12.9 Sensors and Data Acquisition

The Anduril 3 Sensors and Data Acquisition project is a set of sensors and accompanying data converters with the purpose of gathering pressure, temperature and strain measurements during Anduril 3's launch. The projects internal requirements include:

1. Obtain an experimental estimate of strain at the point of max bending
2. Obtain an experimental estimate of Anduril 3's Airspeed.
3. Obtain an experimental estimate of the pressure gradient over the Nosecone
4. Obtain temperature readings from the fuselage surface to calibrate strain readings

The resulting functional requirements for the DAQ hardware were determined as:

1. Receive Data from 12 3-strain gauge rosettes
2. Receive Data from 4 SPI output pressure ports
3. Receive Data from 4 Platinum RTD temperature sensors
4. Transmit data from all sensors to the Flight computer

This project has as objectives to minimize cost, maximize resolution and sampling rate and minimize measurement error. The relevant launch canada requirements are:

LC-DTEG-R6.1.2 – All onboard electrical systems (including GPS and telemetry) shall be tested as an integrated system to confirm no mutual interference.

LC-DTEG-R6.2.2 – Wiring and cables shall include sufficient slack at connections to prevent de-mating under launch loads.

LC-DTEG-R6.1.1 Electrical assemblies and devices shall be compatible with the external and self-induced electromagnetic environments that will exist during flight or testing

LC-DTEG-R6.1.1 Electrical systems shall be designed to limit or prevent a short in one system from disabling other flight- or safety-critical systems

The project integrates with the Anduril 3 Flight Computer over a 1MHz CAN Bus (non volatile data storage). Additional integrations are with the modular power supply (serves as a 5v supply) Nosecone (bonding) and Fuselage (bonding).

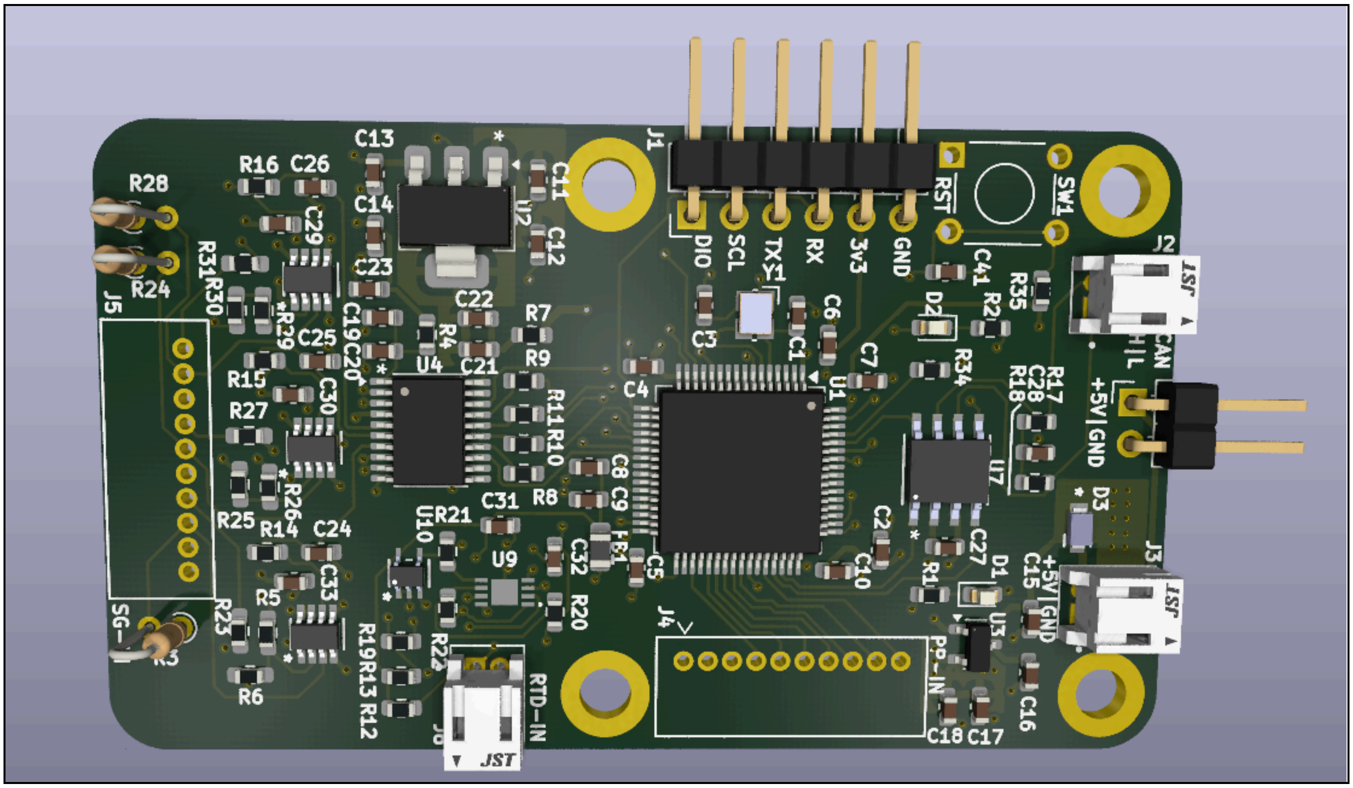

Figure 1: DAQ Sensor Node

Detailed design (Hardware)

The hardware for this project consists of 13 data acquisition modules. The subsystems for each module include the module I/O circuitry, power distribution, the 4 channel, 24 bit ADC circuitry, RTD and strain gauge signal conditioning, and the microcontroller.

I/O

Each DAQ module supports 3 350Ω strain gauge inputs (J5), a 100Ω RTD input, and 4 SPI pressure port inputs. All data is output on a CAN Bus operated at 1MHz connected to the flight computer. The connectors chosen for the module were the JST-ZH. They are keyed, and friction locking and support 26-32 AWG wiring rated for 1A.

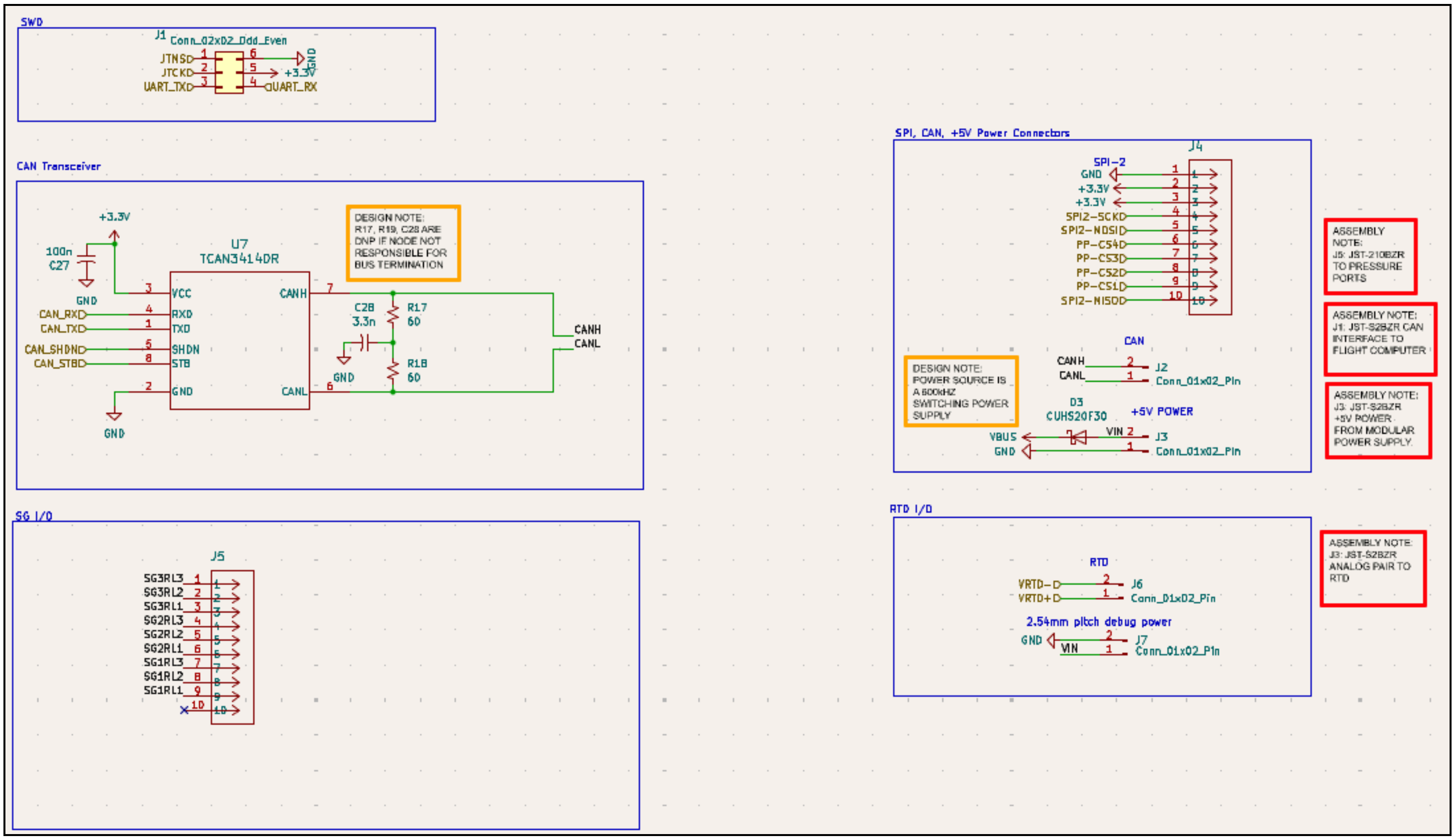

Figure 2: DAQ Node I/O

The power input is 5V. A TVS diode rated for 30V and 2A provides reverse polarity protection.

Signal Conditioning

Signal conditioning is performed on all analog inputs. Signal conditioning consists of bridge completion followed by an amplification stage and a low pass filter. The resistive strain and temperature sensors are placed in a quarter bridge configuration. The output characteristics of wheatstone bridge circuits (half supply common mode voltage, differential output) facilitate the design of the amplification stage. A through hole resistor can be placed across the strain gauge terminals for shunt calibration purposes. Note that the bridge is unbalanced at 0 strain since the bridge completion resistors are 360 ohms. Calculations justifying this decision are presented in 12.6.2.

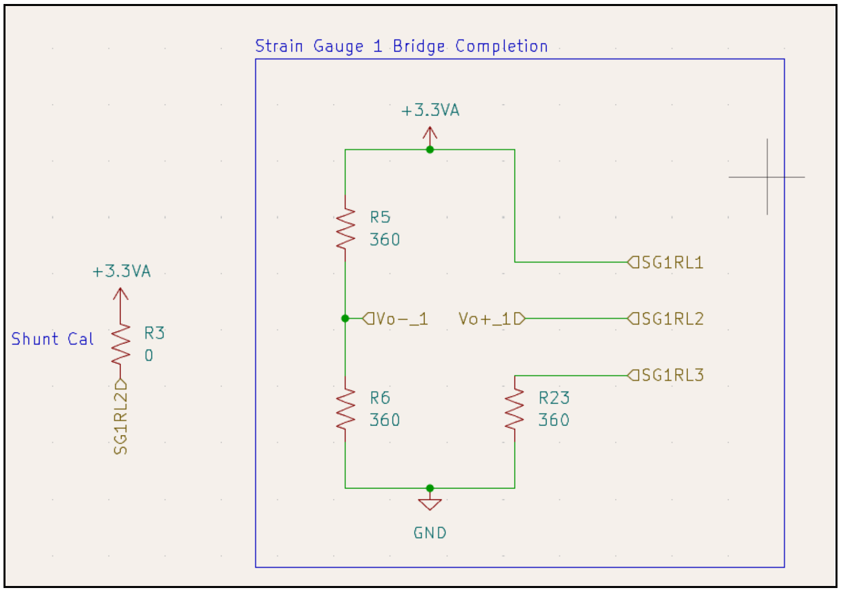

Figure 3: Bridge Completion

The amplification stage scales the input to the full scale range of the ADC . This maximizes the effective resolution as shown in equation 1 [1]. The amplification stage is based on the INA351 for strain and the MCP611N for temperature. These instrumentation amplifier ICs provides gains of 30 and 2 respectively and convert the signal from differential to ground referenced.

$$Effective\ Resolution = \log_2 \frac{Full\ Scale\ Input\ Voltage\ Range}{ADC\ RMS\ Noise} \quad (1)$$

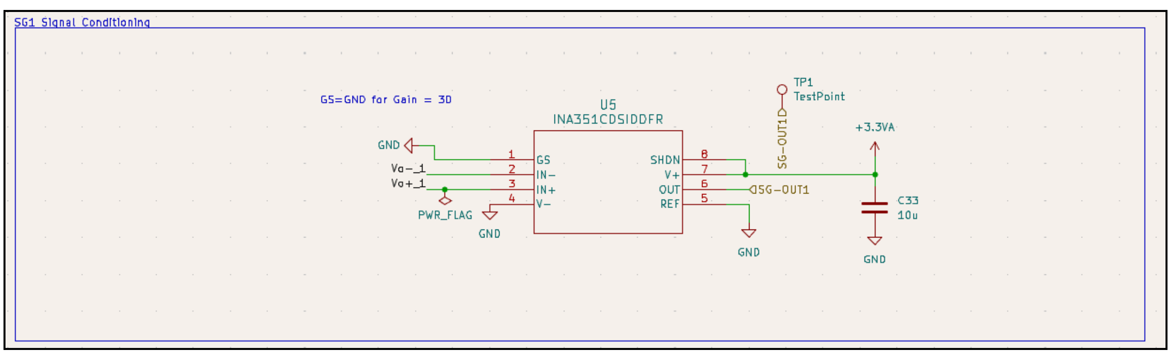

Figure 4: Strain Gauge Amplification

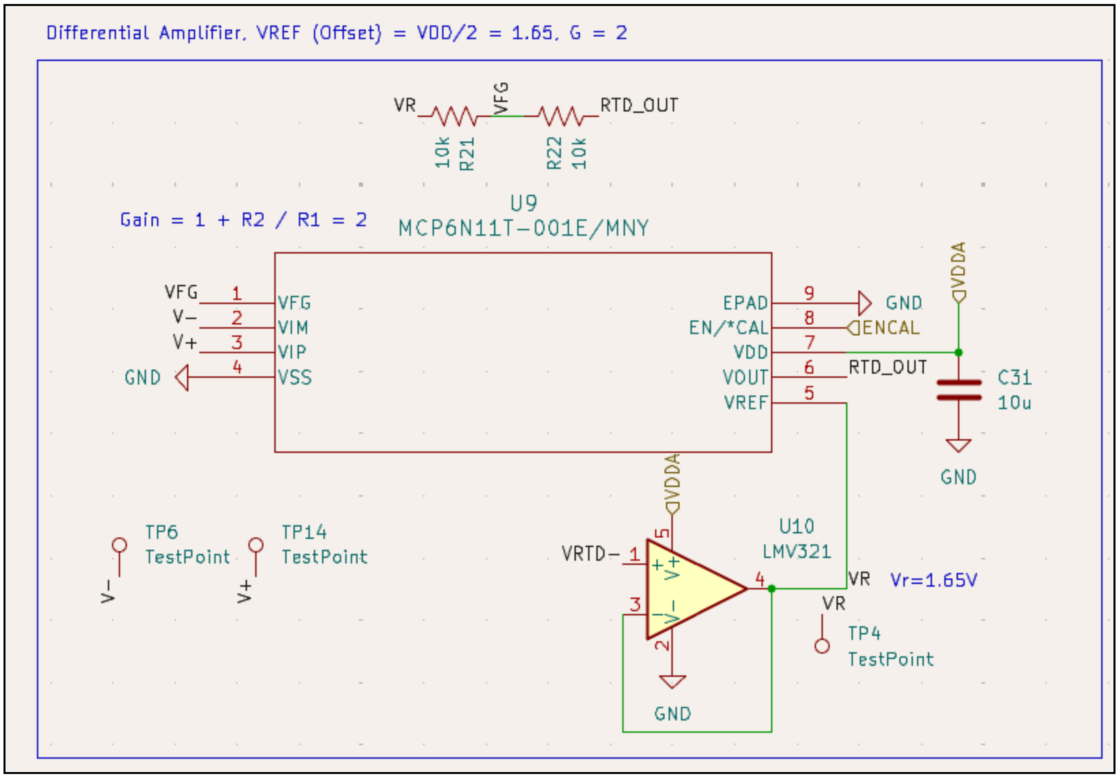

Figure 5: RTD Output Amplification

The low pass filter reduces the output referred noise of the ADC and provides anti-aliasing. A single pole RC filter was selected due to the low cost. The filter specifications are discussed in section 12.6.3.

Microcontroller

The DAQ nodes are built around an STM32G431. The specifications for this microcontroller are summarized below:

Processor: ARM Cortex M4

Memory: 128kB flash / 22kB SRAM

Clock Speed: 170MHz

Peripherals: 2x SPI. 3x I2C, 1x FDCAN, 12 bit ADC

This microcontroller was selected for STM32's rich developer support, the supported peripherals, and high clock speed. The schematic for the microcontroller is shown in Figure x. An external 16MHz oscillator serves as the main clock. Power and status LEDs are included for increased interpretability. The MCU controls CAN Bus transmissions, receives data over SPI from the external 24 bit ADC and external pressure ports and samples from the RTD temperature sensor using its internal 12 bit ADC.

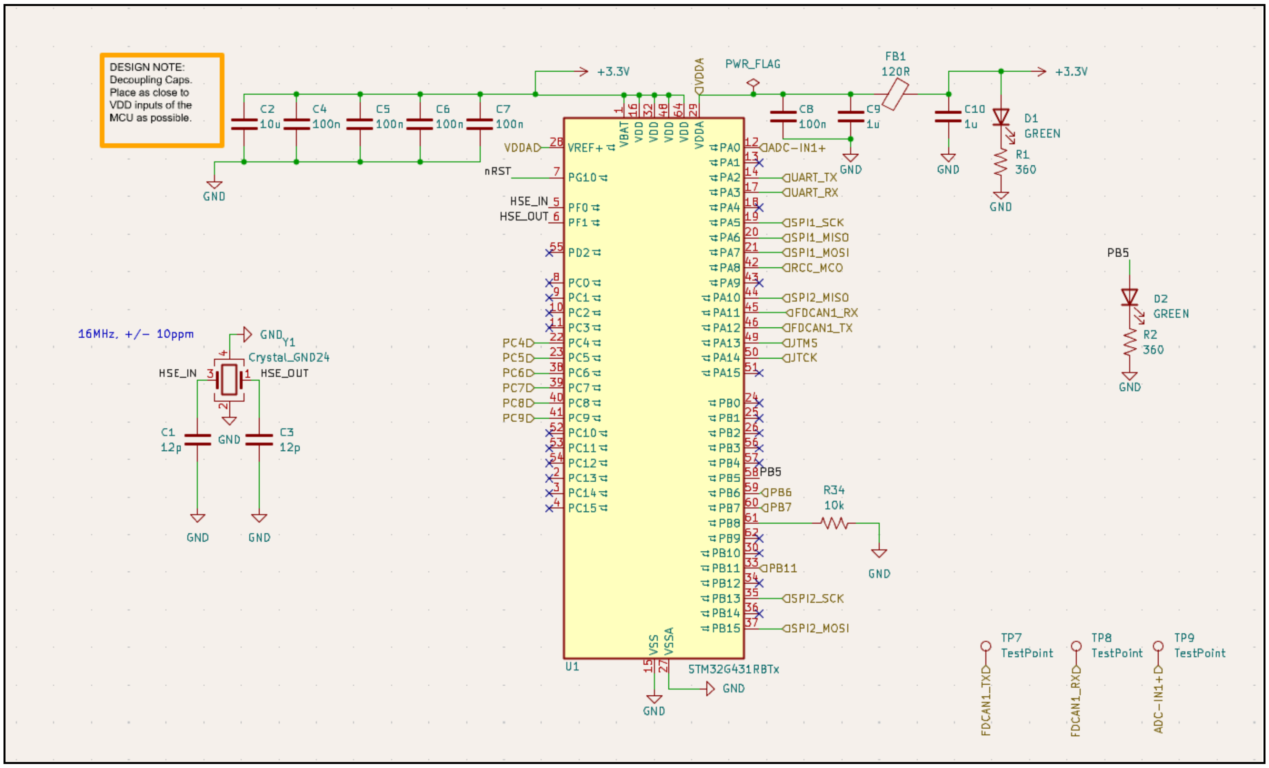

Figure 6: Microcontroller Schematic

Power distribution

Power is distributed to separate 3.3V analog and digital rails. This done by two linear voltage regulator ICs (MCP1702T and MCP1825S). These regulator can step down a wide range of input voltage (2.1V - 6V), and hae overtemperature protection. Their maximum output current is 500mA.

Figure 7: Power Distribution

The analog regulator PSRR is 60dB at 100Hz. As the Modular Power supply on Anduril 3 uses a buck-boost switching regulator, a high PSRR is important to ensure switching noise does not couple into the analog sensor inputs.

ADC

The MCP3562 is a 4 channel 24 bit ADC with a maximum sampling rate of 153.8 ksps. It has an onboard programmable gain amplifier which can be set to a gain of 0.33 to 64. This ADC was selected primarily due to its low noise. This ADC samples the three strain gauge inputs at 200Hz each and transmits measurements to the MCU over SPI. The ADC is highly configurable with 12 user programmable configuration registers. It supports scan mode and has an onboard timer to configure the delay between scan cycles. The ADC also includes internal calibration registers that can be programmed with offset and gain error calibration values.

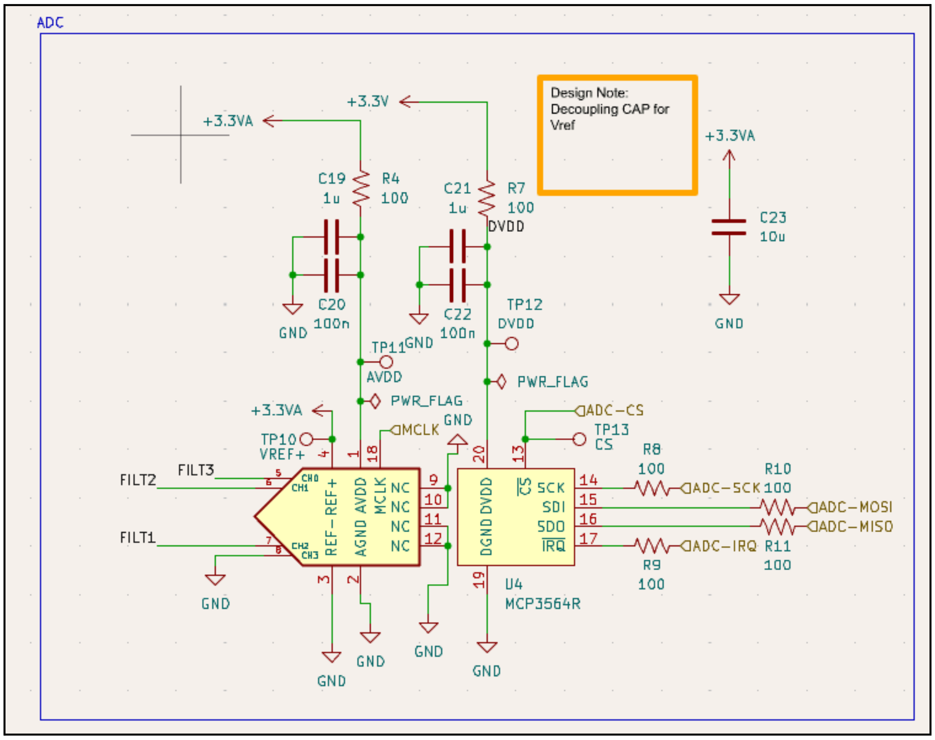

Figure 8: 24 bit External ADC

Layout

The DAQ Node PCB is 4 layers. The PCB layer stackup is shown in Figure 9.

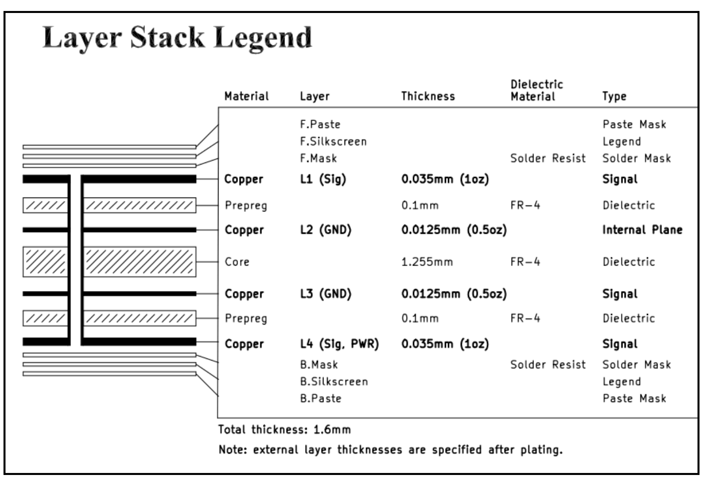

Figure 9: PCB Stackup

As both analog and high speed digital signals are present, the layout attempts to isolate the analog traces from the digital. As discussed in [2], a popular method for isolation is to use separate analog and digital rails and a split ground plane with a net tie. This risks increasing the length of the return path of signals which cross the split which can increase susceptibility to EMI. An alternative is to use separate analog and digital rails with a shared ground plane. Traces are routed to ensure the return paths for digital and analog signals do not intersect.

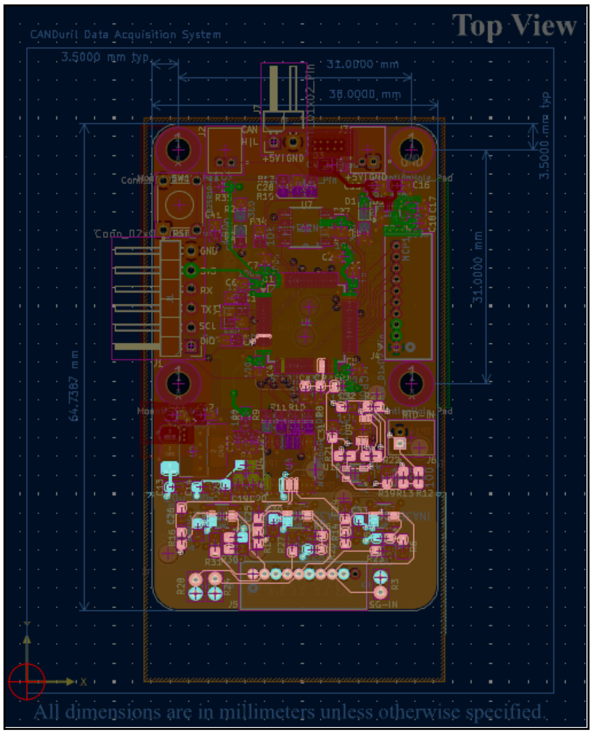

Figure 10: DAQ Analog Trace Routing

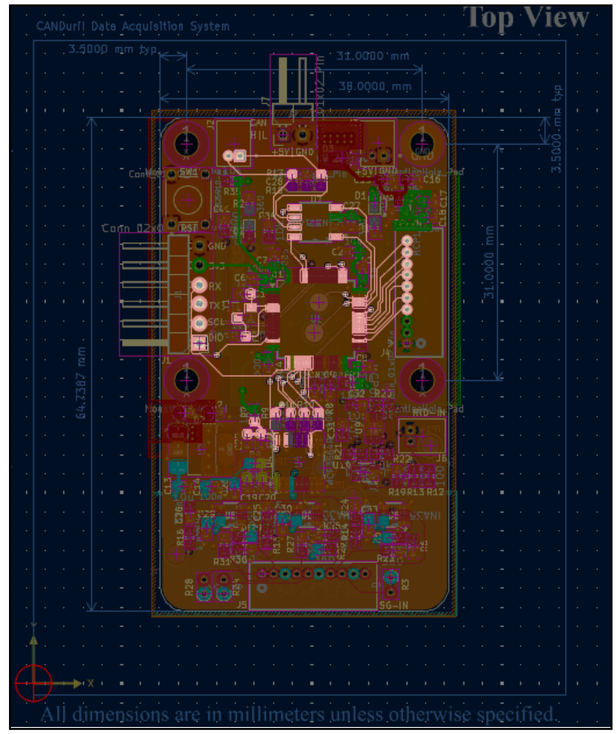

Figure 11: DAQ Digital Trace Routing

Sensors

The sensor suite consists of 4 sensor types listed below;

1. Temperature
2. Absolute pressure
3. Differential Pressure
4. Strain

Sensor placement is based on the objectives of the project. The pressure port placement is based on the following plot of the estimated pressure gradient (Figure 12)

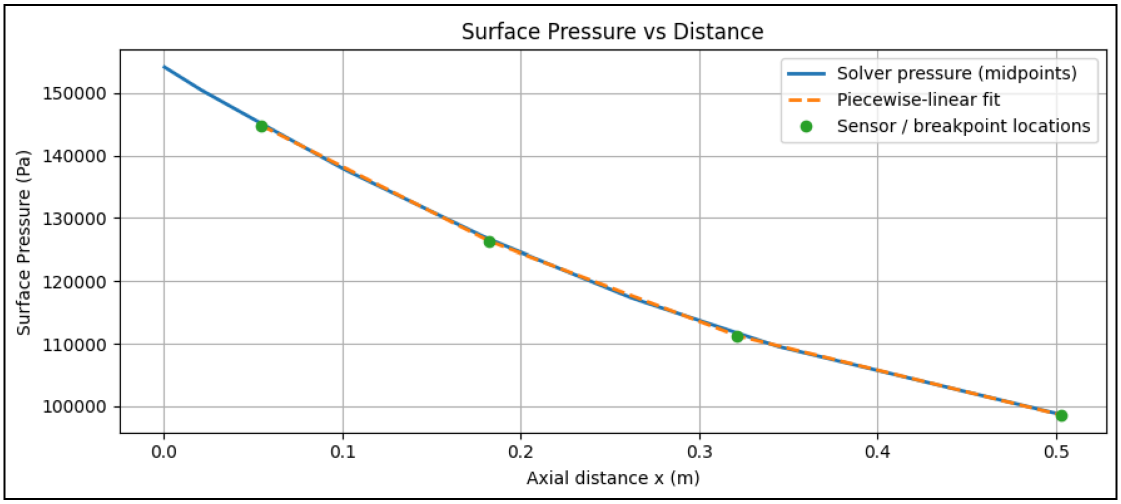

Figure 12: Simulated Nosecone Pressure Gradient

The plotted sensor locations allow for linear interpolation of the pressure gradient with minimal error.

The expected magnitude of the surface pressure was used to select the pressure ports. The resulting selections are summarized below:

1. ABP2DANT150PGSA3XX (150 psi max pressure rating)
2. HSCMRRN060PDSA3 (60 psi max pressure rating)

For the strain gauges, the placement and specification of strain gauges was based on the Skopinski method of strain measurement. In this method, 0,45,90 strain gauge rosettes are applied to the test specimen. For calibration, a vector of known loads are applied at points of interest. Loads refer to either known shear, torque, or bending moment at a known position relative to a common reference. The resulting strain readings are recorded producing a strain vector. As discussed in [3], the assumption that the strain readings have a linear relationship to the loads may not be valid. The linear equations take the form:

$$\mu_1 = \alpha_{11}V + \alpha_{12}M + \alpha_{13}T \quad (2)$$

Where V, M and T represent shear, moment and torque loads respectively. Because a load applied at a point x,y has the relationship $T = Vx$ and $M = Vy$ we can write the equations as

$$\mu_1 = \alpha_{11}V + \alpha_{12}Vx + \alpha_{13}Vy \text{ and } \frac{\mu}{V} = \alpha_{11} + \alpha_{12}x + \alpha_{13}y$$

Thus, knowing the coefficients, strain, and point of application allows estimation of the shear. The shear can be used to solve for the moment and torque. The coefficients must be found in this case by solving a system of 3 unknowns in three equations. To estimate the loads at one point, a minimum of three gauges are required.

It is possible that fixing y and plotting $\frac{\mu}{V}$ results in a non linear curve. This is an indication that higher order terms must be included in the equation. The paper indicates that even slight nonlinearity can introduce large error in the coefficients (and thus the measurements). It is most practical to apply as many gauges (j) as available and then apply n > j loads. The equations that result are shown below. The number of gauges dictates the number of higher order terms that can be used in the determination of the coefficients.

$$\begin{Bmatrix} V'_1 \\ V'_2 \\ \cdot \\ \cdot \\ \cdot \\ V'_n \end{Bmatrix} = \begin{Vmatrix} \mu_{11} & \mu_{12} & \cdots & \mu_{1j} \\ \mu_{21} & \mu_{22} & \cdots & \mu_{2j} \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \mu_{n1} & \mu_{n2} & \cdots & \mu_{nj} \end{Vmatrix} \begin{Bmatrix} \beta_{11} \\ \beta_{12} \\ \cdot \\ \cdot \\ \cdot \\ \beta_{1j} \end{Bmatrix} \qquad 13a)$$

Figure 13: Skopinski Method System of Equations [3]

The coefficients are computed via the least squares solution to the normal equation (3). The least squares solution finds $\{\beta\}$ that minimizes the sum of squared residuals $|V' - \mu\beta|^2$ (as more loads are applied then gauges, the system is overdefined and an infinite number of possible $\{\beta\}$ exist).

$$\{\beta\} = (|\mu|^T|\mu|)^{-1}\{|\mu|^T V'\} \quad (3)$$

As the point and magnitude of max bending can vary with height (z) and angle θ on the cylindrical surface of the fuselage, it is of interest to calibrate the system for a large quantity of applied loads at various heights z and angles θ. In this way, the coordinates and magnitude can be estimated with sufficient resolution to be of use. The system targets 12 strain gauge rosettes (36 gauges total) placed in the locations shown in Table 1. This placement consists of 4 rings of rosettes with 120 degree separation of rosettes within each ring. An RTD is placed in each ring for post flight temperature calibration of the strain readings.

Table 1: Target Strain Gauge Rosette and RTD Placements on Anduril 3

Strain Gauge / DAQ / RTD	Coordinates with nosecone tip at origin (z, r, θ)
SG1 / DAQ2 / RTD1	(52, 5.5, 0)
SG2 / DAQ3 / NA	(52, 5.5, 120)
SG3 / DAQ4 / NA	(52, 5.5, 240)
SG4 / DAQ5 / RTD2	(55, 5.5, 0)
SG5 / DAQ6 / NA	(55, 5.5, 120)
SG6 / DAQ7 / NA	(55, 5.5, 240)
SG7 / DAQ8 / RTD3	(61, 5.5, 0)
SG8 / DAQ9 / NA	(61, 5.5, 120)
SG9 / DAQ10 / NA	(61, 5.5, 240)
SG10 / DAQ11 / RTD4	(64, 5.5, 0)
SG11 / DAQ12 / NA	(64, 5.5, 120)
SG12 / DAQ13 / NA	(64, 5.5, 240)

Analysis

Power Calculations

Table 2: DAQ Power By Rail (VBUS is the input)

Rail	voltage (V)	current sleep (mA)	current run (mA)	max rated current (mA)	minimum trace width (mm)
DVDD	3.3	37.21	148.29	250	0.005
AVDD	3.3	93.32	97.11	500	0.0113
VBUS	5	143.58	269.93	2000	0.05626

Table 3: DAQ 3v3D Rail Power

MCP1825S	Power Rail: AVDD	Current Draw Run (mA)	Current Draw sleep (mA)
MCP3562 AVDD	AVDD	2.5	0.00022
LMV321AIDCKR	AVDD	0.0007	0.0007
MCP6N11T	AVDD	0.8	0.8
Bridge 1	AVDD	9.23	9.23
Bridge 2	AVDD	9.23	9.23
Bridge 3	AVDD	9.23	9.23
Bridge 4	AVDD	33	33
INA351CDSIDDFR	AVDD	0.1	0.1
MCP1825S Loss	AVDD	33.01642121	31.72865576
	Total current	97.10712121	93.31957576

Table 4: DAQ 3v3A Rail Power

MCP1754S-3302xDB	Power Rail: DVDD	Current Draw Run (mA)	Current Draw Sleep (mA)
ABPDANV030PGSA3 (Pressure transduce)	DVDD	3.90	3.90
ABPDANV030PGSA3	DVDD	3.90	3.90
ABPDANV030PGSA3	DVDD	3.90	3.90
HSCMRRN060PDSA3 (Pressure Transducer)	DVDD	2.80	2.80
STM32G431	DVDD	35.00	0.059
MCP3562 DVDD	DVDD	0.37	0.00017
LED1	DVDD	10.00	0
LED2	DVDD	10.00	10.00

TCAN3414DR	DVDD	28.00	0.00005
MCP1754S Loss	DVDD	50.42	12.65
	Total current	148.29	37.21

Total Estimated Power Draws

Fuselage: 2773.89mA

Nosecone: 148.29mA

Gain Calculations

Gain settings for both RTD and Strain measurement must be calculated.

$V_{ref} = 3.3V$ - ADC reference voltage for both strain (ADC: MCP3562) and RTD (ADC: STM32) measurements.

R_2 - the active bridge element (gauge / RTD)

K - The gauge factor (2 for BF350)

R_0 $-$ Nominal RTD resistance (100Ω for PT100)

Strain gauge 0 strain bridge output:

$$V_o = V_s\left(\frac{R1}{R1 + R2} - \frac{R_4}{R_{3+R_4}}\right) \quad (4)$$

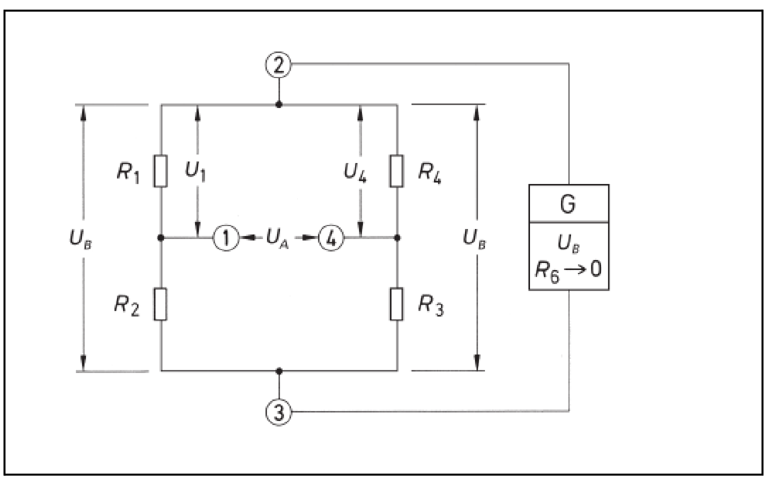

Figure 14: Wheatstone Bridge Circuit

R1, R3, R4 = 360 Ω, R2 = 350 Ω, $V_s = 3.3V$. This results in $V_o = 23.2mV$

RTD 25C bridge output:

R1 = R2 = R3 = R4 = 100Ω

$V_o = 0$

For the strain gauges, an offset voltage of 0V is applied. The bridge unbalance is used to offset the output voltage from 0 allowing both compressive (decrease in gauge resistance) and tensile (increase in strain resistance) to be measured. This was done due to the high cost of 350Ω bridge completion resistors. For the RTD measurement, an offset voltage of 1.65V is applied to the output via the MCP611N instrumentation amplifier (shown in Figure 5). This allows measurement of temperature above and below 0C.

The gain applied must scale the full scale range of the input signal to the full scale range of the ADC. The gain should not cause clipping (a voltage below 0V or above V_{ref}).

The strain measurements range from $-15000\mu\epsilon$ to $15000\mu\epsilon$ (the maximum rating of BF350 strain gauges).

The resulting bridge output swing can be calculated using equation 6-3.7 from [4].

$$\Delta R_2 = R_2 (K\epsilon) \quad (5)$$

The expected range of R_2 is 341.5Ω to 359.5Ω. Note that since no offset voltage is being injected, strain beyond $15000\mu\epsilon$ cannot be measured as it would lead to negative bridge output.

The resulting bridge output is calculated using equation 2. V_o ranges from $1.143mV$ to $45.93mV$.

Now we can compute the ideal gain:

$$G = \frac{V_{ref}}{V_{o-max}} = \frac{3300mV}{45.93mV} = 71.84 \quad (6)$$

The INA351 instrumentation amplifier will provide a gain of 30. The MCP3562 programmable gain amplifier will provide a gain of 2. The resulting total gain is G=60 effective resolution is computed using equation 1 to be 20.88 bits (the MCP3562 datasheet value of $1.7\mu Vrms$ at 4096 oversampling ratio and G=2 was used as the ADC rms noise). This is only slightly lower than the ideal value of 21.1 bits at these settings.

A similar procedure is applied for the RTD measurements. The only difference is that the position of R_2 and R_1 is swapped. This ensures positive change in resistance causes positive bridge output voltage.

The relationship between RTD voltage and temperature is given by the Callendar Van Dussen equation:

$$R_{RTD}(T) = R_o(1 + 3.9083 \times 10^{-3}T - 5.775 \times 10^{-7}T^2) \quad (7)$$

The target measurement range for temperature is between 0C and 400C. This yields expected resistance range of between 100Ω and 247Ω. The resulting full scale range of the input signal V_o is between 0V and 0.699V. The ideal gain is

$$G = \frac{V_{ref}}{V_{o-max}} = \frac{3300mV}{700mV} = 4.7 \quad (8)$$

The MCP611N will provide a gain of G=2 and the programmable amplification feature of the internal STM32 ADC will provide a gain of G=2. The datasheet specified value for typical ADC rms noise is $809\mu V$ [5]. This gives an effective resolution of 11.75 bits.

Filter Calculations

Two RC lowpass filters were designed. The strain gauge sampling frequency is 250Hz. The Nyquist criterion means the filter should attenuate signals above 125Hz. The cutoff (-3dB) frequency of the filter was placed at 100Hz. The component values were calculated using:

$$f_c = \frac{1}{2\pi RC} \quad (9)$$

To ensure source loading is minimized, the value of R was chosen to be $4.87k\Omega$ (a standard value above $1k\Omega$ is a rule of thumb). The resulting C is 330nF.

The same process was applied for the RTD signal. The sampling rate is 5Hz. This results in a Nyquist frequency of 2.5Hz. The cutoff frequency was placed at 1.5Hz. This results in $R = 10k$ and $C = 10u$.

The filter Bode Plots are shown below:

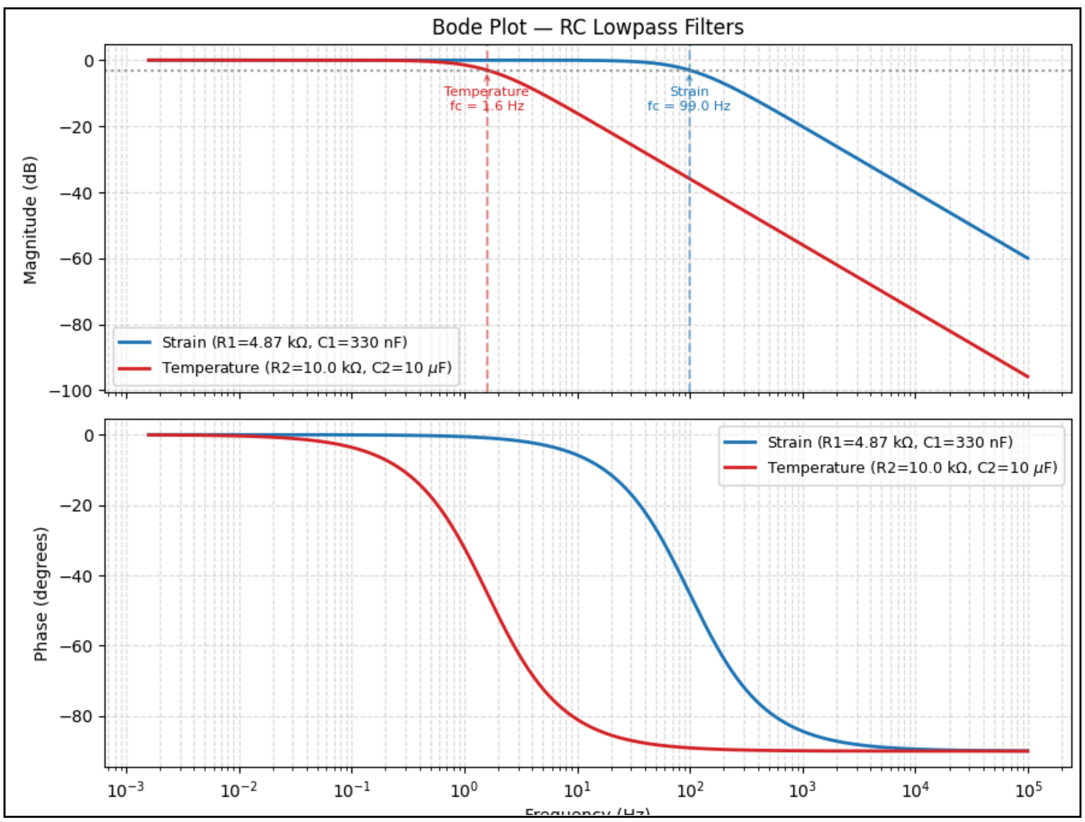

Figure 15: RC Lowpass Filter Bode Plots

Signal Chain Analysis

The MPLAB signal chain analysis software from Microchip was used to estimate the effective resolution resulting from the entire signal chain [6]. The model circuit used is shown below.

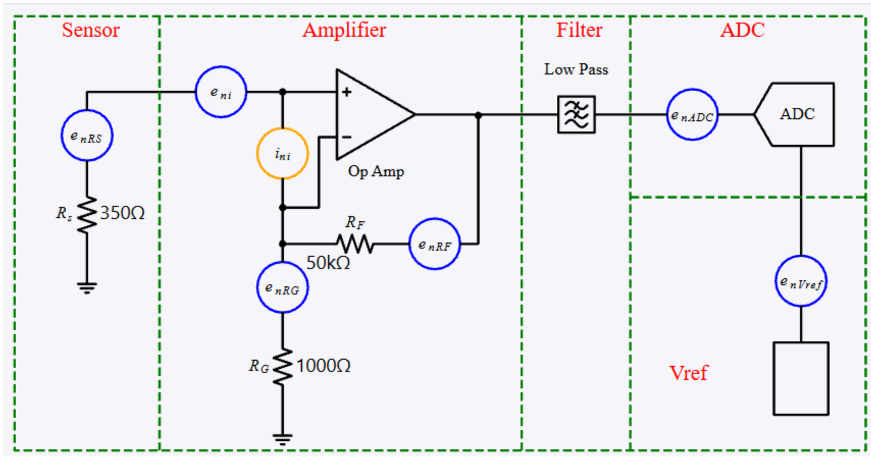

Figure 16: Model Circuit

The software supports the MCP3562 ADC natively. Datasheet values for Vref (MCP1825S) and the amplifier (INA351) were used. The resulting parameters are shown in Figure 14:

Signal Chain Signal-to-Noise Ratio, SNR	78.78 dB
Effective Resolution (~ ENOB)	13.08 bits
Signal voltage, Vrms	0.901 Vrms
Total Integrated Noise	103.65 uVrms
Total Peak-to-Peak Noise	684.09 uVpp
Noise Power Bandwidth (NPBW)	75 Hz
Suggested signal chain gain to maximize SNR	66 V/V
Suggested new RG value	769.23 Ω

Figure 17: Signal Chain Analysis Results

The calculator indicates that noise introduced by the instrumentation amplifier reduces the effective number of bits to 13.08 bits. This provides a resulting strain precision of +/-4.88με. Signal chain analysis was not performed on the RTD measurements as the precision specifications are more lenient.

Software

The DAQ software targets the STM32G41 microcontroller. This microcontroller is based on the ARM Cortex M4 processor. arm-non-eabi-gcc was used as the compiler toolchain and CMake was used as a build tool. The software requirements are summarized below:

- ID: REQ-FUNC-001: The system shall use the MCP3562 ADC to sample from 3 strain gauges each at 250Hz.

-ID: REQ-FUNC-002: The system shall use its internal ADC to sample the RTD data at 5Hz

- ID: REQ-FUNC-003: The system shall acquire pressure port data from 4 pressure ports over SPI

- ID: REQ-FUNC-004: The system shall use its onboard LED to indicate operational status

- ID: REQ-FUNC-005: The system shall use its CAN interface and the onboard TCAN3414 CAN transceiver to communicate with the flight computer over CAN

The STM32 HAL library [7] was used to interface with the microcontroller peripherals. The open source Apache licenced MCP3562 driver found in [8] was used to interface with the external ADC. FreeRTOS was used to manage sensor reading, status LED control, and CAN Bus transmissions. A block diagram of the FreeRTOS tasks implemented is shown in Figure 18:

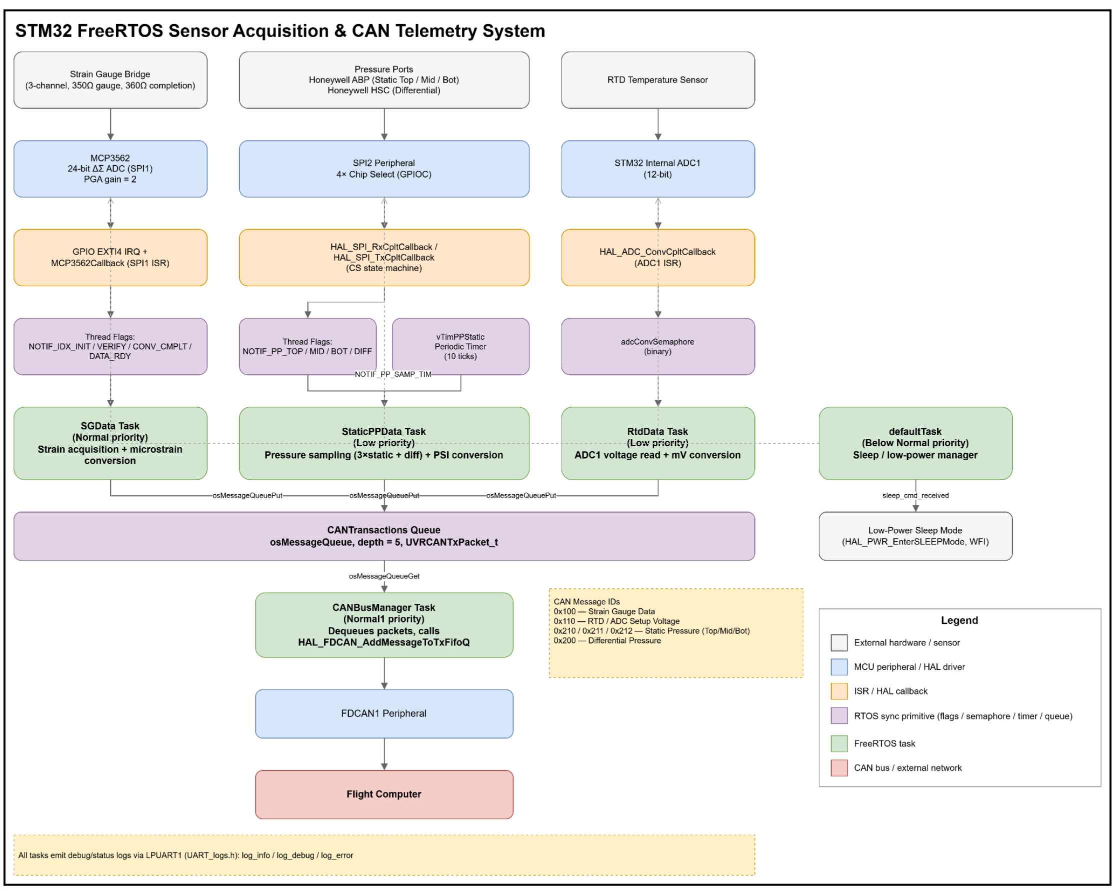

Figure 18: DAQ Software Block Diagram

Summary

Figure 16 shows the final assembled A3-Sensors-DAQ PCBS. Software and integration testing has been completed. Calibration is pending based on completion of Anduril 3's Fuselage and is scheduled for July 15th.

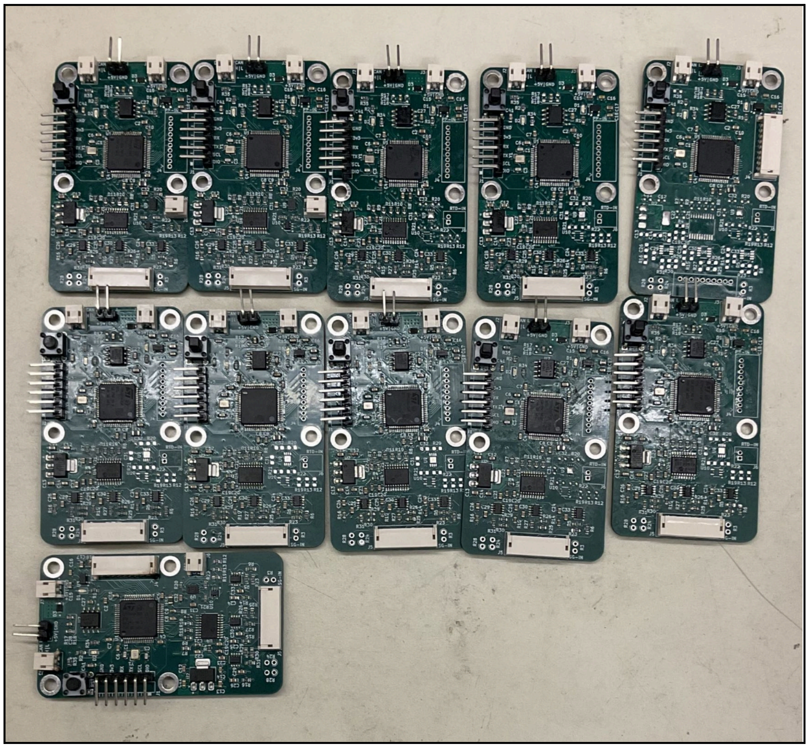

Figure 19: Assembled DAQ PCBs

The A3-Sensors-DAQ project is made publicly available on github. All source code and KiCAD project files are included and can be found at the link below.

https://github.com/UVicRocketry/A3-Sensors-DAQ

References

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