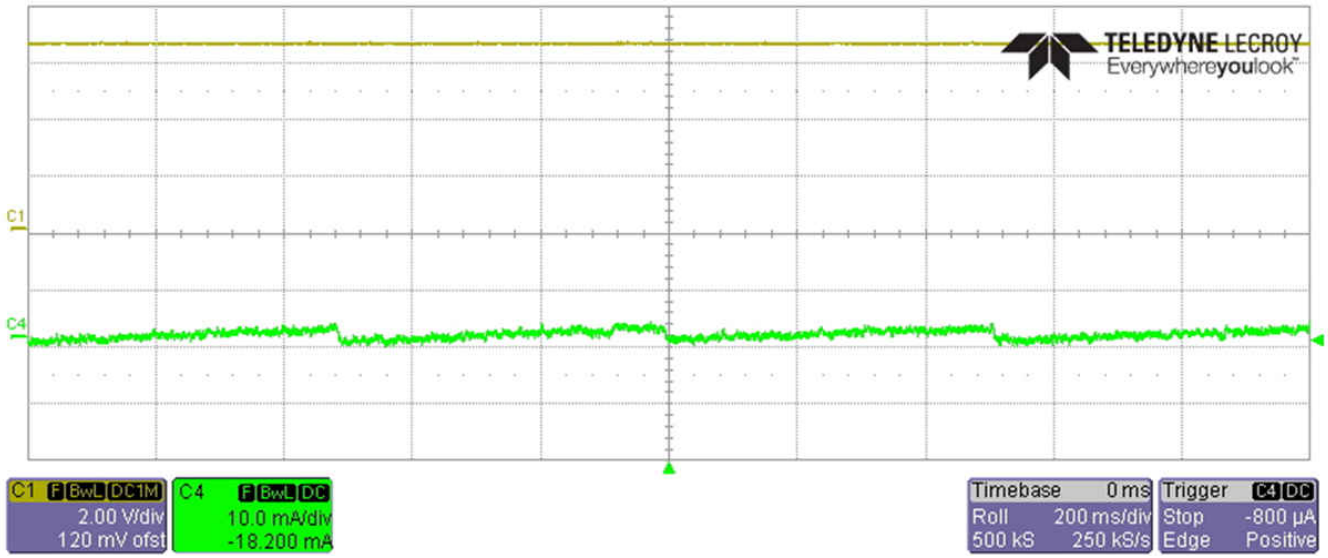


Figure 3-20. Adjustable 4-mA Current Source 6.5-V Input

4 Design and Documentation Support

4.1 Design Files

4.1.1 Schematics

To download the schematics, see the design files at TIDA-010197.

4.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010197.

4.2 Documentation Support

1. Texas Instruments, *MSP430FR5969-SP Radiation Hardened Mixed-Signal Microcontroller* data sheet
2. Texas Instruments, *LMP7704-SP Radiation Hardness Assured (RHA), Precision, Low Input Bias, RRIO, Wide Supply Range Amplifiers* data sheet
3. Texas Instruments, *ADC128S102QML-SP Radiation Hardened 8-Channel, 50 kSPS to 1 MSPS, 12-Bit A/D Converter* data sheet
4. Texas Instruments, *DAC121S101QML-SP Radiation Hardened 12-Bit Micro Power Digital-to-Analog Converter With Rail-to-Rail Output* data sheet
5. Texas Instruments, *TI Space Products selection guide*
6. Texas Instruments, *Analog Engineer's Calculator*
7. Texas Instruments, Analog Engineer's Circuit: Low-side bidirectional current sensing circuit

4.3 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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