Development of a Control System for a Liquid Rocket Engine Test Stand

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The University of Alabama in Huntsville

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Tartarus Project Introduction (1/2)

Objective

- To provide opportunities for hands-on liquid propulsion experience for UAH students covering all facets of the project design lifecycle

Safety briefing before cold flow

Tartarus Project Introduction (2/2)

A visit from our sponsor AVCO

Subteams

- **Controls**: data acquisition and system control
- **Fluids**: plumbing and ground systems
- **Propulsion**: engine design, modeling, and analysis
- **SE&O**: scheduling and systems management

Team Structure

Project Lead

Chief Engineer

Propulsion

Responsibilities
- Engine Design
- Engine Development

Fluids

Responsibilities
- Test Stand Design
- Test Stand Construction and Maintenance

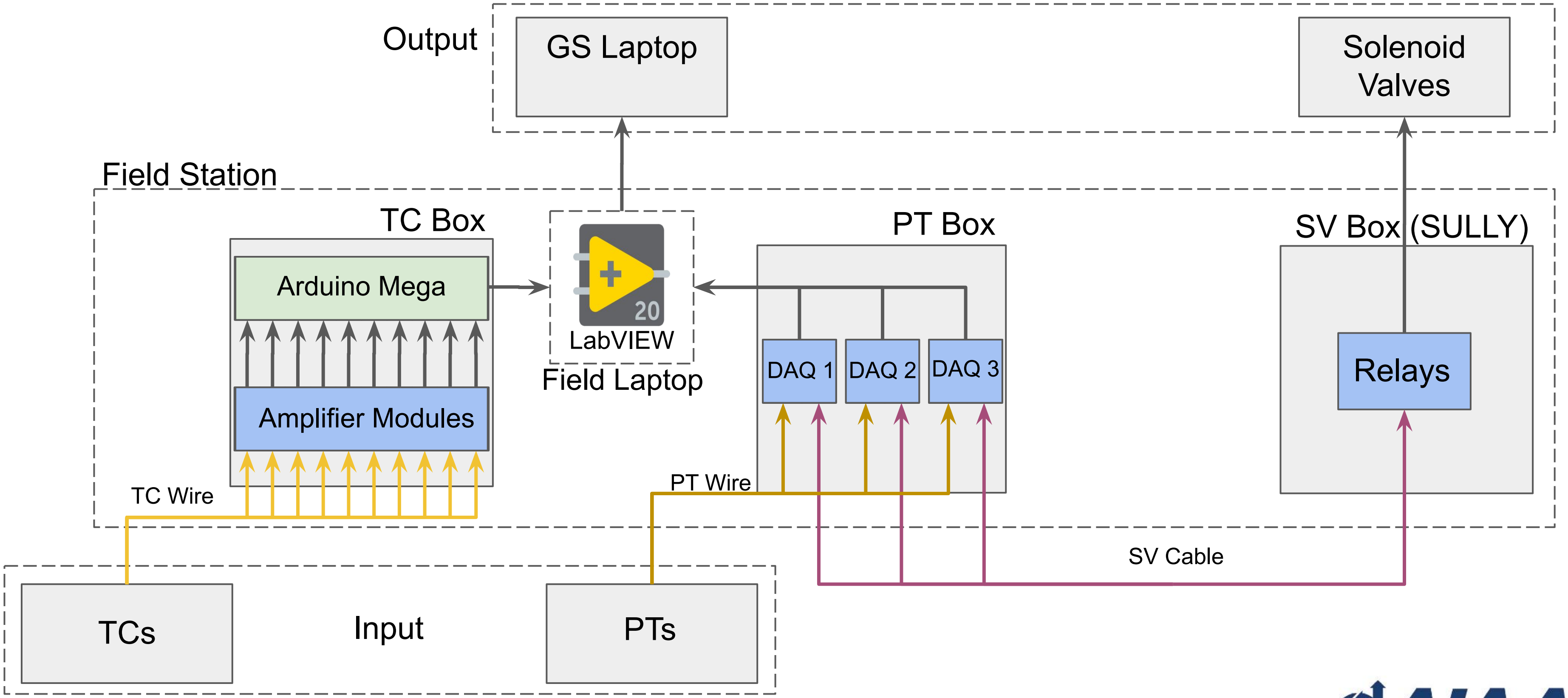
Controls

Responsibilities
- Controls System Design
- Data Collection

Systems Engineering and Operations

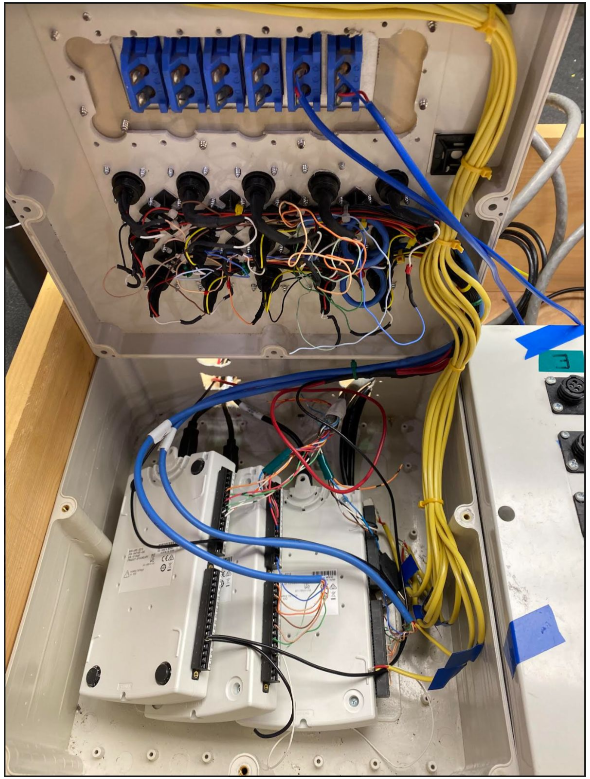
Responsibilities
- Safety Analysis
- Schedule and Work Flow
- Media Relations

The Old Control System



Issues With The Old System

- Programed in NI LabVIEW
- Poor connector choice
- Confusing UI
- Hard limit to expandability
- Low data fidelity
- Unreliable
- Unable to meet new requirements



Goals For The New System

The 3 R's

- Expandable
- Reliable
- Reasonably priced

New System Improvements

- Base Station Laptop → 2 NUCs
- Field Laptop, TC box, PT box, SV box → MTS Controller
- NI DAQs → CCI boards
- NI LabVIEW → C++ and Python
- The removal of discontinued or antiquated parts
- User Friendly UI
- More detailed documentation of the entire system

New System Requirements (1/2)

#	Requirements
1	The MTS Computer shall be able to fit inside one of the CCI Boards enclosure with said CCI Board.
2	The MTS Computer shall communicate live data to the base station via ethernet.
3	Live data shall be communicated with the base station at a packet rate of 60 Hz

New System Requirements (2/2)

#	Requirements
4	The MTS Computer shall be able to communicate with all CCI boards at the same time via UART.
5	Communication with each CCI board shall be at a baud of 115200

MTS Controller Requirements (1/2)

#	Requirements
1	The entire MTS Controller shall be housed in an area no more than 4 square feet.
2	The MTS Controller shall be housed in a server rack system that allows for ease of assembly and upgradability.

MTS Controller Requirements (2/2)

#	Requirements
3	The housing will also hold the network switch used for sending data from the MTS Controller to the base station.

CCI Board Requirements(1/6)

#	Requirements
1	The CCI boards, and MTS computer must mount into standard 3U server chassis, to allow them to be rack mounted
2	Each board shall have 16 total instrument inputs
3	Each board shall have 8 inputs with amplifiers for TCs

CCI Board Requirements(2/6)

#	Requirements
4	Each board shall have 8 inputs for PTs
5	Boards shall communicate with the MTS computer via UART
6	Each board shall have an enclosure with 3 K-type TC connectors

CCI Board Requirements(3/6)

#	Requirements
7	Each board shall have an enclosure with 5 T-type TC connectors
8	Each board shall have an enclosure with 8 XLR inputs for PTs/Analog input
9	Each CCI board shall have 8 relays, controlled by the microcontroller

CCI Board Requirements(4/6)

#	Requirements
10	Each relays shall be able to pass a minimum of 1A @ 24V
11	Each CCI box shall have 8 XLR ports connected to the relays for commanding valves

CCI Board Requirements(5/6)

#	Requirements
12	CCI boards shall have a method of measuring valve actuation status
13	CCI box shall have an XLR input for MTS computer UART control
14	CCI boards shall be powered by a 12V supply

CCI Board Requirements(6/6)

#	Requirements
15	The relays shall be able to either output the 12V input to the board, or a different voltage from an external input.
16	Reliability and durability shall be prioritized and as such the system shall prioritize industry grade COTS components.

Base Station Requirements(1/2)

#	Requirements
1	Must consist of a desktop and all physical buttons and switches needed for safe firing
2	The desktop will have at minimum 3 monitors to display our custom GUI with data readouts, valve actuation, and camera feeds

Base Station Requirements(2/2)

#	Requirements
3	The monitors must have a screen size of a minimum of 24 inches for easy of reading a large amounts of information on them
4	There must be a physical abort button, connected with with a separate wire, that can stop the engine in the event of an emergency

Software Requirements(1/6)

#	Requirements
1	The GUI must be easy to use and interpret
2	The GUI must have live graphs of important data like pressure, temperature, and thrust output.

Software Requirements(2/6)

#	Requirements
3	The GUI will have an interactive P&ID, that shows status of all sensors and valves connected to the CCI boards
4	The GUI must be able to command valves to open and close, and to command system events like engine startup

Software Requirements(3/6)

#	Requirements
5	The GUI must have live camera feeds from cameras positioned around the ETS and in the trailer

Software Requirements(4/6)

#	Requirements
6	The GUI must generate its own system event logs from the data received from the CCI boards/MTS computer. Faults and other conditions such as overpressure events must be recorded in this log

Software Requirements(5/6)

#	Requirements
7	The system must output data into a CSV file that includes appropriately named headers for each column
8	The software for all components must be well documented, and should be written to be understandable. Software should follow applicable best practices

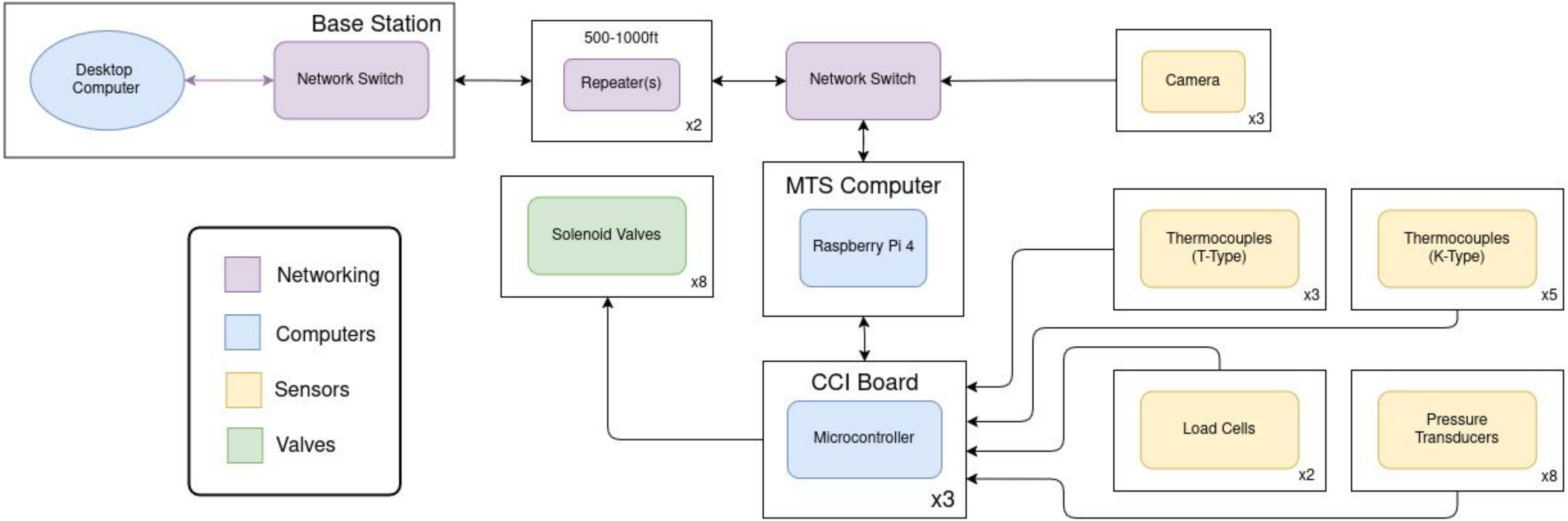
Software Requirements(6/6)

#	Requirements
9	Version management software like GitLab or GitHub must be kept up-to-date for all software components

Control System Overview

- MTS Controller
  - Contains MTS Computer and CCI Boards
- CCI Boards
  - Command control and instrumentation
- Base Station
  - Graphical user interface
- Igniter
  - COTS automotive ignition coil and spark plug

Control System Block Diagram



MTS Computer

TARTARUS

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Raspberry Pi 4s

- Communicate live data to the base station via Ethernet
- Communicate with all of the CCI boards using a UART connections

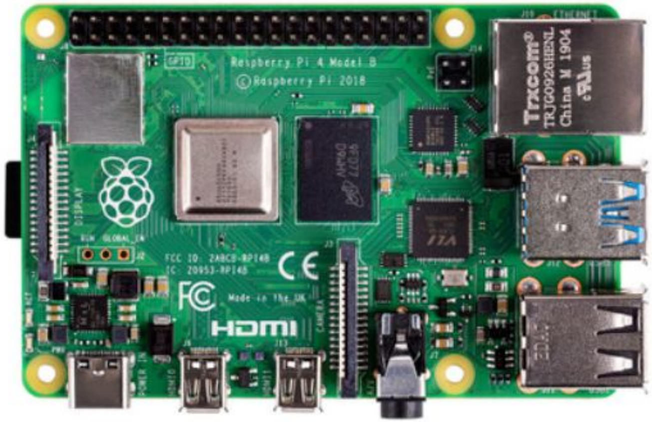


Image Credit: Raspberry Pi

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Network Switch

Dell Powerconnect 5324 features:

- 24 Gigabit Ethernet ports
- 4 SFP Fiber ports
- Configurable
- Remotely managed

Image Credit: Dell

MTS Power System

APC Back-UPS RS 1500

Sportsman Series 1000-Watt 2-Cycle Generator

Image Credit: APC, Sportsman

MTS Controller Power Budget

Components	Max Quantity	Voltage (V)	Max Current (mA)	Total Wattage (W)
MCP9600 TC Amp	24	3.3	0.3	0.024
TE Connectivity M3041	24	12	3.5	1
Solenoid Valve	24	24	200	115.2
RPi4S	1	5	1800	9
CCI Board	3	24	2000	144
Network Switch	1	120	800	96

MTS Controller Power Budget

Total Power	Generator Load
365 W	41%

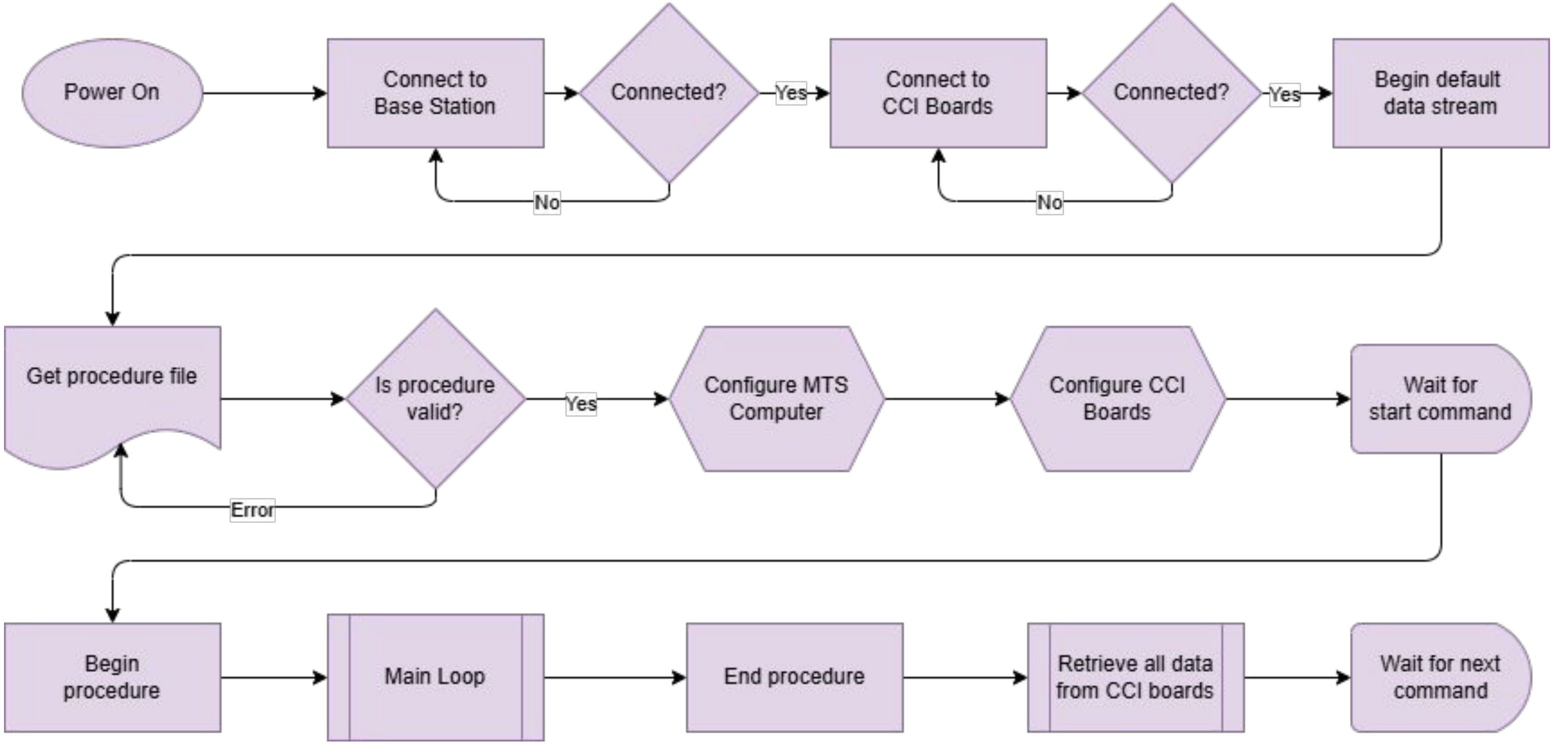
Base Station Power Budget

Components	Quantity	Voltage (V)	Max Current (mA)	Total Wattage (W)
Intel NUC	2	19	2580	98
ASUS VE278	2	120	266	64
Dell P2417h	1	120	325	39
Network Switch	1	120	800	96

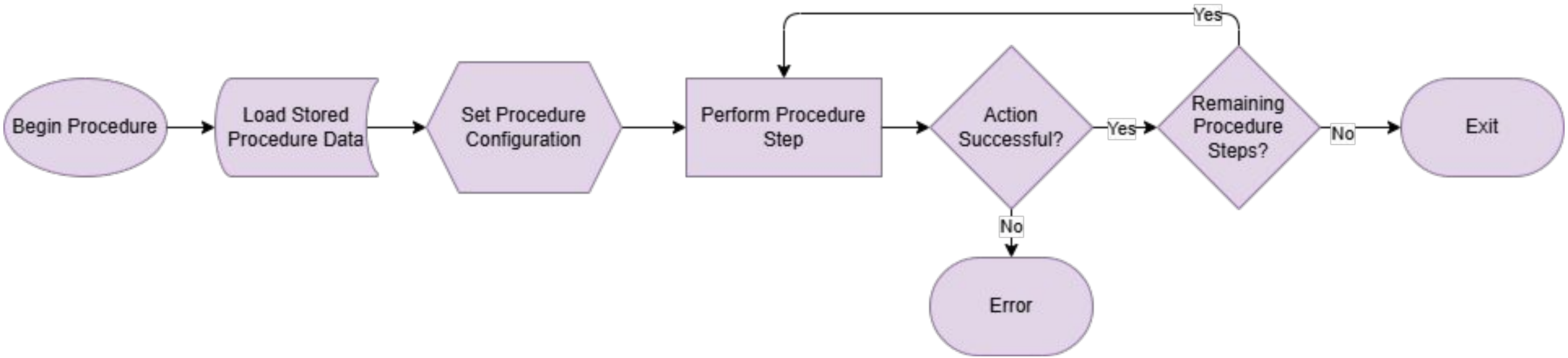
Base Station Power Budget

Total Power	Generator Load
297 W	33%

MTS Computer Initialization



MTS Computer Main Loop



Data Processing

Time	System State	PT0	…	PT23	TC0	…

TC23	LC0	LC1	SV0 State	…	SV23 State	TC23

MTS to Base Station Communication

- TCP over an Ethernet connection
- Procedures sent as TOML files
- Individual commands in SCPI 1999 format
- Data begins transmitting upon connection

```
[config]
name = "Valve Open Example"
data_rate=100 # Data rate in packets/second

# Procedure

[step.1]

# Open Solenoid Valve 1
command=":CONTrol:SV1:ENABle ON"
time=100 # Trigger at 100ms after start
delay=10 # Send error if valve not actuated in 10ms
# whether to error and continue, hold further steps,
# or shutdown after delay has passed
severity=1

[step.2]

# Close Solenoid Valve 1
command=":CONTrol:SV1:ENABle OFF"
time=200
delay=10
severity=2
```

MTS to Base Station Communication

```
[config]
name = "Valve Open Example"
data_rate=100 # Data rate in packets/second
```

MTS to Base Station Communication

```
[step.1]

# Open Solenoid Valve 1
command=":CONTrol:SV1:ENABle ON"
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severity=1
```

MTS to Base Station Communication

```
[step.2]

# Close Solenoid Valve 1
command=":CONTrol:SV1:ENABle OFF"
time=200
delay=10
severity=2
```

SCPI

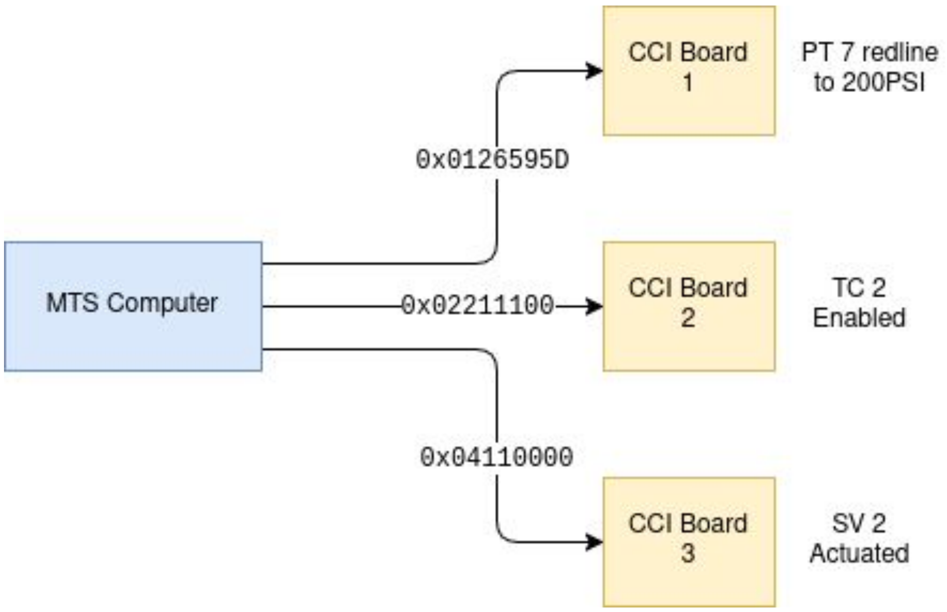
- Human readable
- Plain text
- Industry standard
- Extensible

```
SYSTem
    :UNIT
        :PRESsure PA|PSI|BAR
        :TEMPerature F|C|K|R
    :REDLine
        :PT[1-24]
        :TC[1-24]
        :LC[1-6]
CAL
    :[PT,LC,TC][1:24]<Offset
>
CONTrol
    :ACTuate:SV[1-24]
MEASure
    :[PT,LC,TC][1:24]
```

SCPI

SCPI Command	Operation
`SYST:UNIT:PRES PSI`	Set pressure unit to PSI
`SYST:REDLine PT3 700`	Set PT3 Redline to 700 PSI
`CAL:TC7 -3`	Offset TC7 by -7° fahrenheit
`CONT:ACTuate:SV12 1`	Open solenoid valve 12

MTS Computer to CCI Board



- Human readable
- Plain text
- Industry standard
- Extensible

MTS Computer to CCI Board

0x04140000

Command Valve

Actuate Valve

SV #5

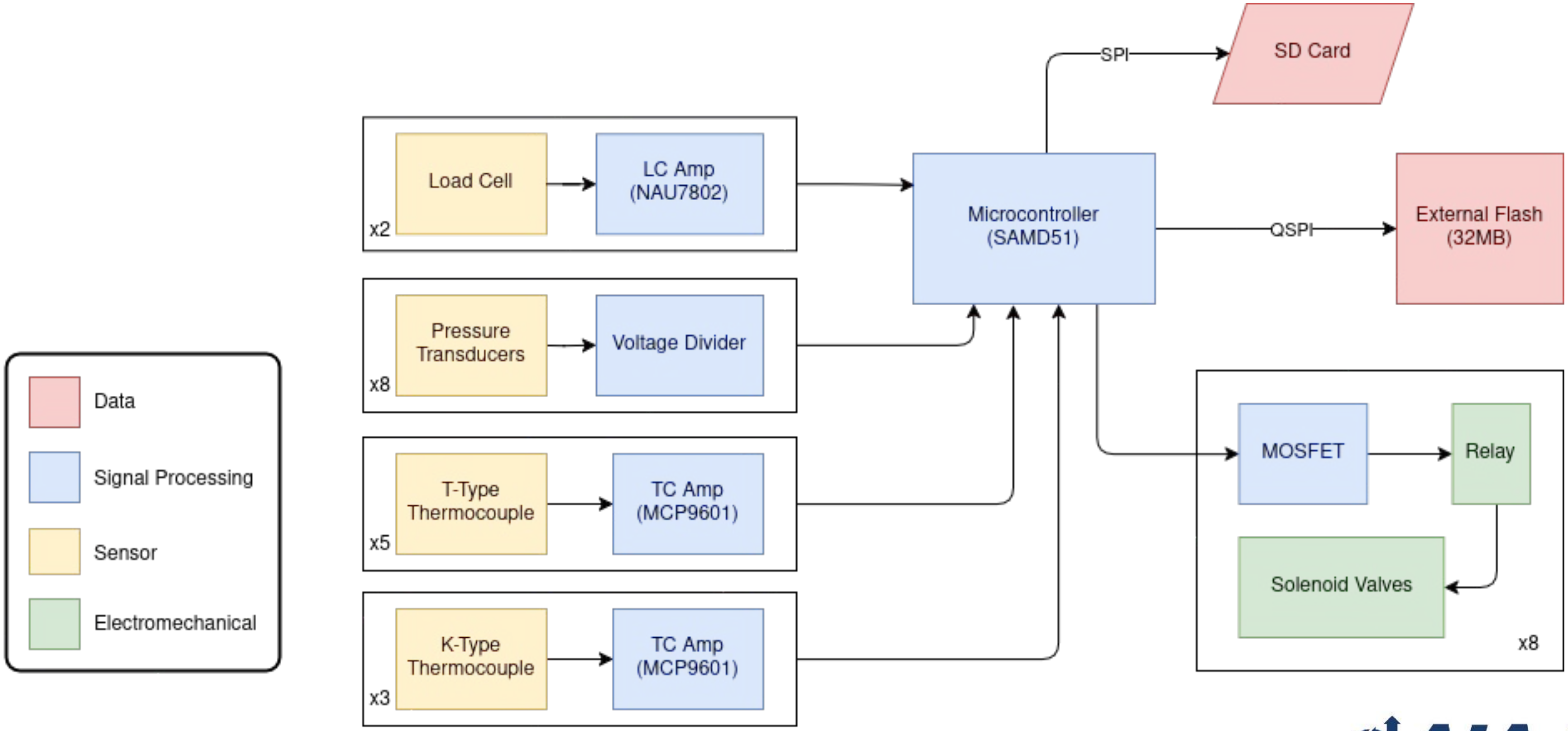
MTS Computer to CCI Board

Code	Operation	Example
0x00	Always a NOP (No Operation)	0x00 0x00 0x00 0x00 → NOP
0x01	Configure redlines ● 0x1[0:7] to TC Number ● 0x2[0:7] to PT number ○ 0xXXXX to redline (16 bit)	0x01 0x25 0x59 0x5D → Set PT 6 redline to 200 PSI (listed in corresponding ADC value)
0x02	Configure sensor ● 0x1[0:7] to TC number ● 0x2[0:7] to PT number ● 0x3[0:1] to LC number ○ 0x1[0:1] to Disable|Enable	0x02 0x31 0x10 0x00 → Configure LC 2 to be disabled
0x03	Measure ● 0x1[0:7] to TC number ● 0x2[0:7] to PT number ● 0x3[0:1] to LC number	0x03 0x12 0x00 0x00 → Measure value on TC 3

MTS Computer to CCI Board

Code	Operation	Example
0x04	Valve Command ● 0x1[0:7] Actuate Valve Number ● 0x2[0:7] Status Valve Number	0x04 0x27 0x00 0x00 → Get the status of SV 8
0x05	Retrieve Sensor Data ● 0x1[0:7] to TC number ● 0x2[0:7] to PT number ○ 0x3[0:1] to LC number	0x05 0x15 0x00 0x00 → Retrieve all data from TC 6
0x06	Passthrough ● 0x1[0:2] to connected CCI number	0x06 0x12 0x00 0x00 0x02 0x30 0x10 0x00 → Configure LC 1 to be disabled on connected CCI Board 3
0x07	End Passthrough	0x06 0x12 0x00 0x00 0x04 0x16 0x00 0x00 0x07 0x00 0x00 0x00 0x05 0x21 0x00 0x00 → Actuate SV 8 on connected CCI Board 3, Retrieve all data from PT2 on upstream CCI

CCI Board Block Diagram



Microcontroller Overview

Image Credit: Microchip

Microchip SAMD51P20A

- ARM Cortex M4 processing core
- Dual, 1 MSPS ADCs
- Direct Memory Access Controller
- 99 GPIO pins
- 3 UARTS, 2 x I2C, 3 x SPI, USB 2.0 D+/-

Flash

GigaDevice Semiconductor GD25Q256EWIGR

- QSPI interface
- 32MB of storage
- Reliable, high speed, SLC NOR flash
- Runs at up to 133 MHz
- 250us page write time

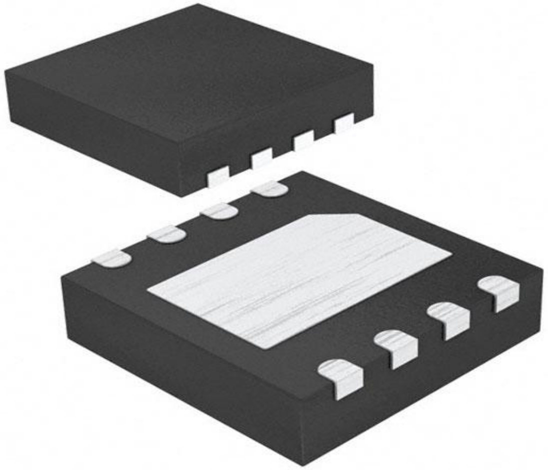
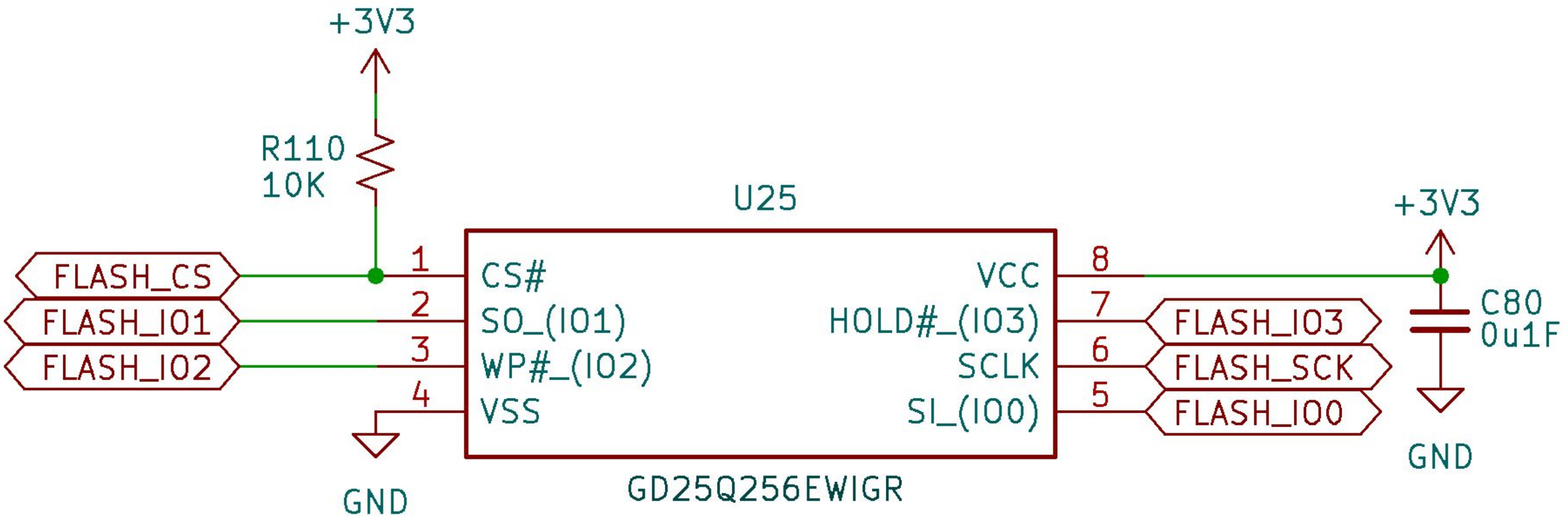


Image Credit: GigaDevice Semiconductor

Flash Schematic



Sensor Data Throughput

Number of Component	Component	Sampling Rate	Number of Bytes per Second
2	Load Cell	320 Hz	1280
8	Thermocouple	200 Hz	3200
2	Pressure Transducer (16-bit)	1000 Hz	4000
6	Pressure Transducer (14-bit)	62000 Hz	744000

Sensor Data Throughput

Total Bytes per Second	752,480

about 0.75MB per second, per CCI Board

Thermocouple Amplifier

Microchip MCP901

- Up to 200 Hz data output rate
- 0.5 ℃ Accuracy
- Supports type K, J, T, N, S, E, B and R thermocouples
- Premade software library

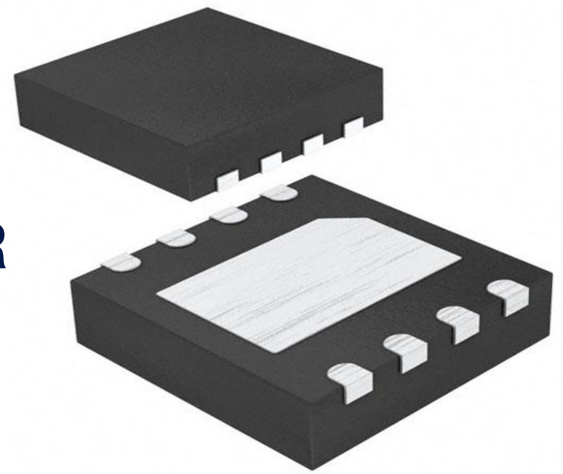
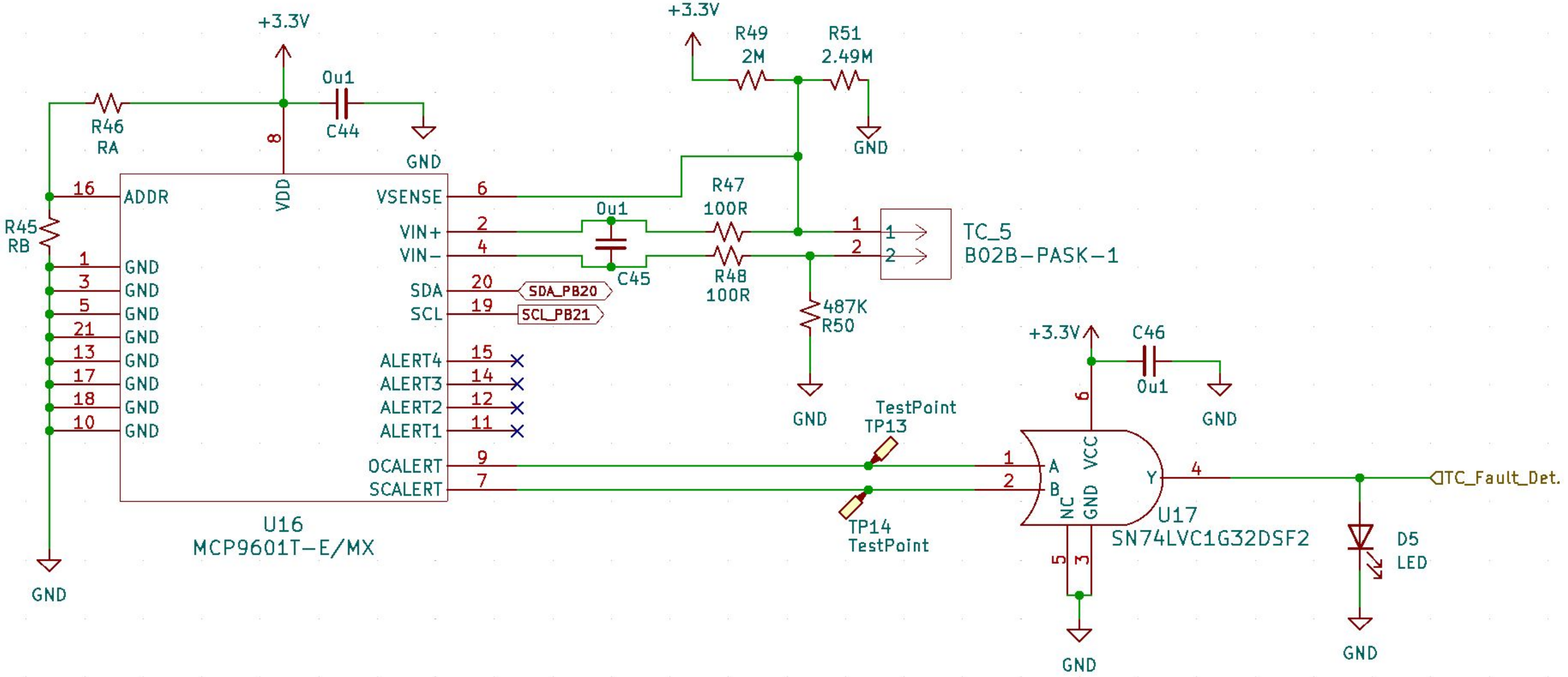


Image Credit: Microchip

Thermocouple Amplifier Schematic



Thermocouple Amplifier Example Code

```
#include <SparkFun_MCP9600.h>

MCP9600 TC;

void setup()
{
  Serial.begin(115200);
  Wire.begin();
  Wire.setClock(100000);
  TC.begin();

  if (!TC.isConnected())
  {
    while(1);
  }
}

void loop()
{
  if(TC.available())
  {
    Serial.println(TC.getThermocoupleTemp());
  }
}

```

Load Cell Amplifier

Nuvoton NAU7802

- High Precision 24-Bit Σ-Δ AD
- Communicates over I2C
- Compact 16-SOP Package
- Premade software library

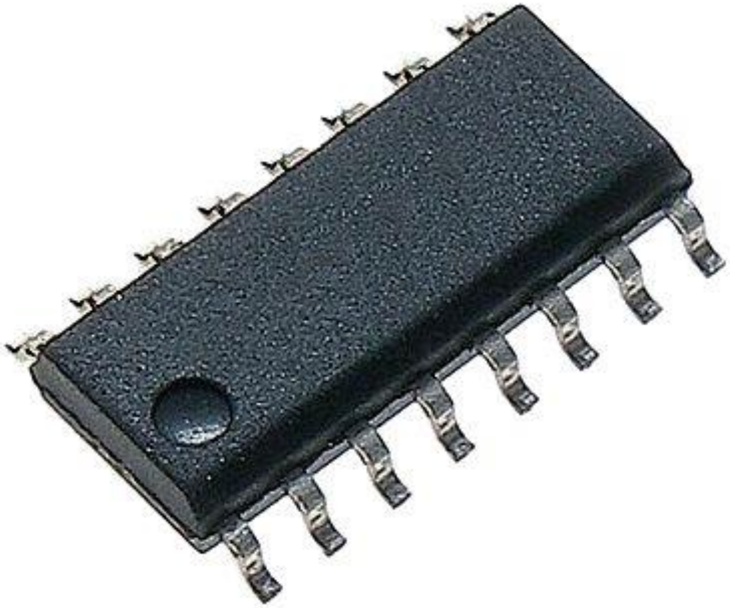
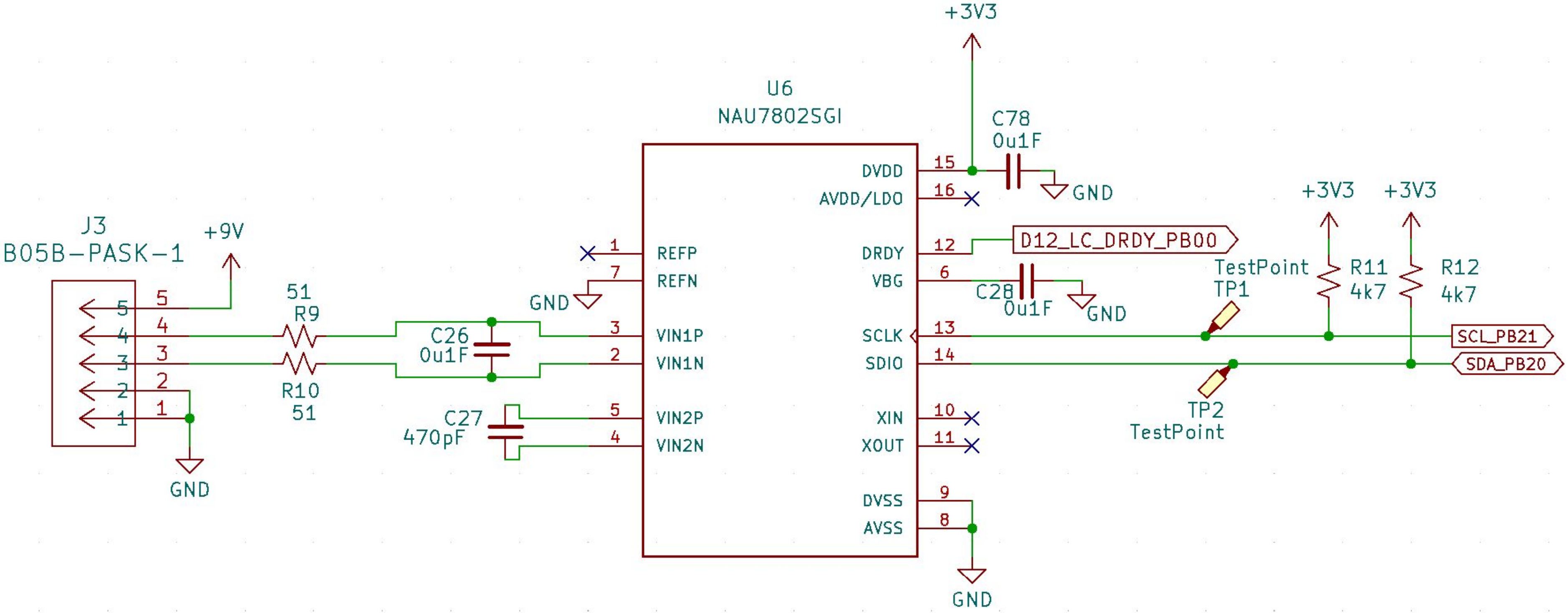


Image Credit: Nuvoton

Load Cell Amplifier Schematic



Load Cell Amplifier Example Code

```
#include <Wire.h>
#include "Sparkfun_Quiic_Scale_NAU7802_Arduino_Library.h"

NAU7802 LC;

void setup()
{
  Serial.begin(115200);
  Wire.begin();

  if (!LC.begin())
  {
    while(1);
  }
}

void loop()
{
  Serial.println(LC.getReading());
}

```

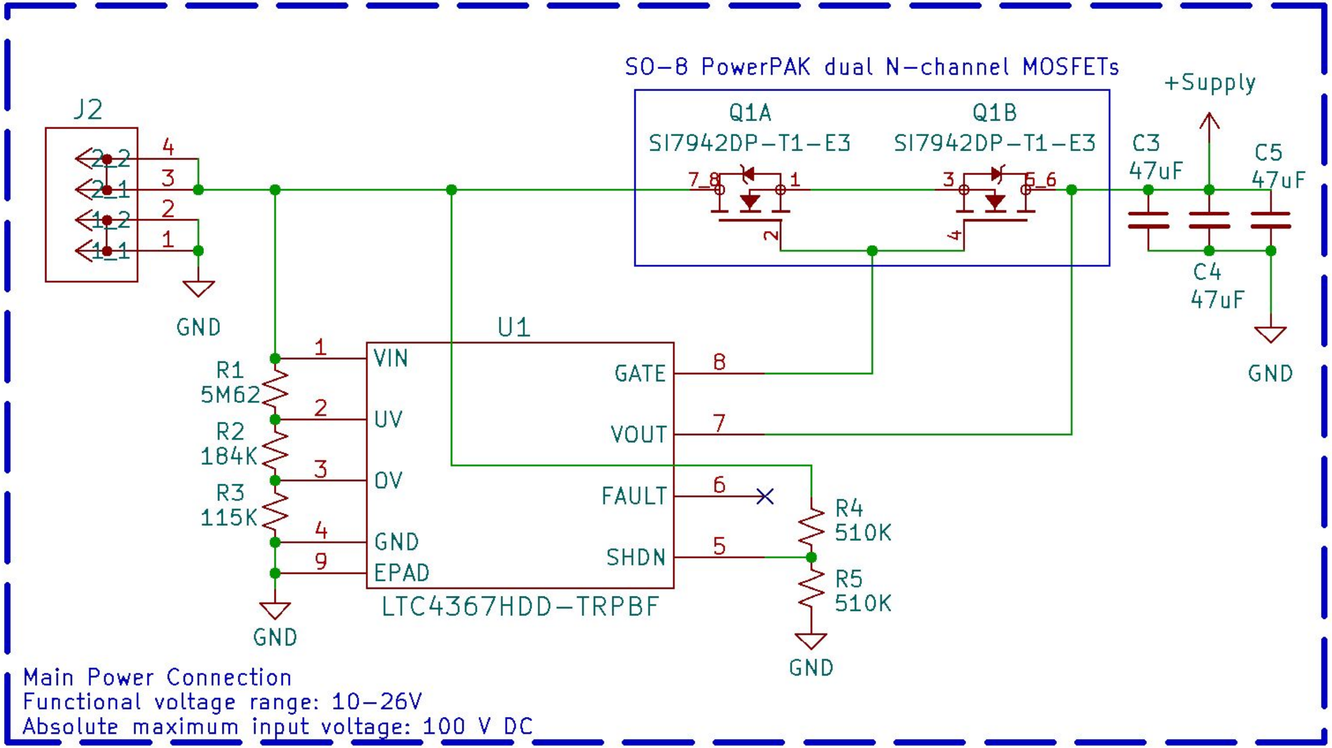
CCI Board Power Subsystem

Voltage	Protected/Regulated
+Supply	LTC4367 IC
+9V	RTQ2569
+6V	AP63201WU-7
+5V	MAX17634B
+3.3V,	AP63203WU-7
+3.3 V_{Ref}	LT6660K

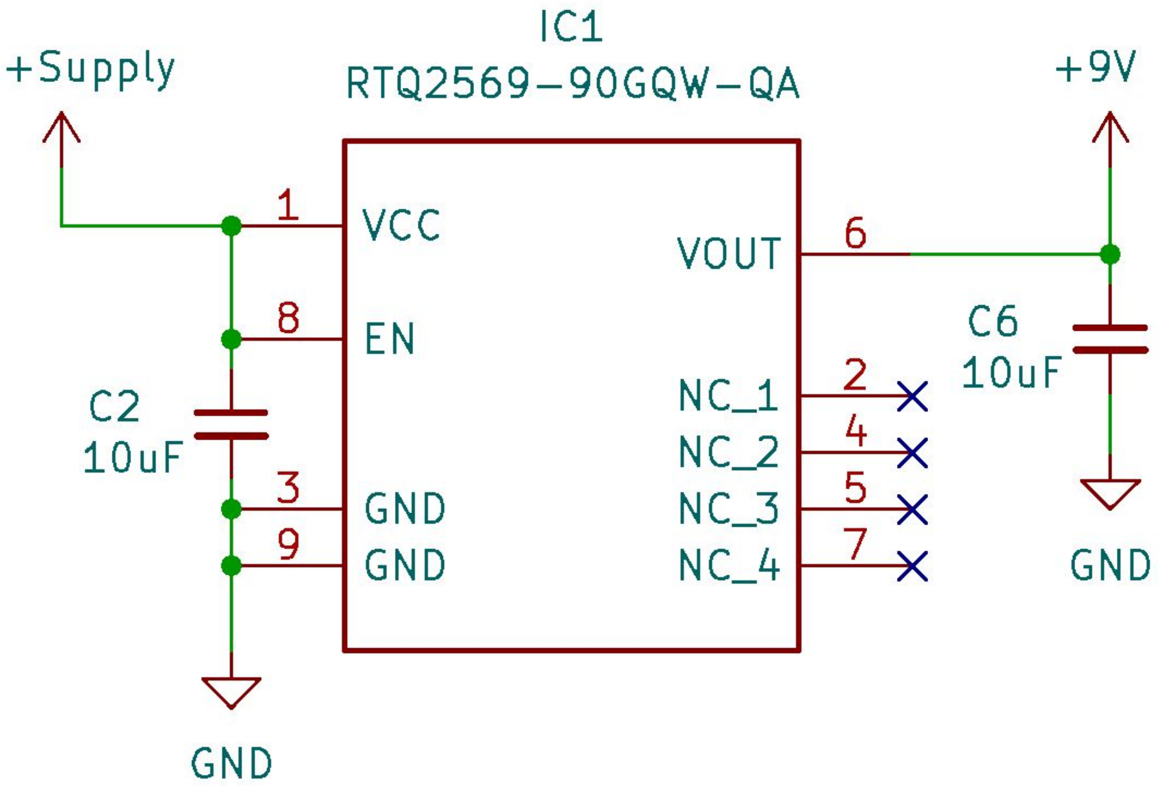
CCI Board Power Subsystem

Voltage	Protected/Regulated
+Supply	PT output, SV output
+9V	Excitation Voltage for Load Cells
+6V	SV Relay Coil Supply
+5V	RGB LEDs, Expansion Ports
+3.3V,	Processor, Sensors, Data Storage
+3.3 V_{Ref}	Processor Precision Voltage

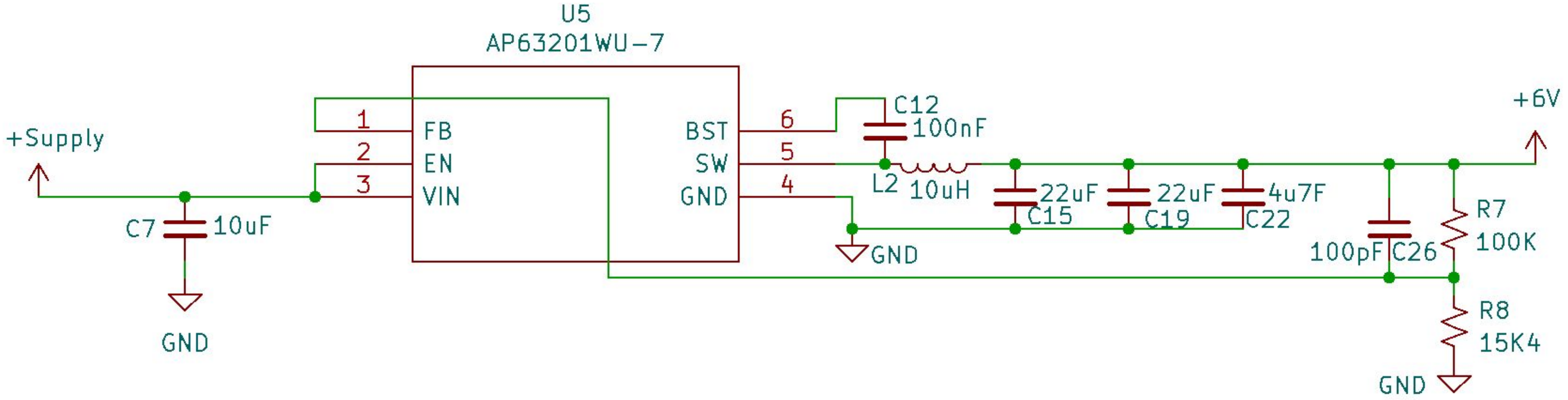
CCI Board Power Subsystem



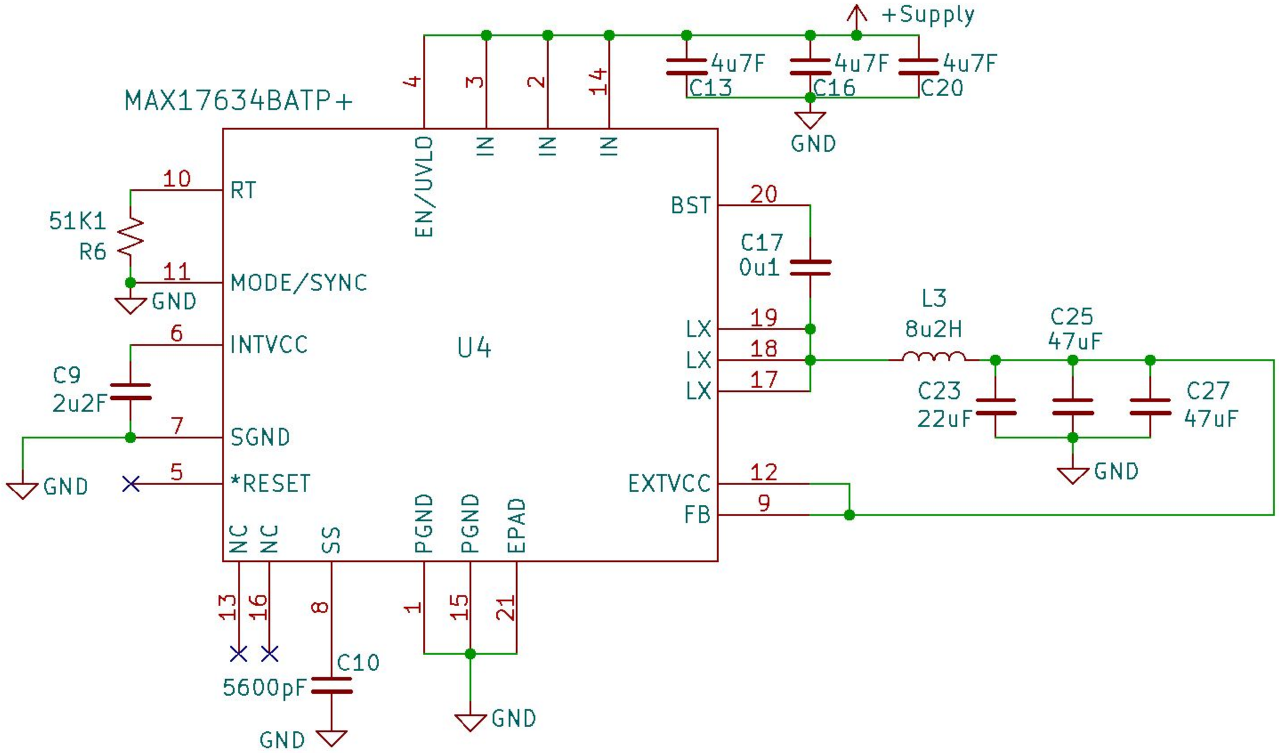
CCI Board +9V Power Rail Supply



CCI Board +6V Power Rail Supply



CCI Board +5V Power Rail Supply



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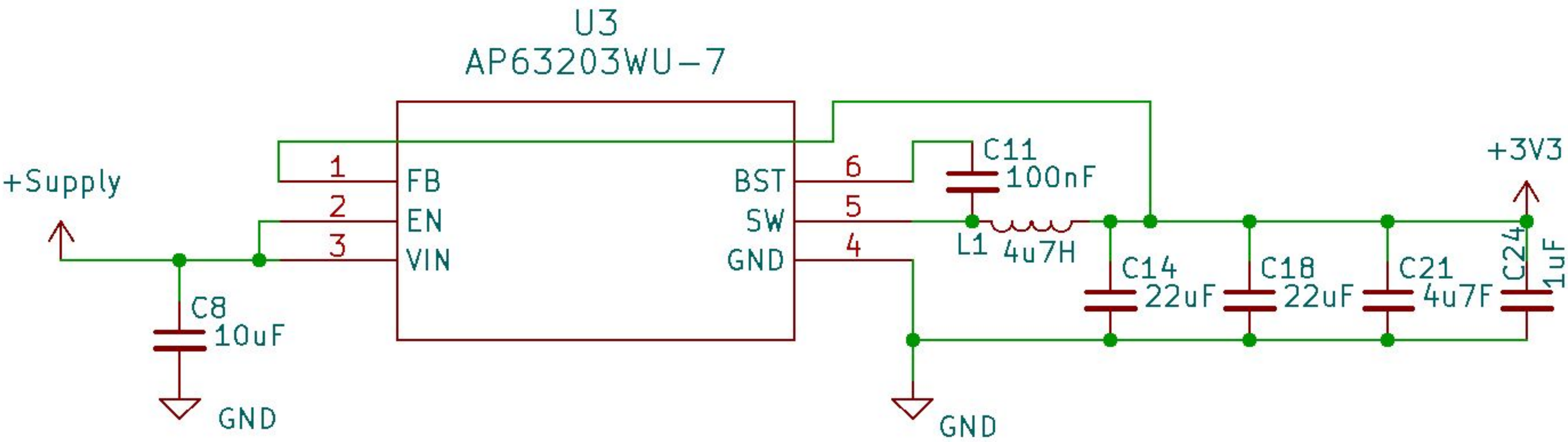
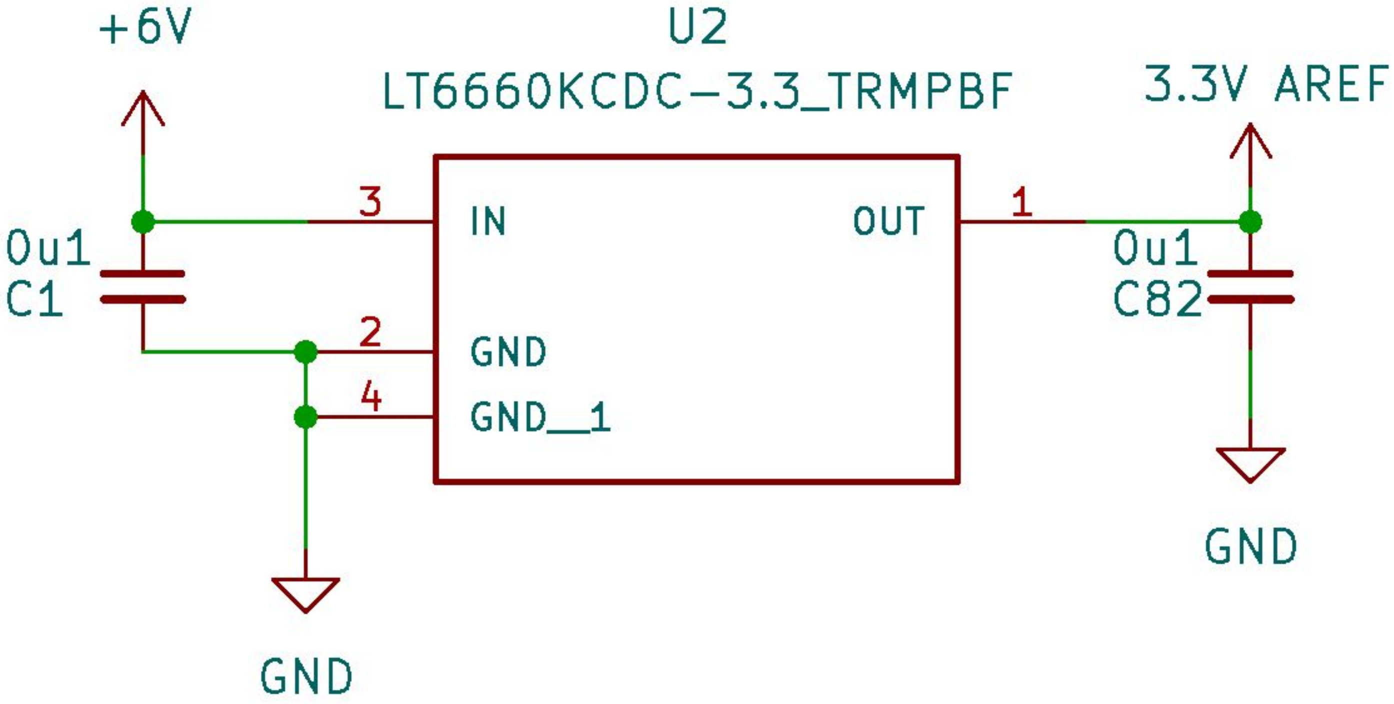
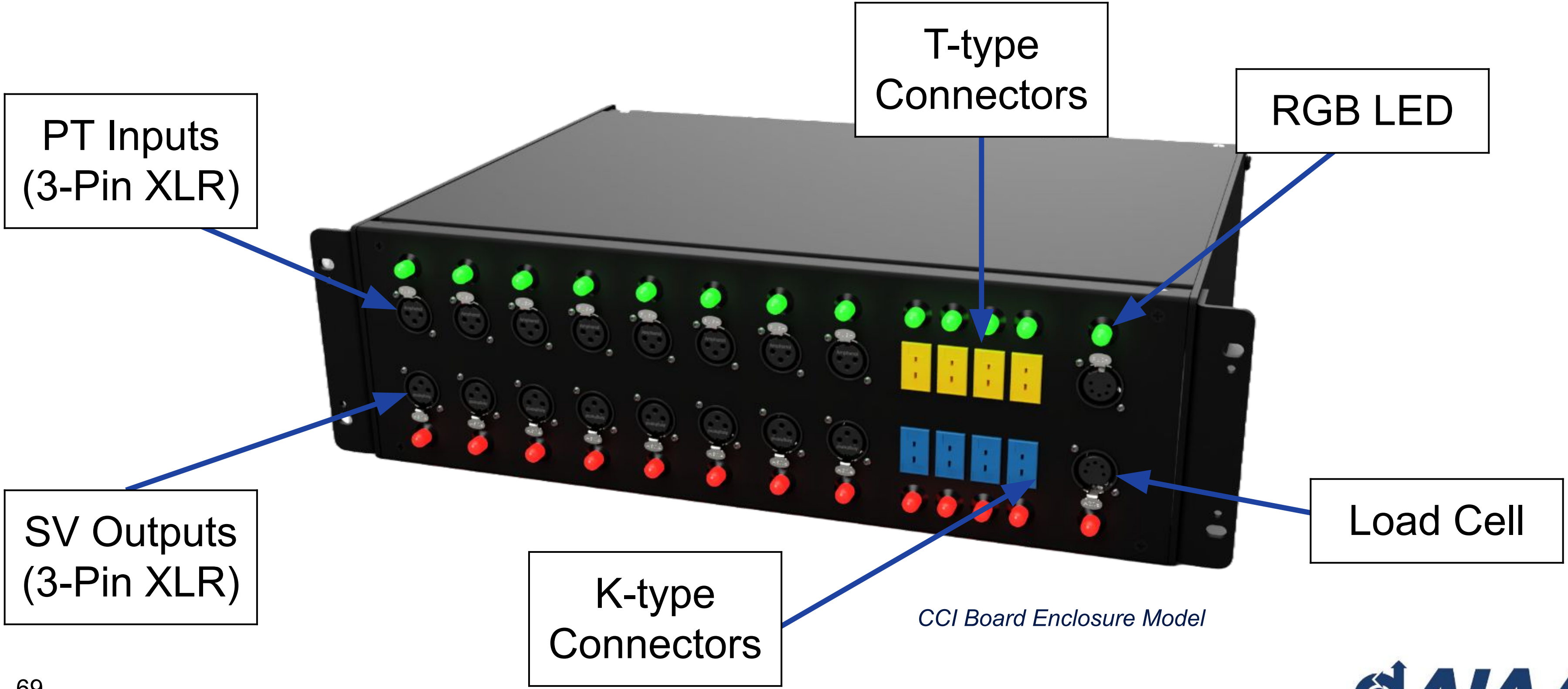
CCI Board +3.3V Power Rail Supply



CCI Board +3.3V$_{ref}$ Power Rail Supply



CCI Board Enclosure

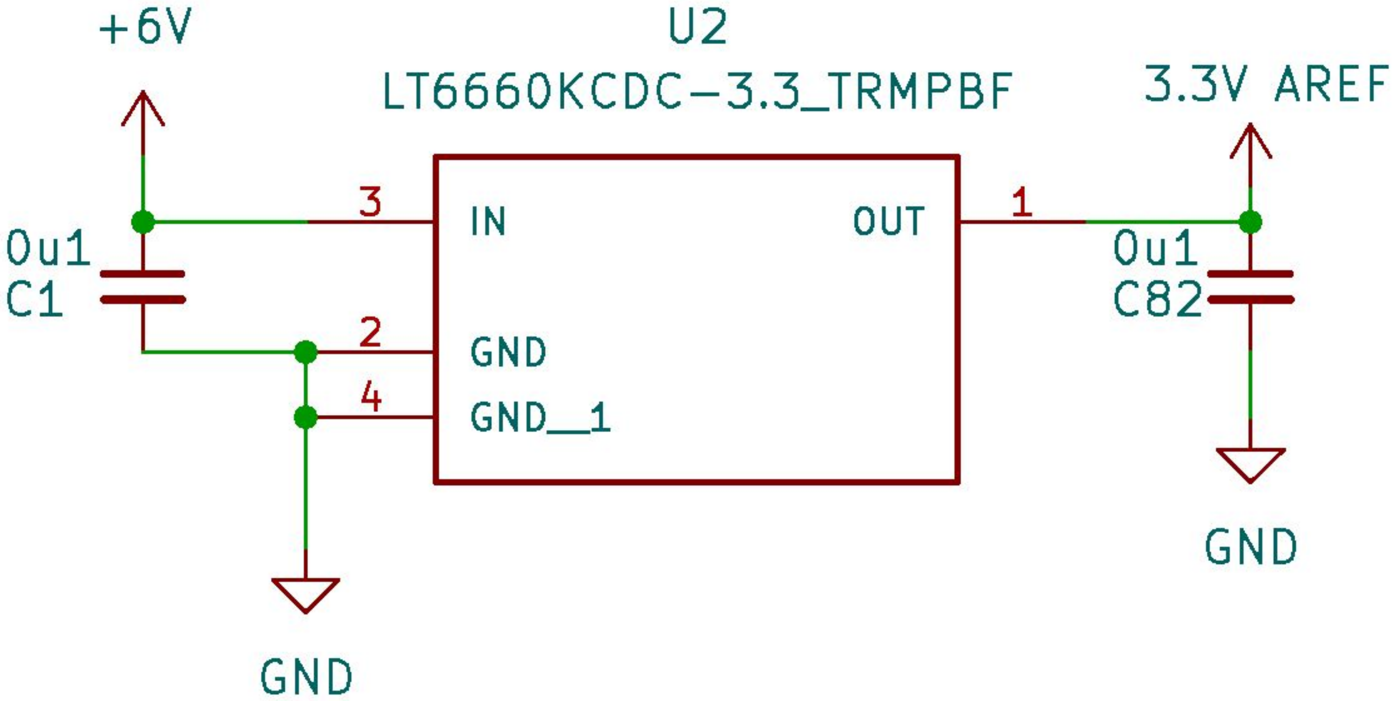


CCI Board Enclosure Model

Pressure

$$PSI = (0.01967)(ADC) - 250$$

CCI Board +3.3V$_{ref}$ Power Rail Supply



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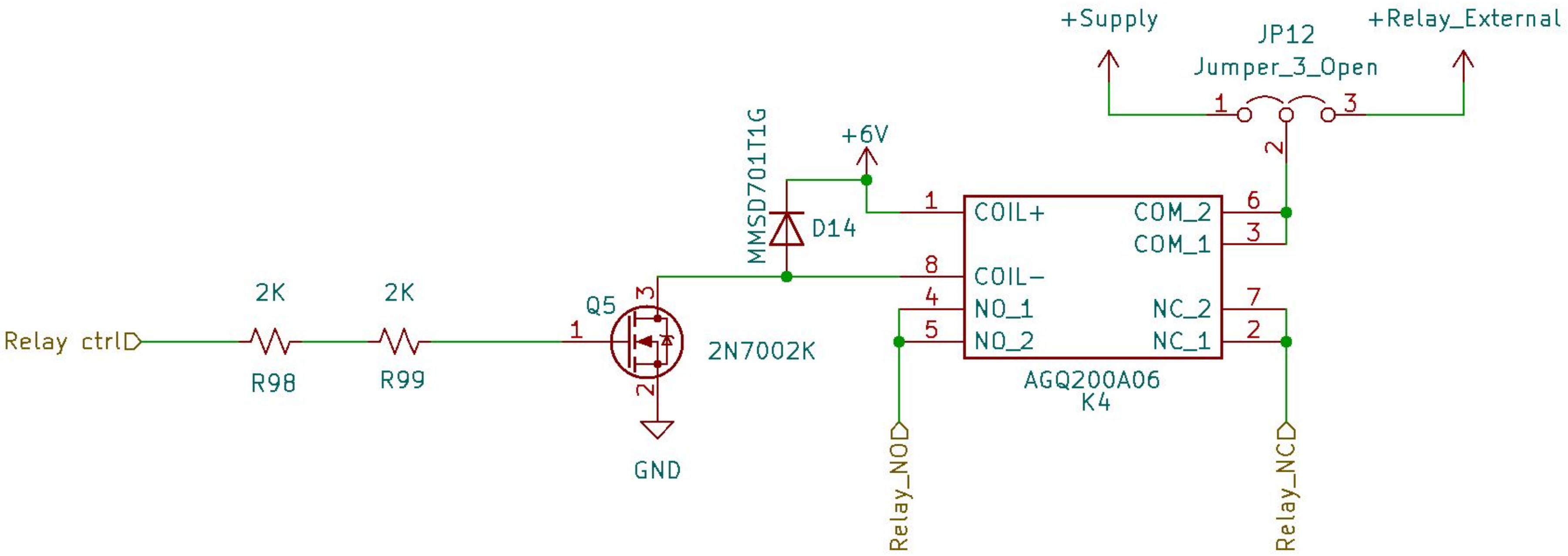
Solenoid Valves Control

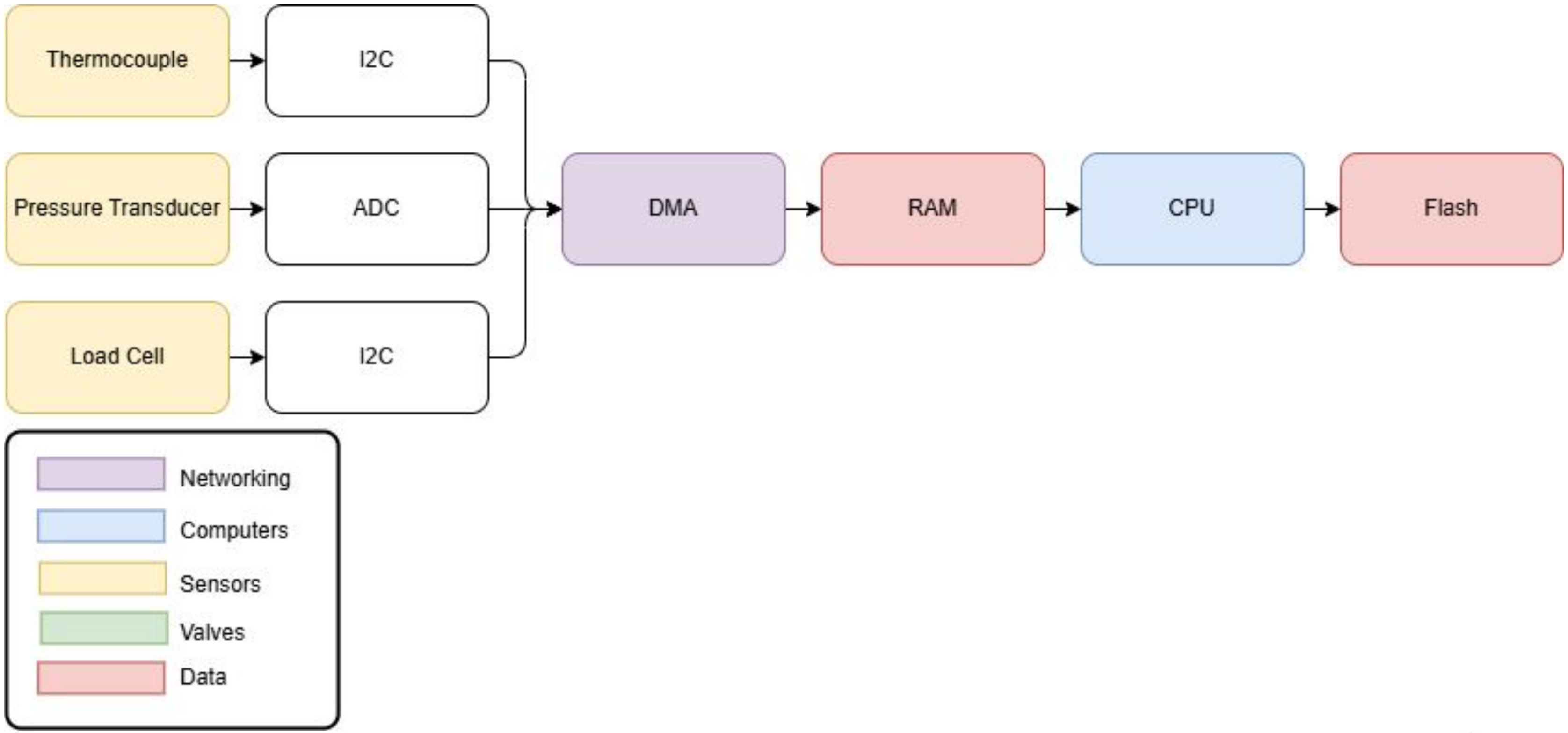
- Actuate up to 8 SVs
- Each SV channel can handle up to 2A at 30V
- Each valve has a limit switch to detect its actual position

Image Credit: AVCO, TEMCo

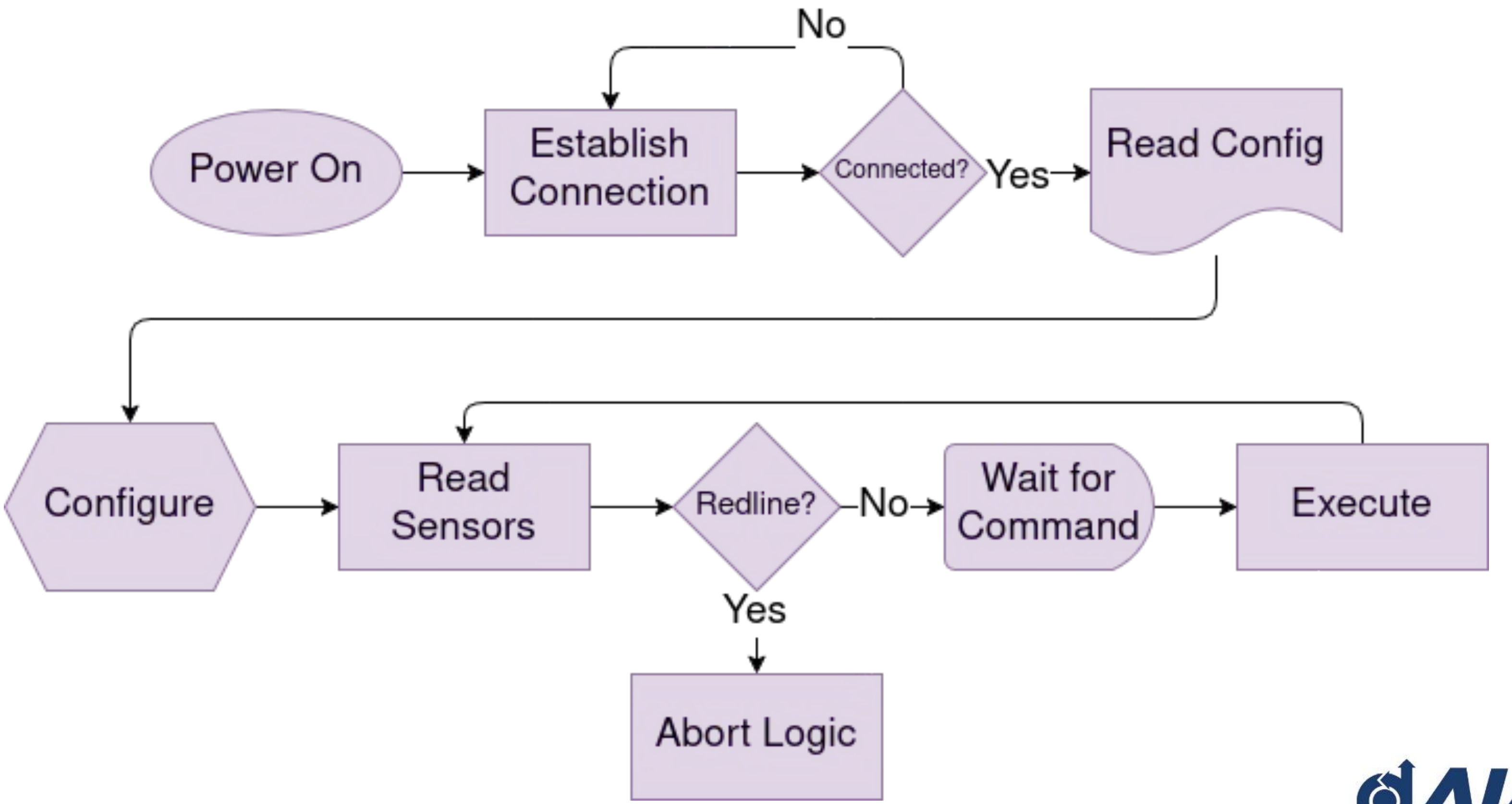
Solenoid Valve Control Schematic



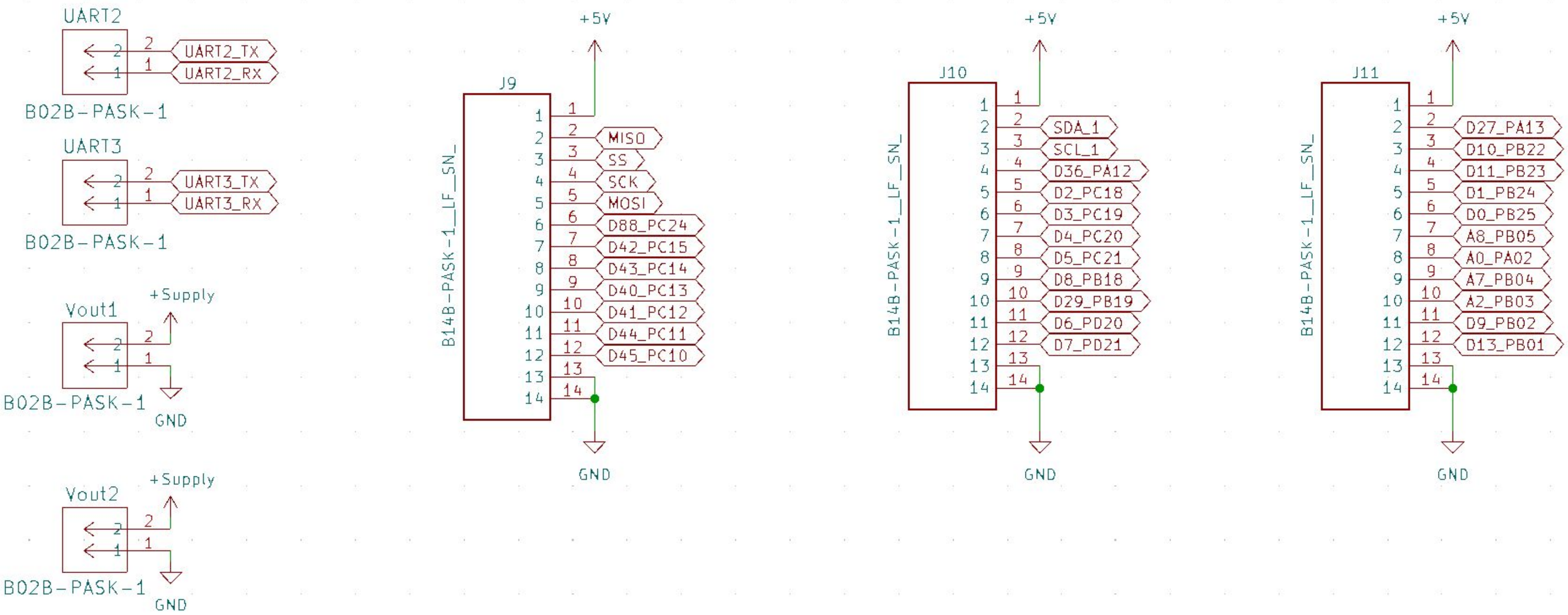
Direct Memory Access



CCI Board Software Flowchart



Future Expandability



Base Station Desktop

- Intel NUC7i7BNH
- Displays GUI
- Runs Base Station backend software
- Displays all live camera feeds to monitors

Image Credit: Intel

Base Station Setup

2x ASUS VE278

Dell P2417H

Image Credit: ASUS, Dell

Base Station Monitors

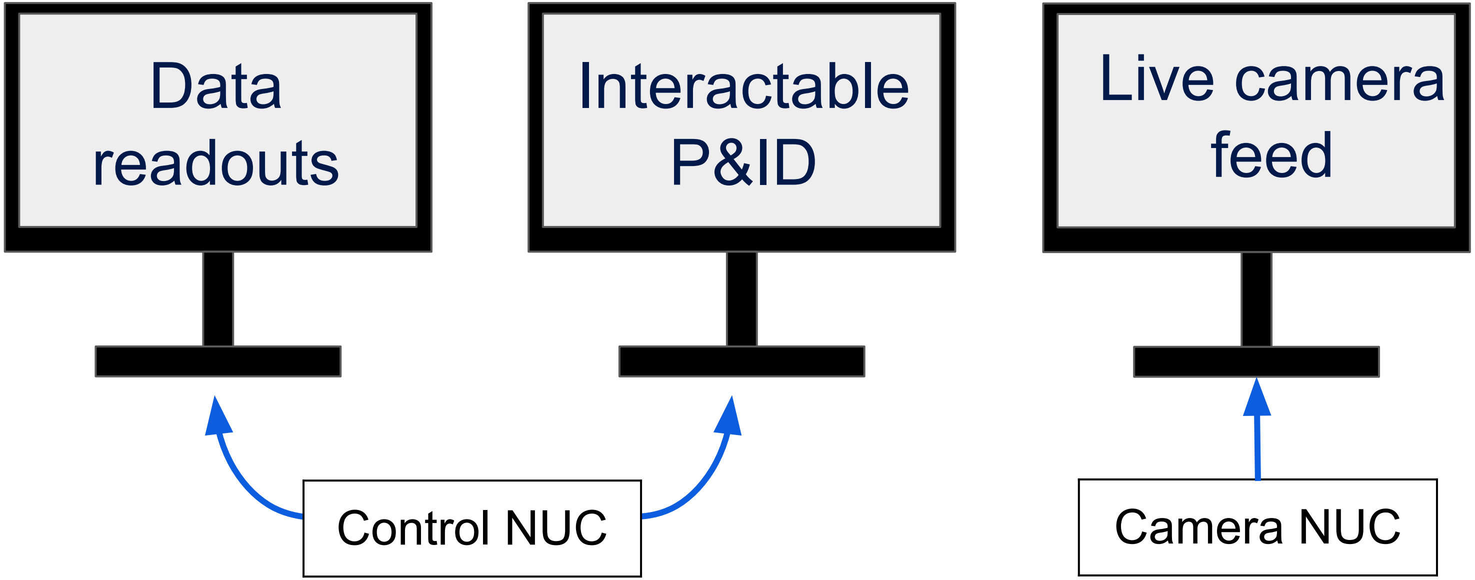


Image Credit: ASUS, Dell

TEMCo PV0173:

- Working Pressure: 21.76 to 116 psi
- Maximum Pressure: 174 psi
- Voltage: 24 VDC
- Operating Temperature: -5 to 60 C

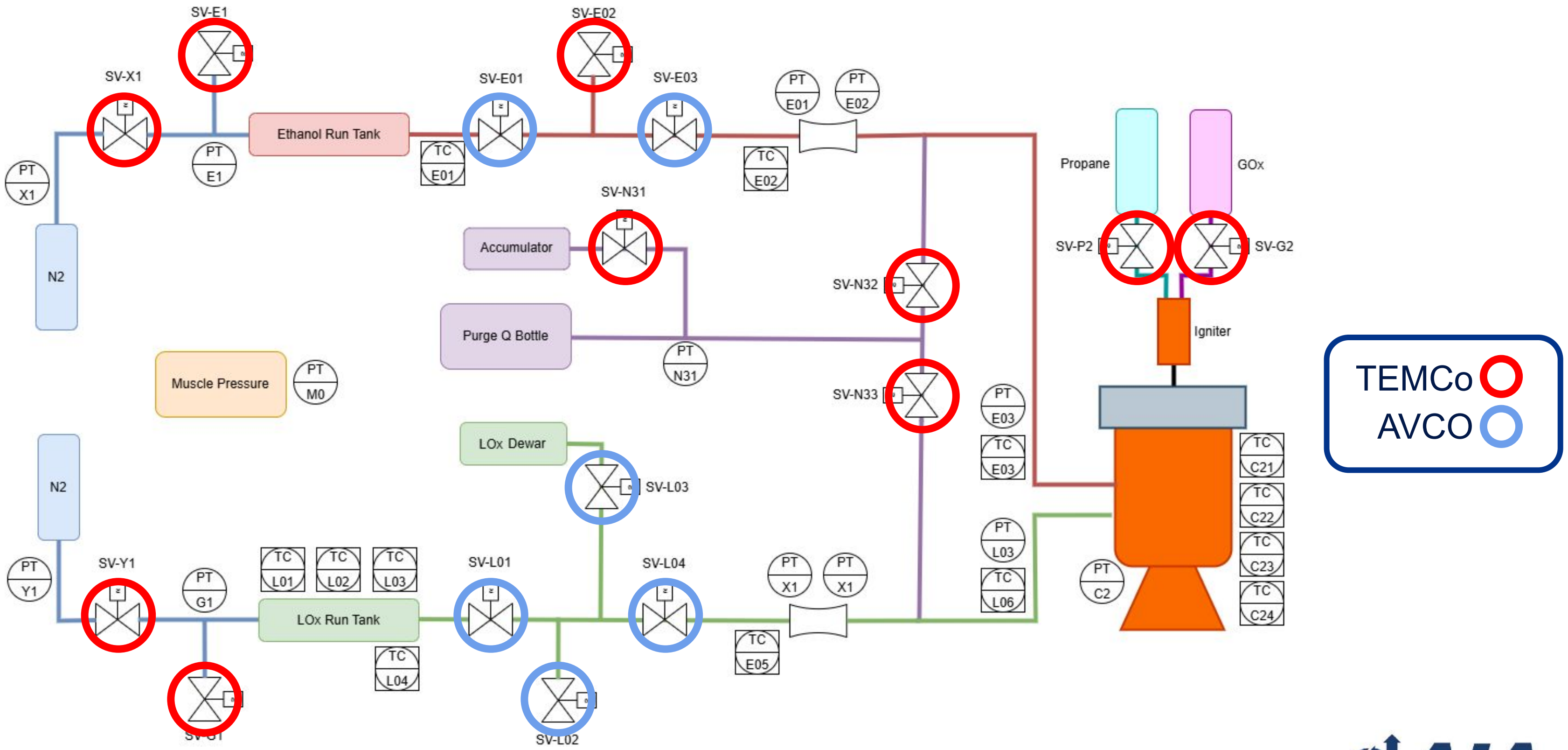
Image Credit: TEMCo

AVCO Solenoid Valves:

- Working Pressure: 35 to 150 psi
- Maximum Pressure: 150 psi
- Voltage: 24 VDC
- Operating Temperature: -17 to 82 C

Image Credit: AVCO

Solenoid Valve Locations



Pressure Transducer Specs

TE Connectivity M3041-000005-01KPG:

- Operating Pressure: 1000 psi
- Burst Pressure: 5000 psi
- Supply Voltage: 10 - 30V
- Operating Temperature: -20 to 85 C

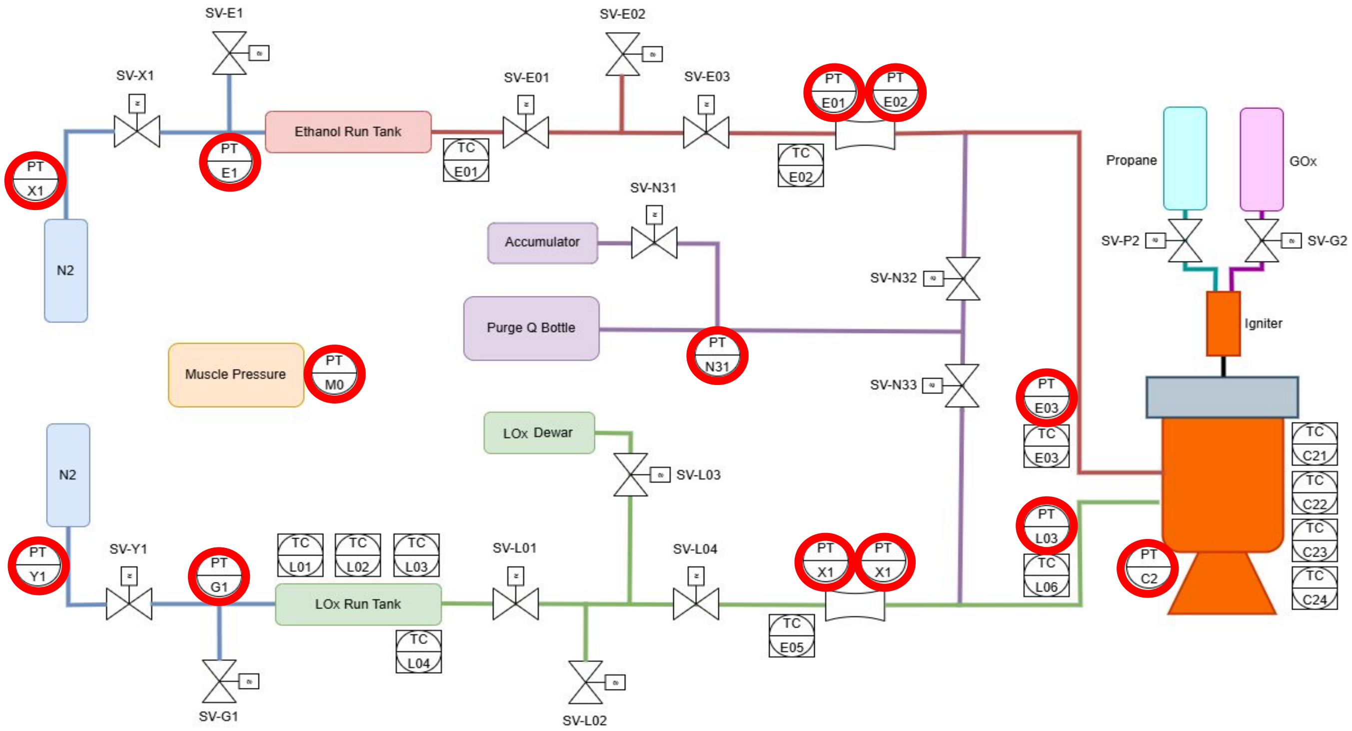
Image Credit: TE Connectivity

PT Protection from Cryogenic LOx

- Cryogenic LOx Temp -183 C.
- PT minimum rated temperature: -20 C
- Thin layer of Krytox GPL201 grease on the internal disk that contacts the liquid oxygen

Image Credit: Krytox

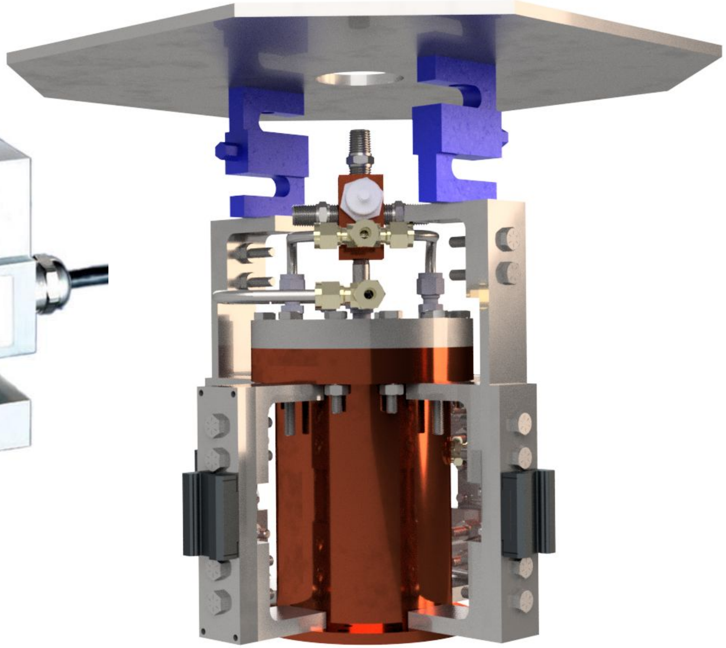
PT Locations



Load Cell Specs

SBA-300LB-I:

- Load capacity: 300lbs
- Safe overload: 150%
- Supply Voltage: 10 - 15V
- Operating Temperature: -10 to 40 C



Engine Cage Load Cell Model

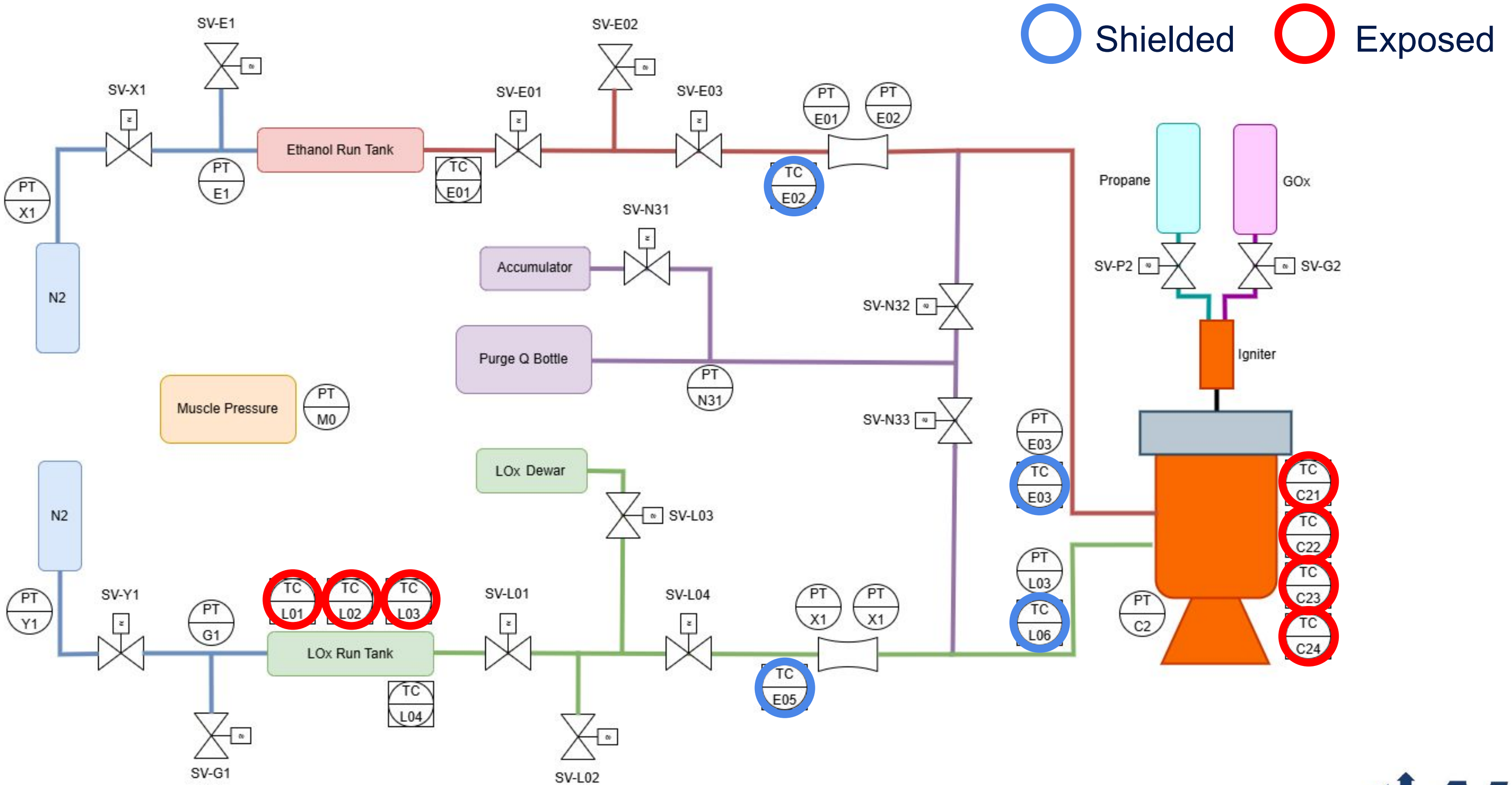
Image Credit: Scales plus

Thermocouple Specs Specs

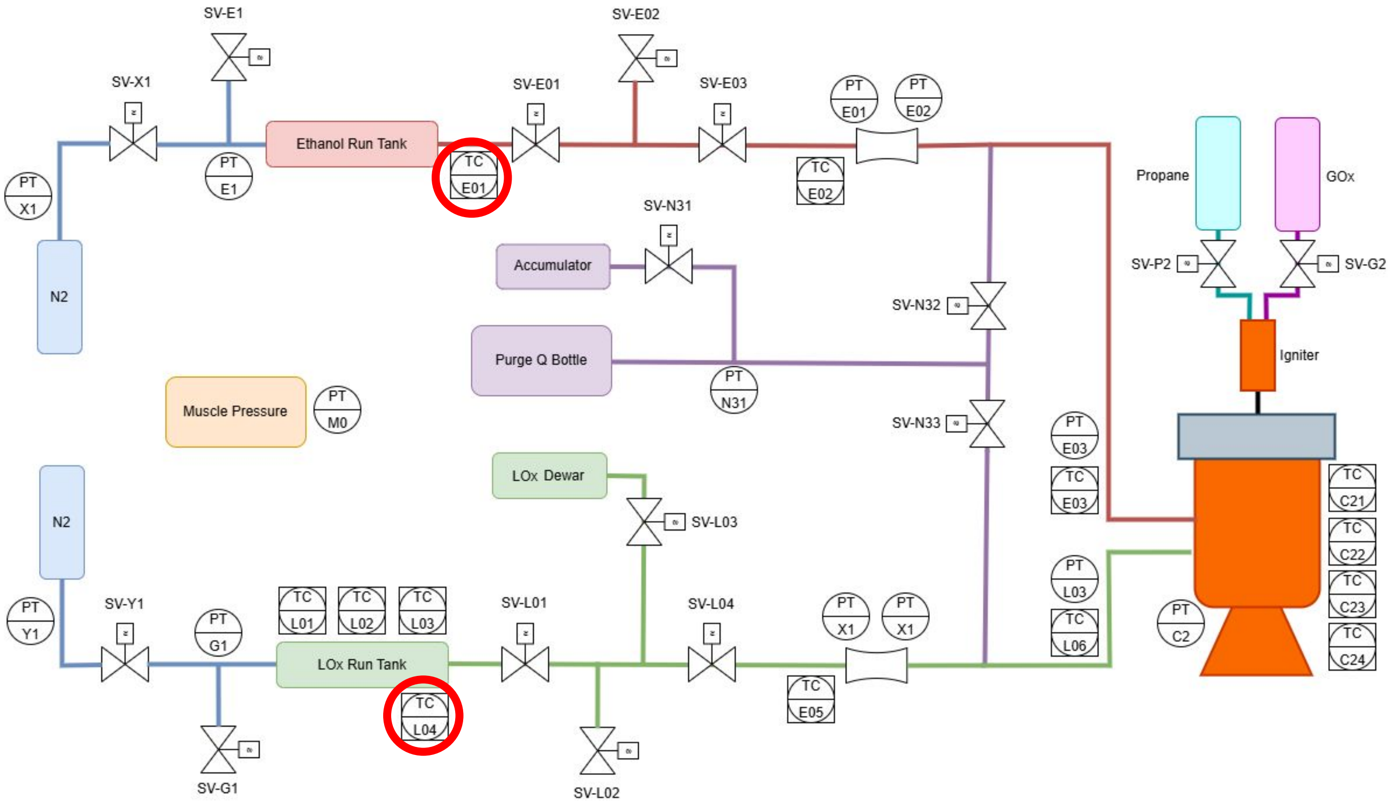
- K-type: Omega KMTXL-062E-6
  - Max temp: 1338 C
- K-type: Omega KMQXL-062G-12
  - Max temp: 1338 C
- T-type: Omega TC-T-1/8NPT-G-72
  - Max temp: 650 C

Image Credit: Omega

TC Locations (K-Type)



TC Locations (T-Type)



Lorex H13

- Resolution of 4K
- Works over IP
- 108 degree field of view

Image Credit: Lorex

GoPro Hero 6/8

- Hero 6
  - 1080p resolution, 240 frames per second
  - 47 minutes of battery life
- Hero 8
  - 4K resolution, 60 frames per second
  - 86 minutes of battery life

Image Credit: GoPro

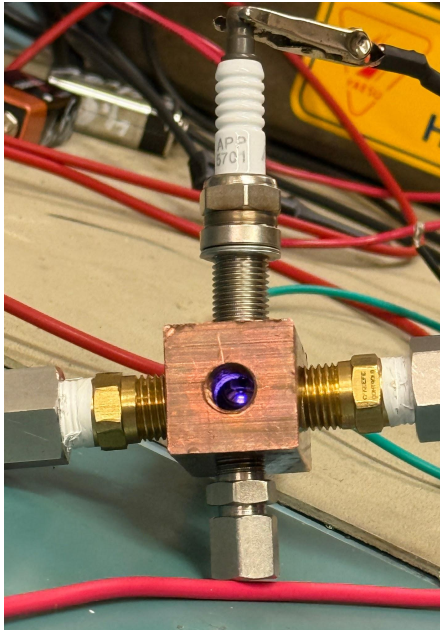
Runcam 5 Orange

- 4K resolution at 30 frames per second
- 2.7K resolution at 60 frames per second
- 105 minutes of battery life

Image Credit: Runcam

Igniter Spark Plug and Coil

- Powered by automotive grade ignition coil
- Receives power from 4 3V 123A batteries in a battery pack
- Actuated via relay controlled by physical switch at base station



Igniter Prototype Assembly

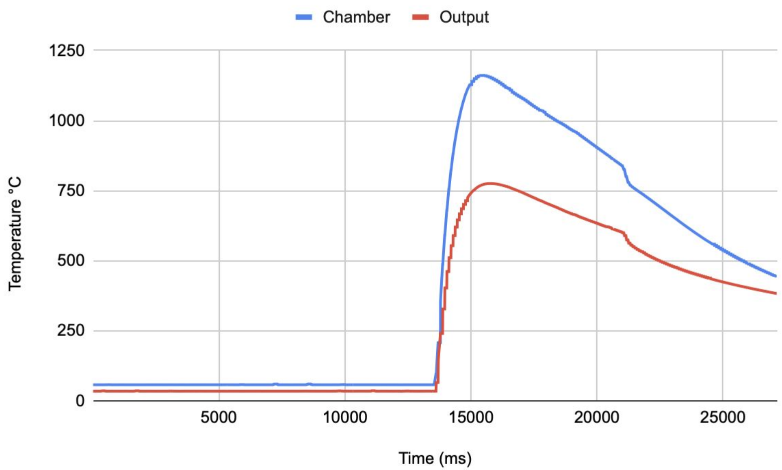
Igniter Enclosure

- Circuitry held within DSE HI Box NE-OOO-1515
- Ignition coil mounted inside
- Entire box then mounted to the back of the ETS

Igniter Box

Igniter Test

- Verified ignition temperature
- Verified ignition control system
- Verified data collection methods



Igniter Test Data

Languages

- Fast and well-supported
- Ease of development

Development Environments

Arduino IDE | **PyCharm CE** | **Microchip Studio**

Image Credit: Arduino, JetBrains, Microchip

Data Collection Test

- Validate the reliability of data collection and processing
- Validate data collection and processing speeds

Long Distance Communication Test

- Verify the reliability of using Ethernet cable and Ethernet repeaters at the required minimum safe distance of 500ft from the ETS

System Set Up Test

- Verify that the system can be efficiently assembled and disassembled.

Integrated Tests

- Low pressure injector test
  - Validate and calculate discharge coefficient of initially machined injector
- Igniter test
  - Verify that our torch igniter reaches 1522K

Integrated Tests

- Venturimeter flow test
  - Verify venturimeter design, the ability to obtain accurate data
- Low pressure leak test
  - Verify that all fittings are connected properly

Integrated Tests

- Water flow test - no injector
  - Verify pressure losses throughout the fluids system
- Water flow test - with injector
  - Verify pressure losses throughout system and discharge coefficient

Integrated Tests

- High pressure water flow test
  - Verify system can operate under expected firing pressures.
- Cryogenic wet dress test
  - Practice standardized procedures to verify all personal are prepared for hotfire

Integrated Tests

- Hotfire
  - Final full system hot fire to verify *Prometheus* engine dynamics and performance of Mobile Test Stand System

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