SPECS

Specialized Propulsion Engine Control System

Critical Design Review

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Presentation Structure

Overview	Purpose and Objectives, Design Solution, CPE’s
Thrust Modification Electronics Communication	Design Requirements and their Satisfaction
Project Risks Verification and Validation	Iterated for each Design Requirement above
Project Planning	

Overview | Thrust Modification | Electronics | Comms | Risk | Verification & Validation | Plans

Overview

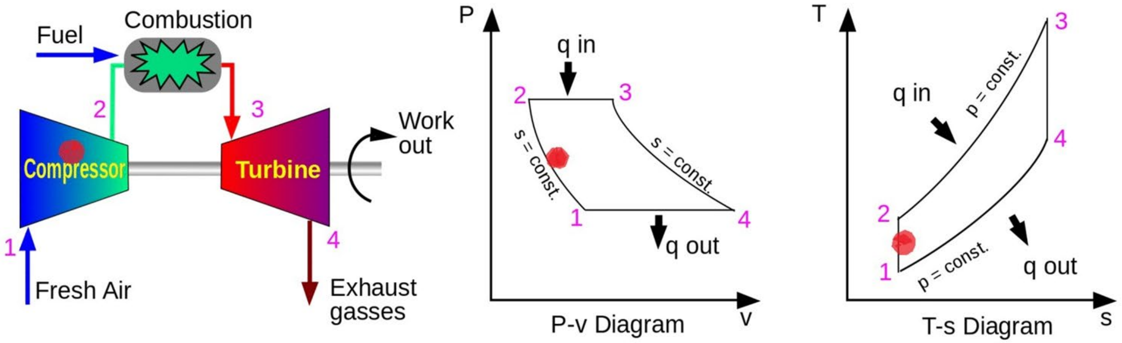
Problem Statement

- Increase Thrust-to-Weight (T/W) Ratio of the JetCat P90-RXi Engine
- The engine must run for an ‘extended period of time’ as defined by CONOPS

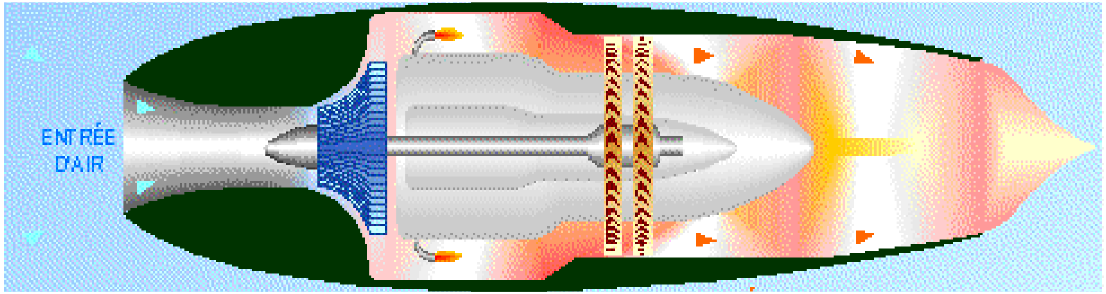
Motivation

- The United States Air Force (USAF) would like to implement a T/W increasing modification into their fleet of Unmanned Aerial Vehicles (UAV)
- Ideal solution would be low cost and easy to implement with minimal modification to existing engine

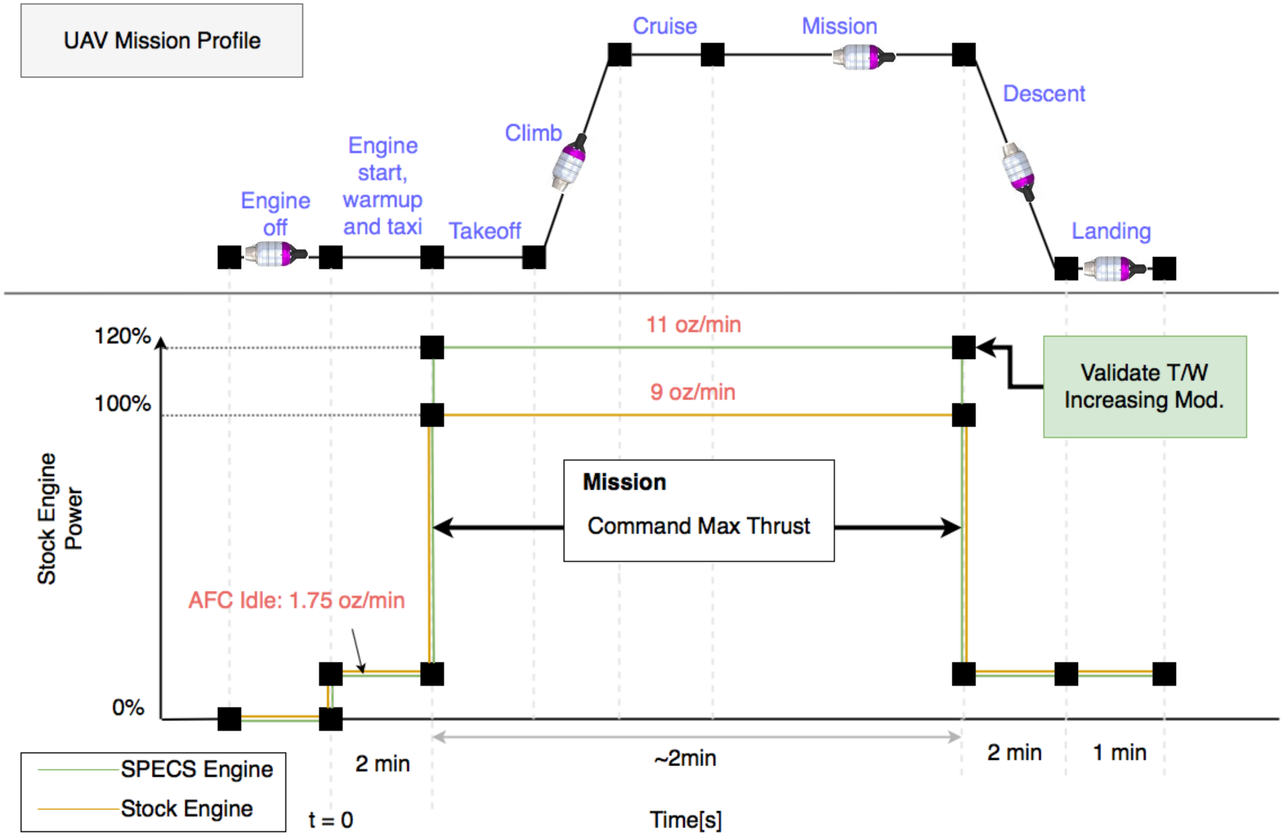
Basic Jet Engine Operation Refresher



Brayton Cycle for Jet Engine



Concept of Operations (Mission Profile)



Functional Requirements

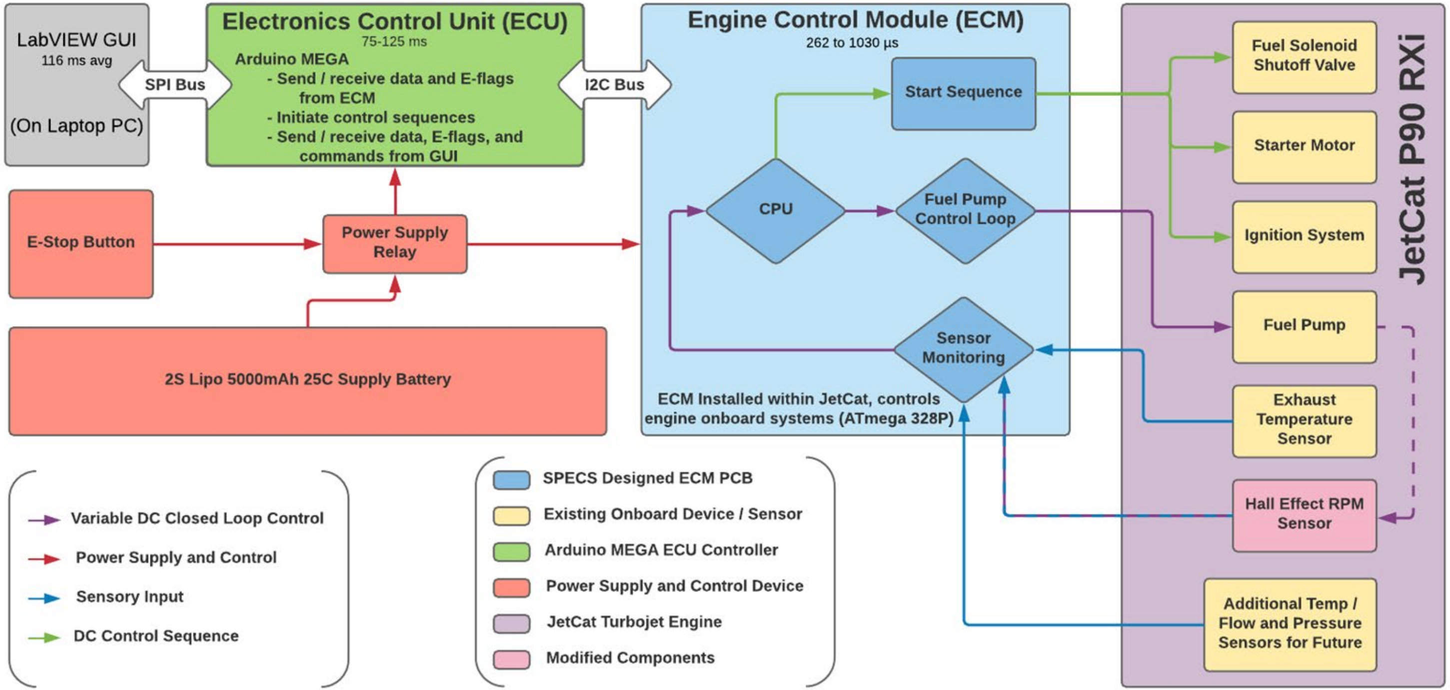
FR1 - The JetCat P90-RXi engine shall have an increased T/W ratio of 20% from stock parameters.

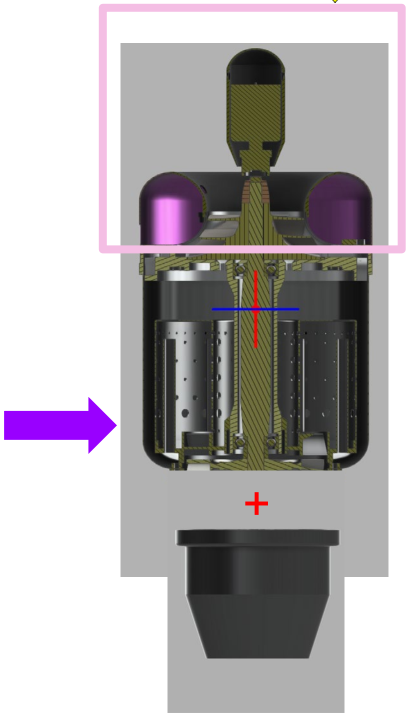
FR2 - SPECS shall control the engine over the entire operational envelope.

FR3 - SPECS shall run the engine in a manner which does not incur damage to property or personnel.

FR4 - SPECS shall have a user interface for engine control.

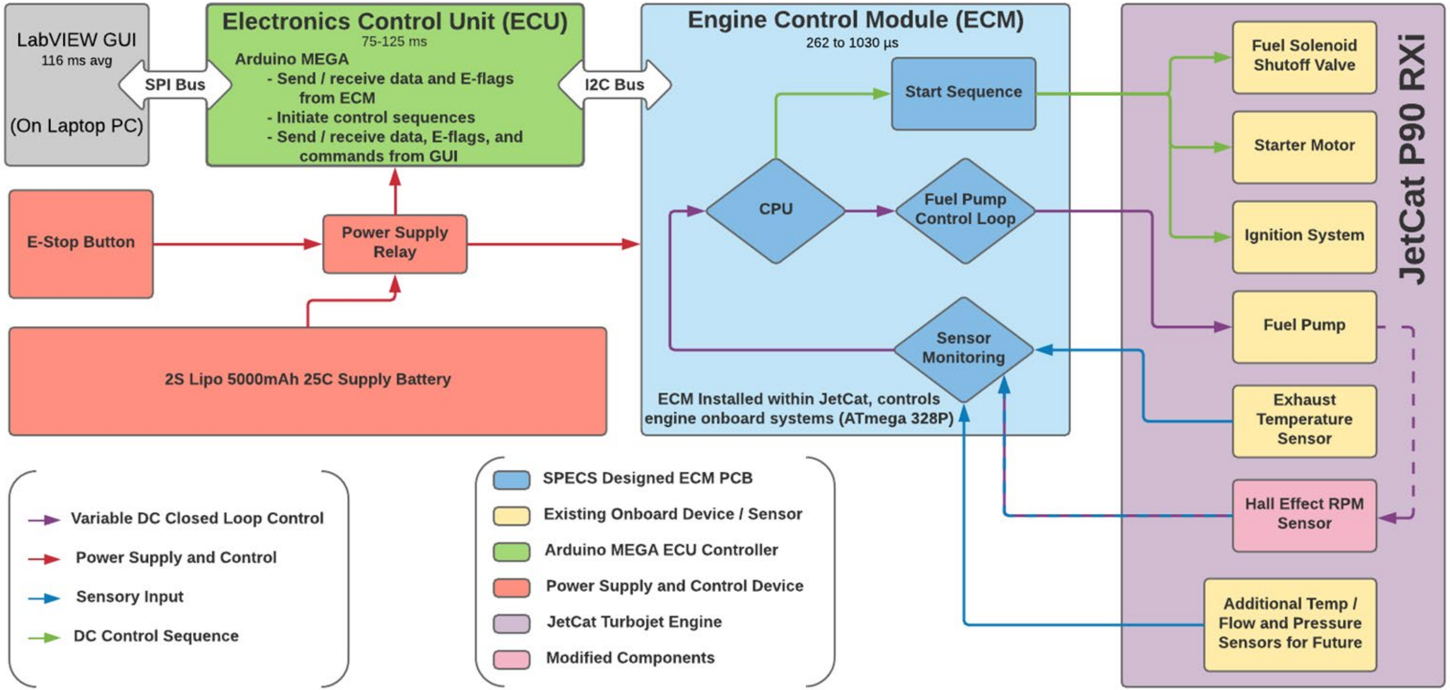
Functional Block Diagram

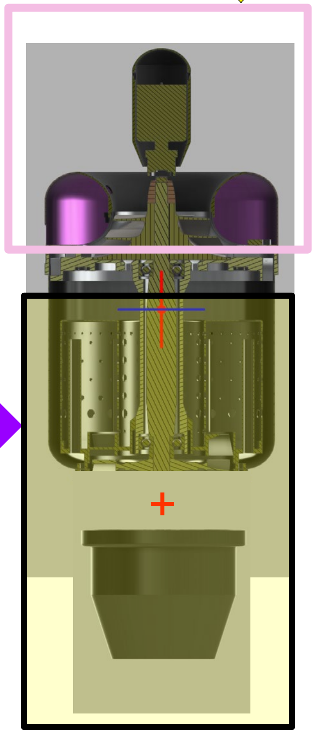




Thrust Improving Modification

Functional Block Diagram





Thrust Improving Modification

Thrust Improvement Modification (π_C)

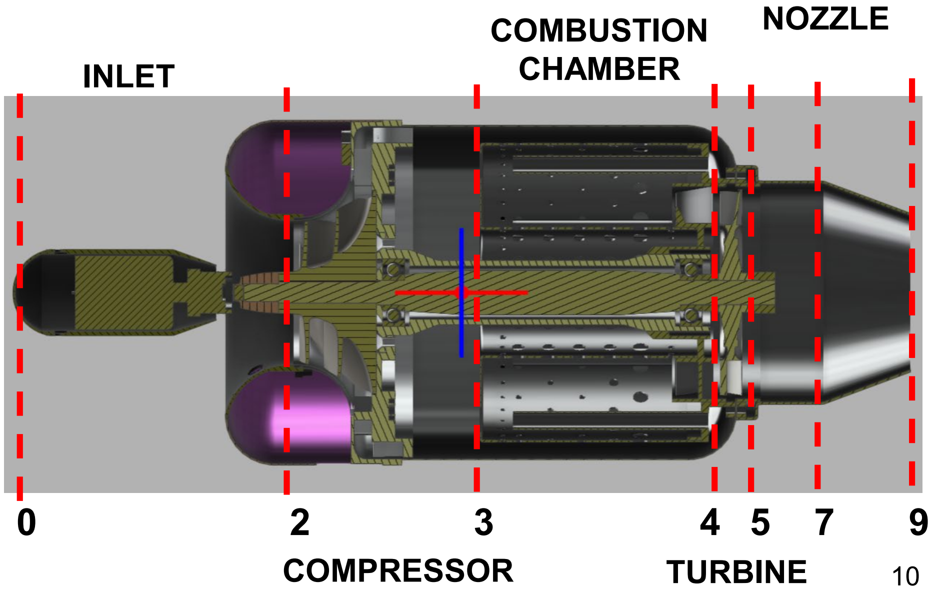
Major Design Elements: - Recharacterizing the JetCat Engine for 20% Thrust Improvement

- Increase RPM → Increase π_C → Increase Thrust

- New Nozzle to properly expand for new, higher π_C

	Thrust	π_C	KRPM
Stock	105 N	2.35	130
Improved	126 N	2.61	140

$$\pi_c = \frac{P_{t_3}}{P_{t_2}}$$



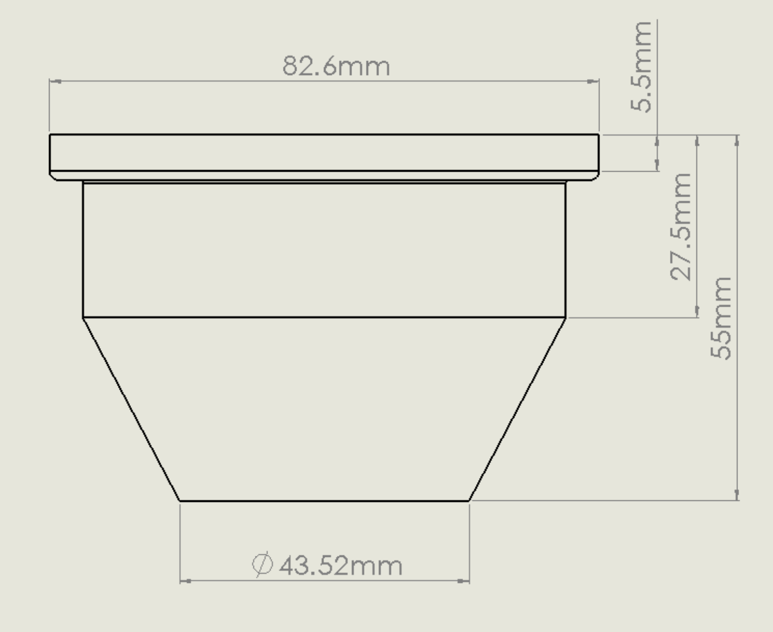
Thrust Improving Modification (Nozzle)

Major Design Elements: - Based on Stock Nozzle Design

- Exit area decreased to properly expand new nozzle pressure

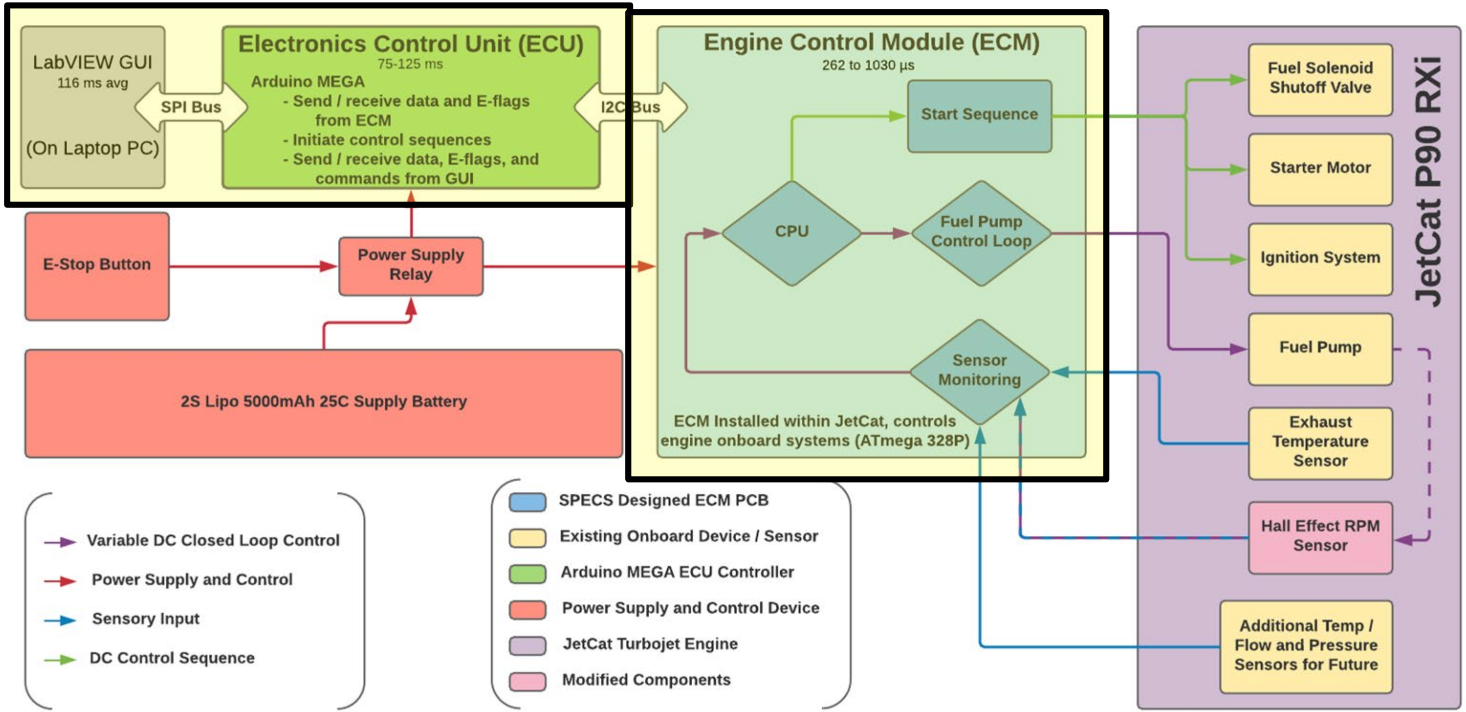
	Material	Weight	Thermal Expansion
Stock	Inconel 718	82.43 g	2.55 %
Improved	Ti 6AL-4V	47.78 g	1.62%

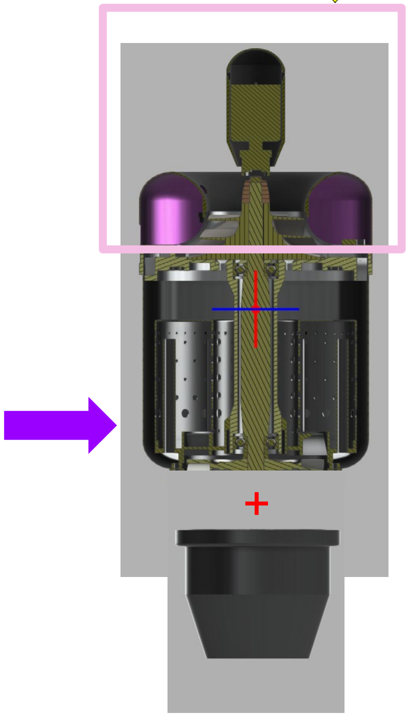
$$F = \dot{m}_0(V_9 - V_0) + (P_9 - P_0)A_9$$



Nozzle Drawing

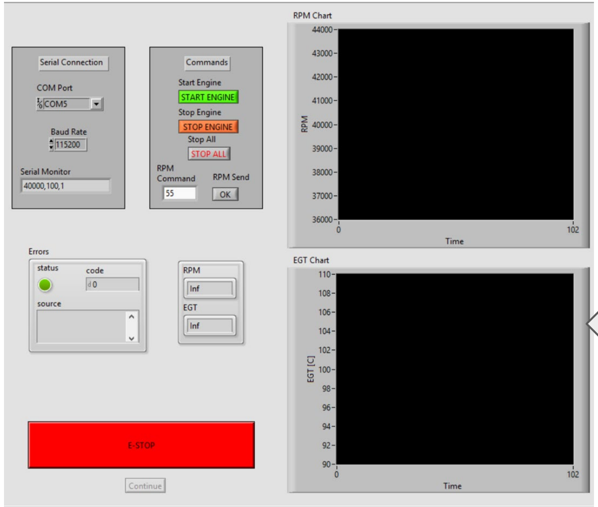
Functional Block Diagram





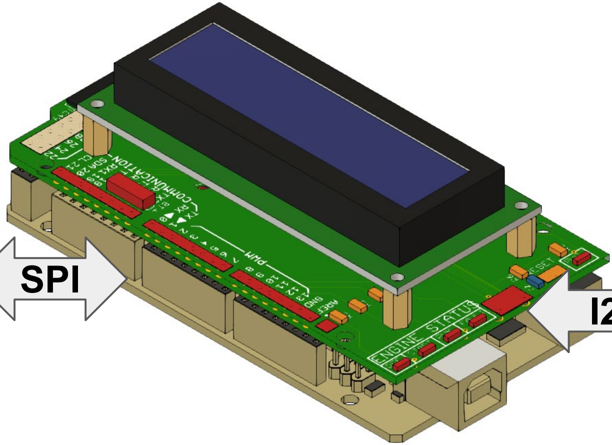
Thrust Improving Modification

Engine Electronics Assembly



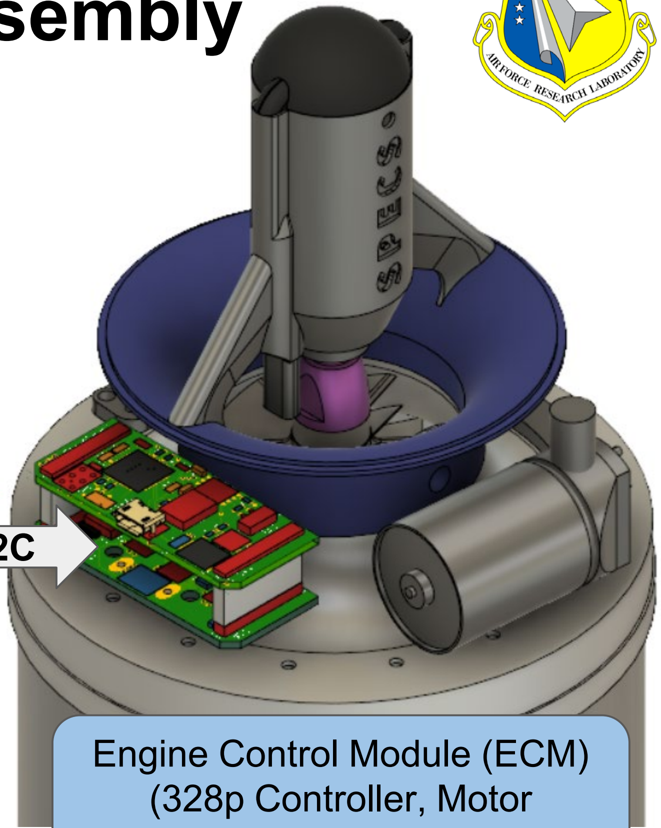
GUI Labview Module

SPI



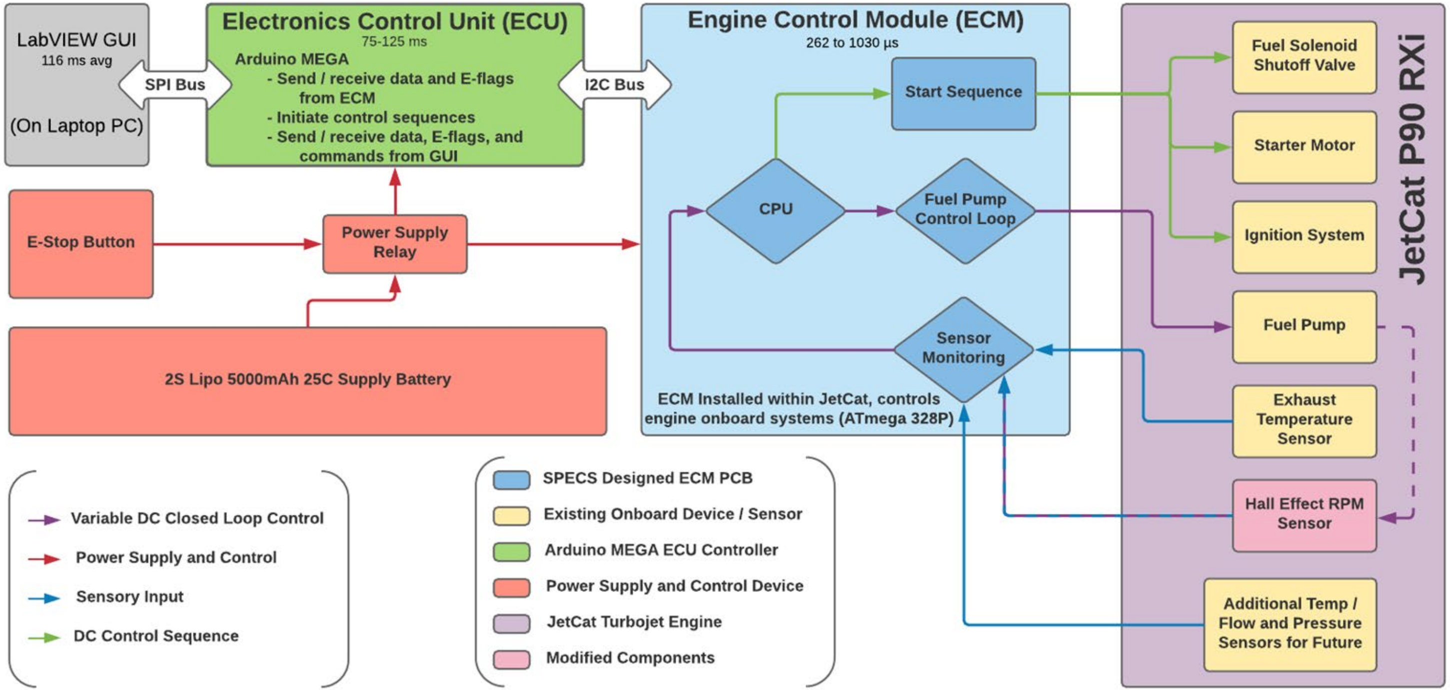
Electronics Control Unit (ECU) (Arduino Mega, Shield, LCD)

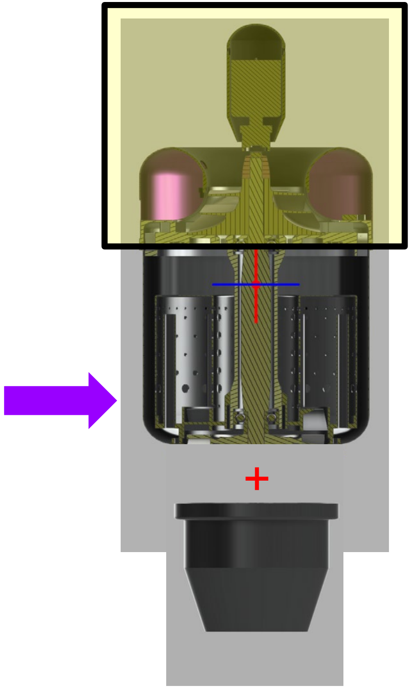
I2C



Engine Control Module (ECM) (328p Controller, Motor Controller)

Functional Block Diagram

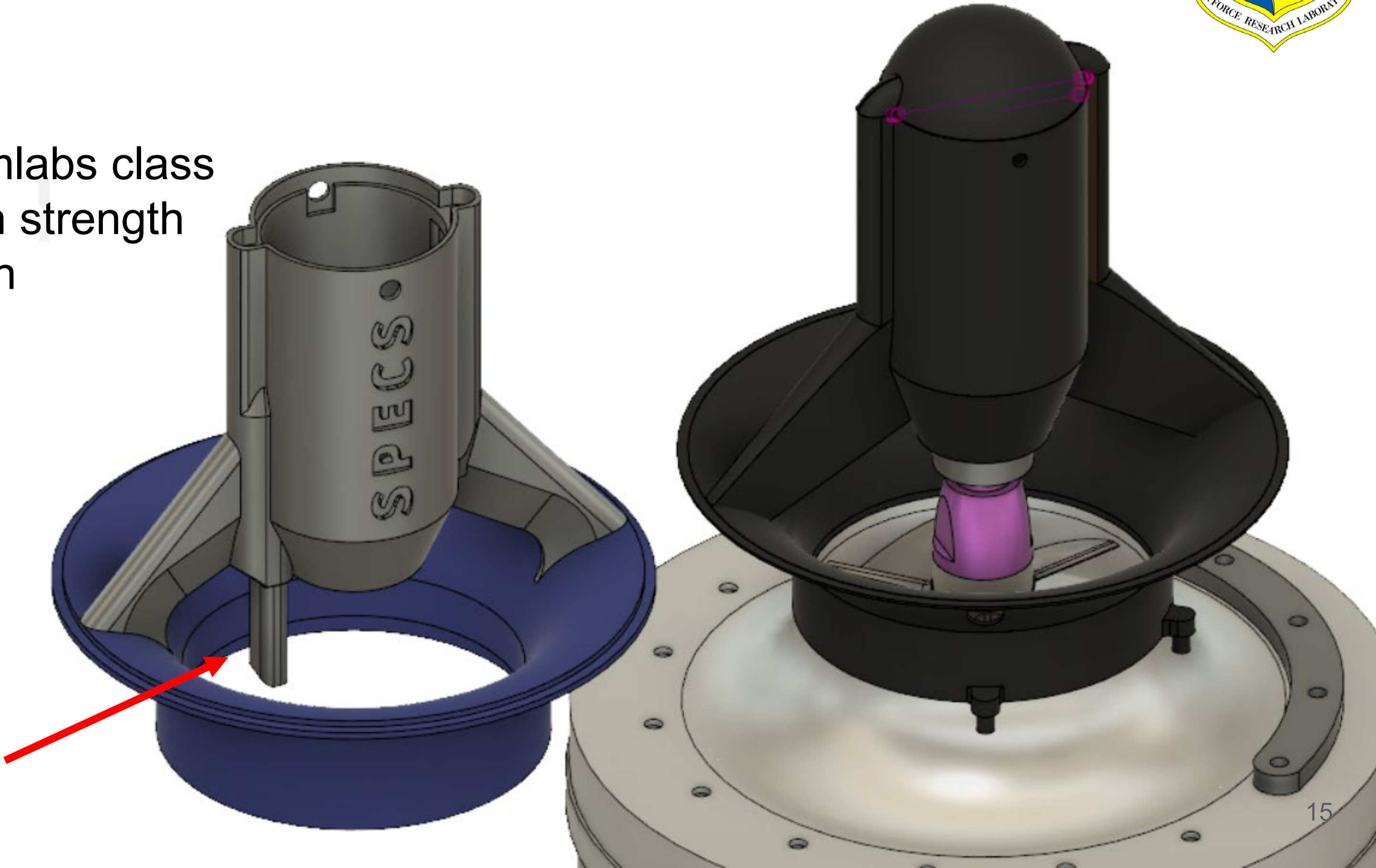




Thrust Improving Modification

Hall Effect Sensor and Inlet Design

Printed with Formlabs class printer using high strength FLGPBK04 Resin



New Hall Effect Sensor Location

Critical Project Elements

Designation	CPE	Critical Characteristics
CPE-1	Material Properties (Thrust Improvement Modification)	Thermodynamic and structural analysis require numerous assumptions on materials and operating conditions. Further analysis will **characterize and define risks**.
CPE-2.1	Engine Control Loop (ECM)	Control algorithms are inherently complex and require additional validation prior to implementation. Certification through the **use of an engine analog is necessary**.
CPE-2.2	Engine Sensors (ECM)	Coordination of engine sensor data acquisition with its utilization by the processor is critical. **Without accurate sensor data, the engine cannot safely operate**.
CPE-3	Communication from User to Engine (ECU)	During initial testing and product development user oversight will **verify safe operation and monitor for anomalies**.

Thrust Modification

Overview | Thrust Modification | Electronics | Comms | Risk | Verification & Validation | Plans

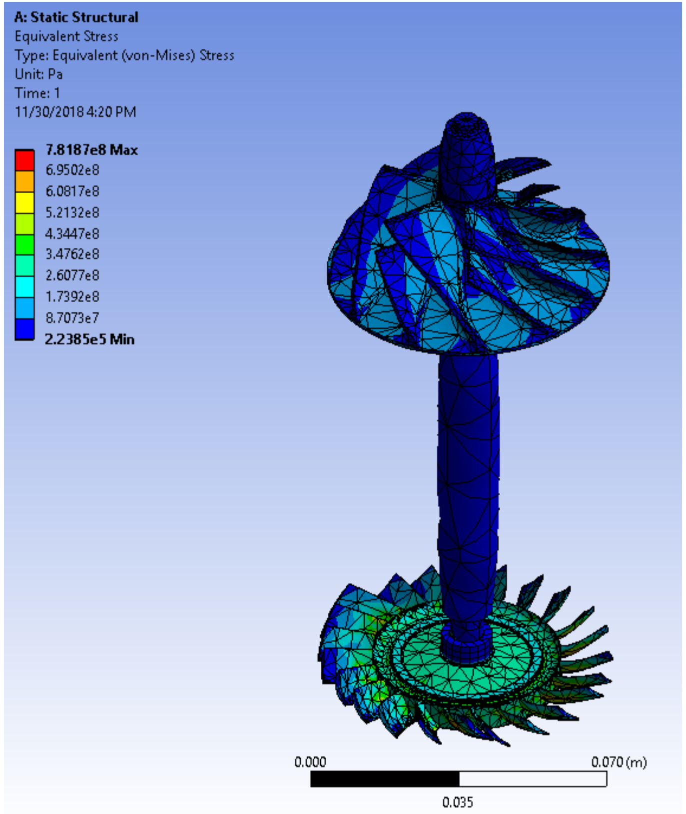
Design Requirements & Satisfaction

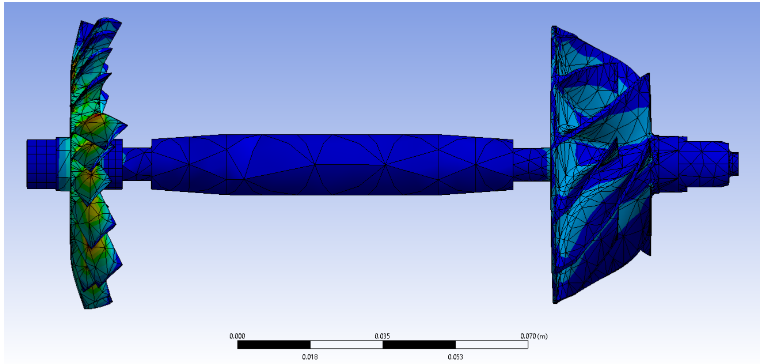
CPE-1: Material Properties (Thrust Improvement Modification)

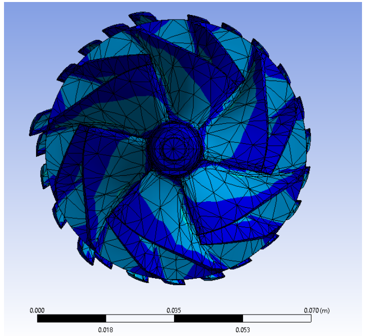
FR.1: The JetCat P90-RXi engine shall have an **increased T/W ratio of 20%** from stock parameters.

- DR 1.2: Any modifications to the engine will **not reduce the factor of safety of any engine component below 1.3** per USAR.

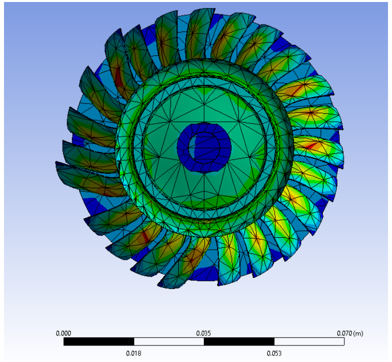
Shaft Assembly FEA







FEA consistent with conclusions drawn from prior calculations

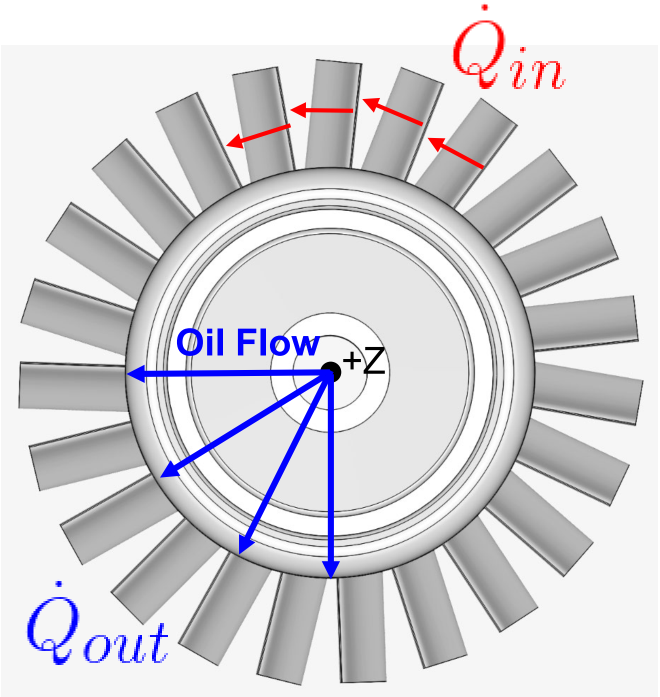


Thermomechanical Turbine Analysis

<u>Goal:</u> Determine the increase in stress on the turbine due to the higher RPM and temperature through thermomechanical simulation (FEA).

<u>Boundary Conditions:</u>

1. Convective heat flux into turbine due to high velocity gas seen by the blades (h = 1653 W/m²-K)
2. Surface heat flux out of turbine due to flow of cooling oil ($\dot{q}$= -155,000 W/m²)
3. Centrifugal force applied everywhere due to angular velocity about the +Z-axis



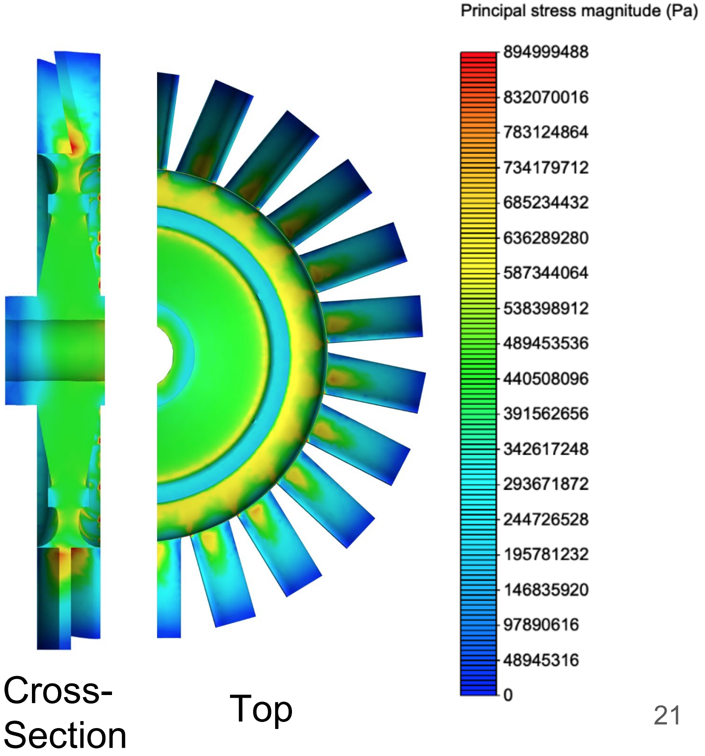
JetCat Turbine Model
Top View

Thermomechanical Turbine Analysis

Results:

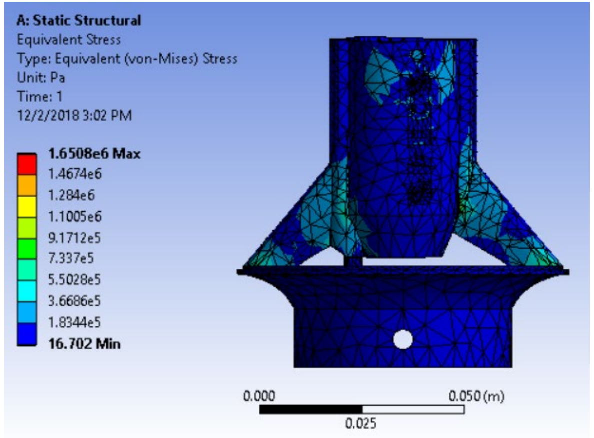
	T_0 [K]	ω [RPM]	Max stress [MPa]	Max temp [K]	S.F
Stock	963	130,000	807	869	1.5
Improved	1000	140,000	892	906	1.36

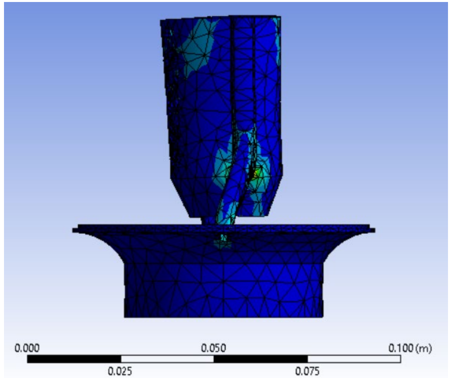
The thrust improvement can feasibly be made without damage to the engine since S.F is > 1.3 as required. (DR 1.2)

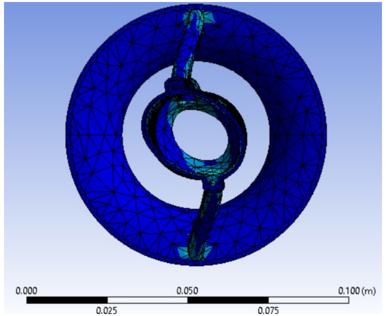


Inlet Re-design FEA

FLGPBK04 Resin	
Tensile Modulus	2.8 GPa
Shear Modulus	1.03 GPa
Bulk Modulus	3.11 GPa
Ultimate Tensile Strength	65 MPa
Poisson's Ratio	0.35
S.F.	39

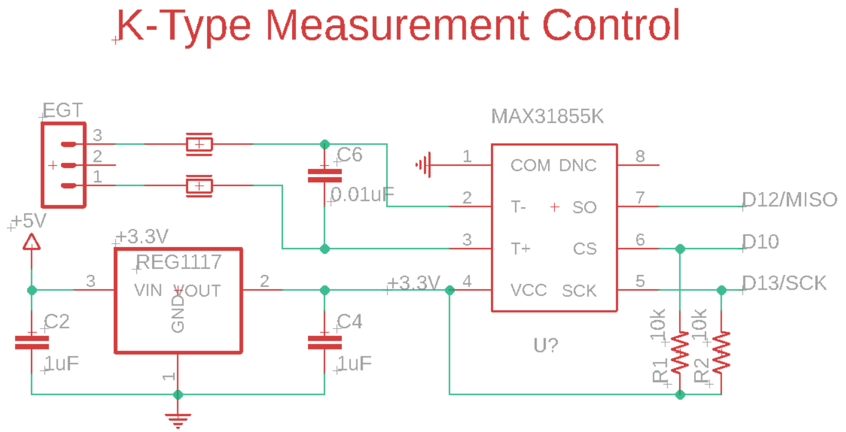






Electrical Circuits and Assemblies

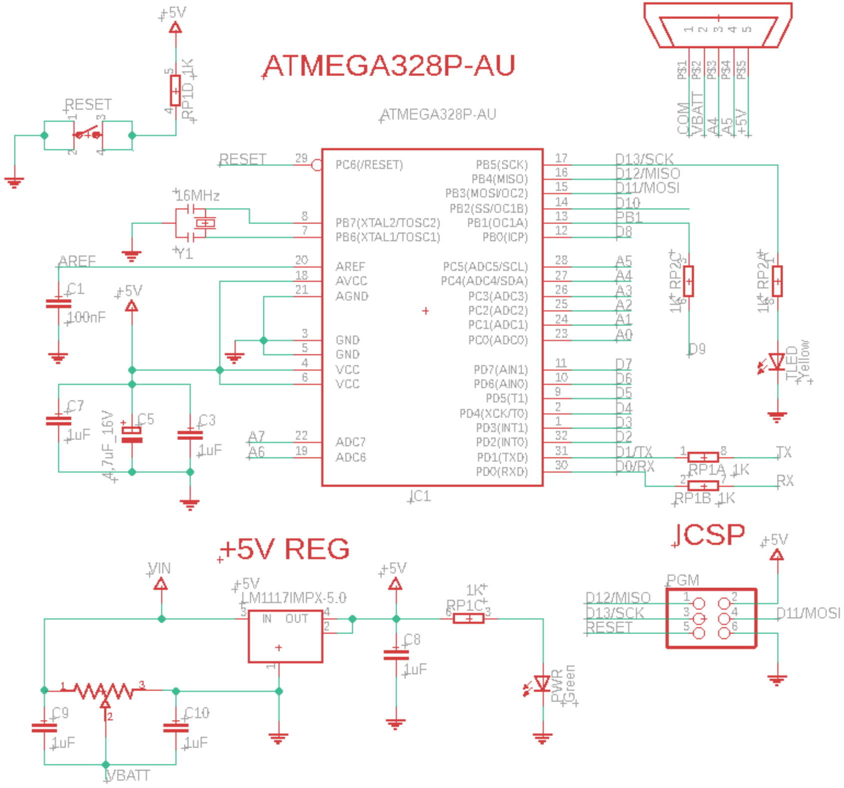
EGT Circuit

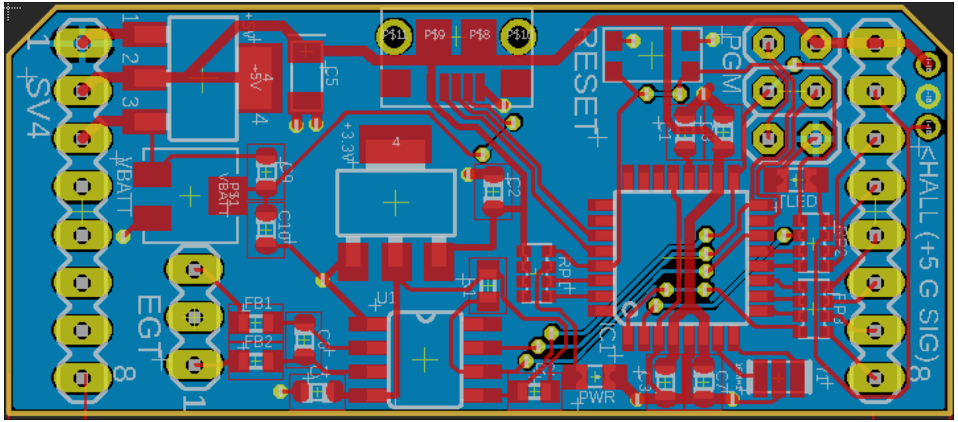


SPECS can accurately measure and transmit EGT temperature up to 730° C or above as needed. (DR 3.2)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
MAX31855K Thermocouple Temperature Gain and Offset Error (41.276µV/°C nominal sensitivity) (Note 4)		$T_{THERMOCOUPLE}$ = -200°C to +700°C, T_A = -20°C to +85°C (Note 3)	-2		+2	°C
		$T_{THERMOCOUPLE}$ = +700°C to +1350°C, T_A = -20°C to +85°C (Note 3)	-4		+4	
		$T_{THERMOCOUPLE}$ = -270°C to +1372°C, T_A = -40°C to +125°C (Note 3)	-6		+6	

ECM Control Board

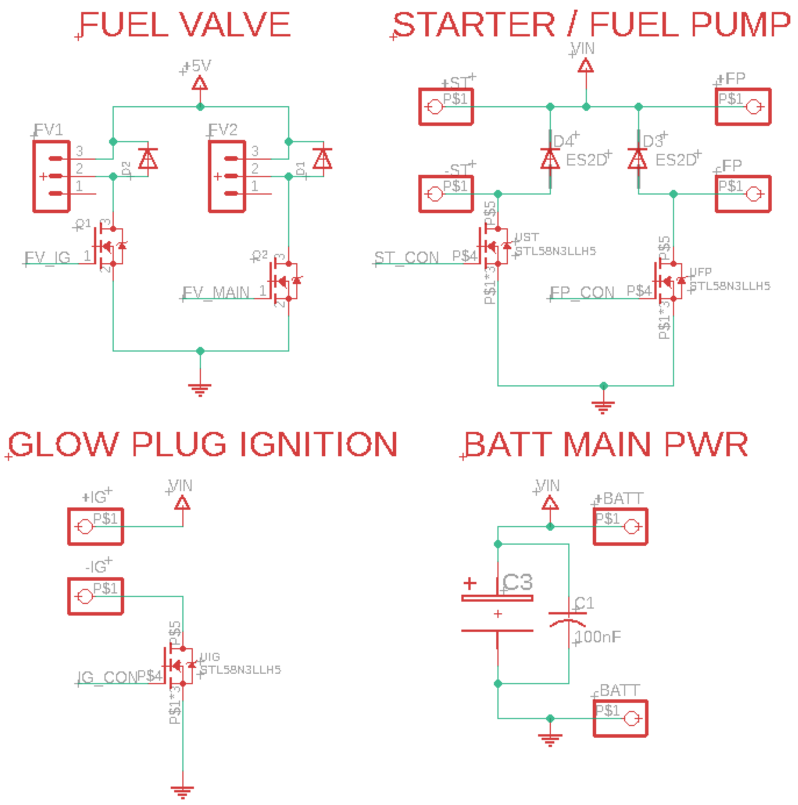


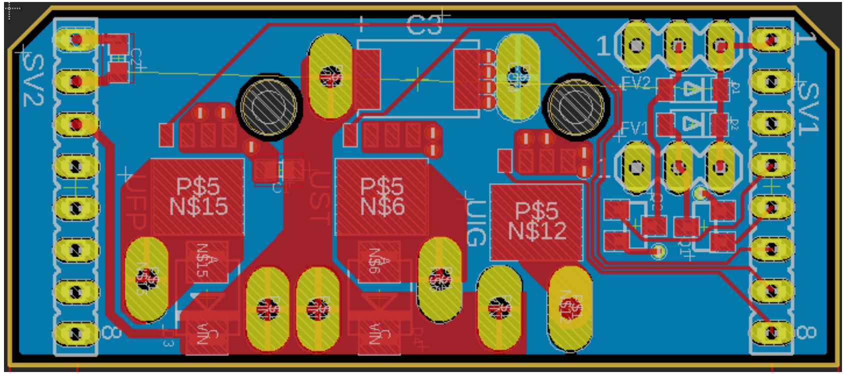


22mm x 50mm

- MicroProcessor
- EGT Sense Circuit
- ICSP Header
- Hall Effect Circuit
- Battery Circuit

ECM Motor Control Board





22mm x 50mm

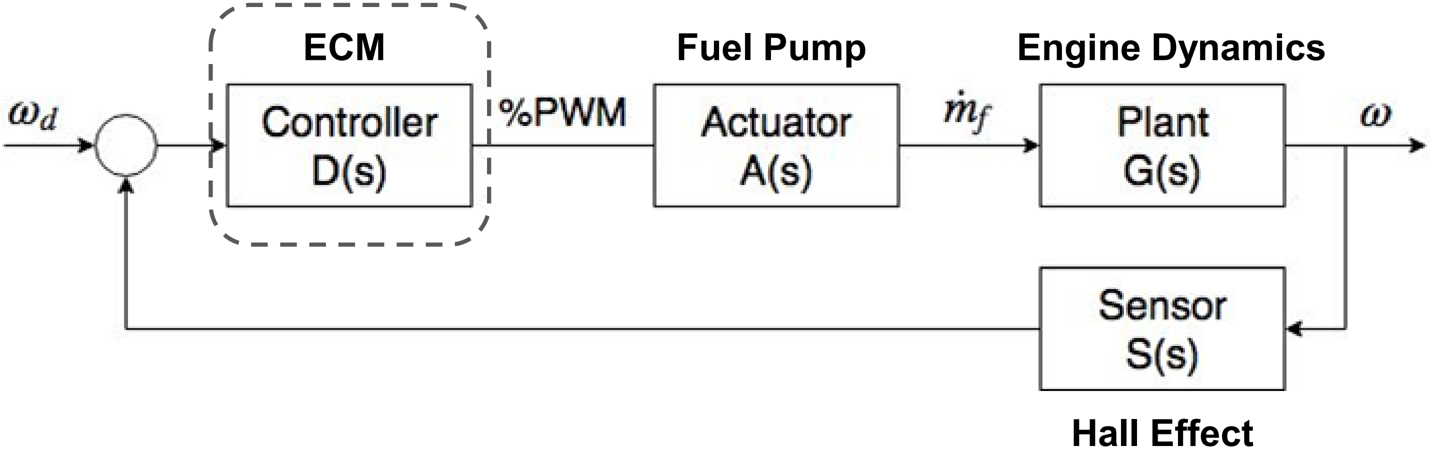
- Large trace pours for high current
- Standoffs for thermal isolation
- Stacked below Control Board

ECM Controller Design Satisfaction Testing

Frequency Response Testing

Main Objectives: Determine the transfer function for the engine system response to satisfy control requirements.

FR 2: SPECS shall control the engine over the entire operational envelope. → Engine System Characterization → Frequency Response Testing



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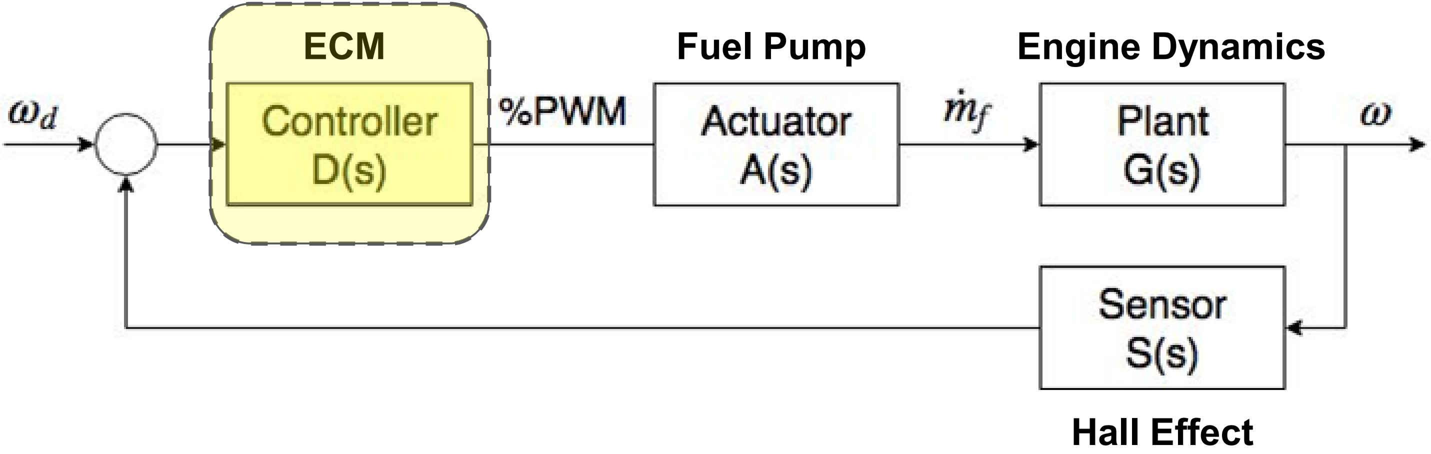

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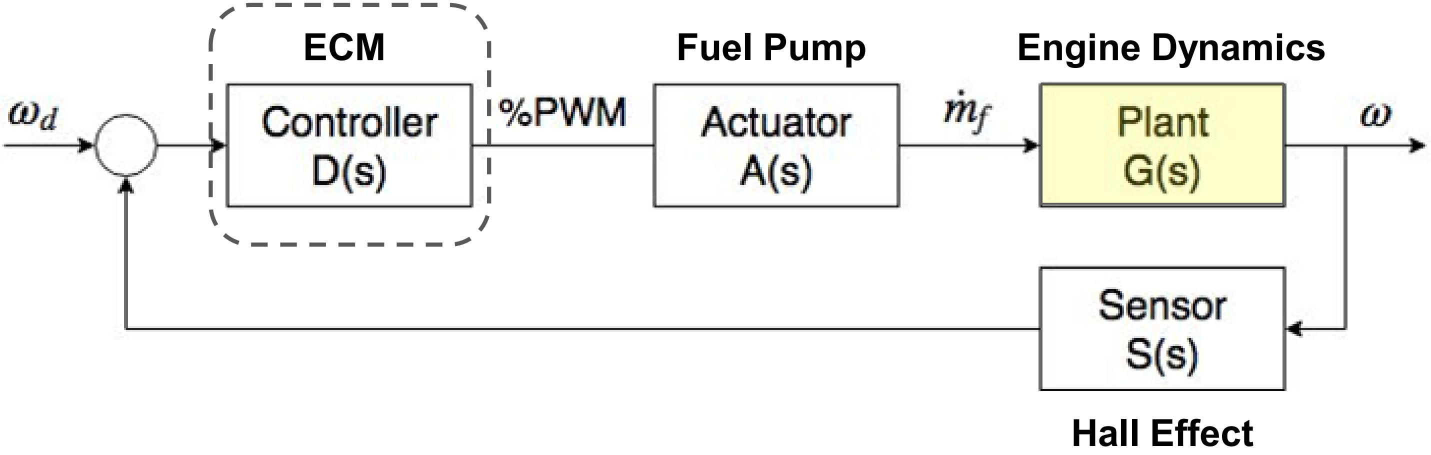

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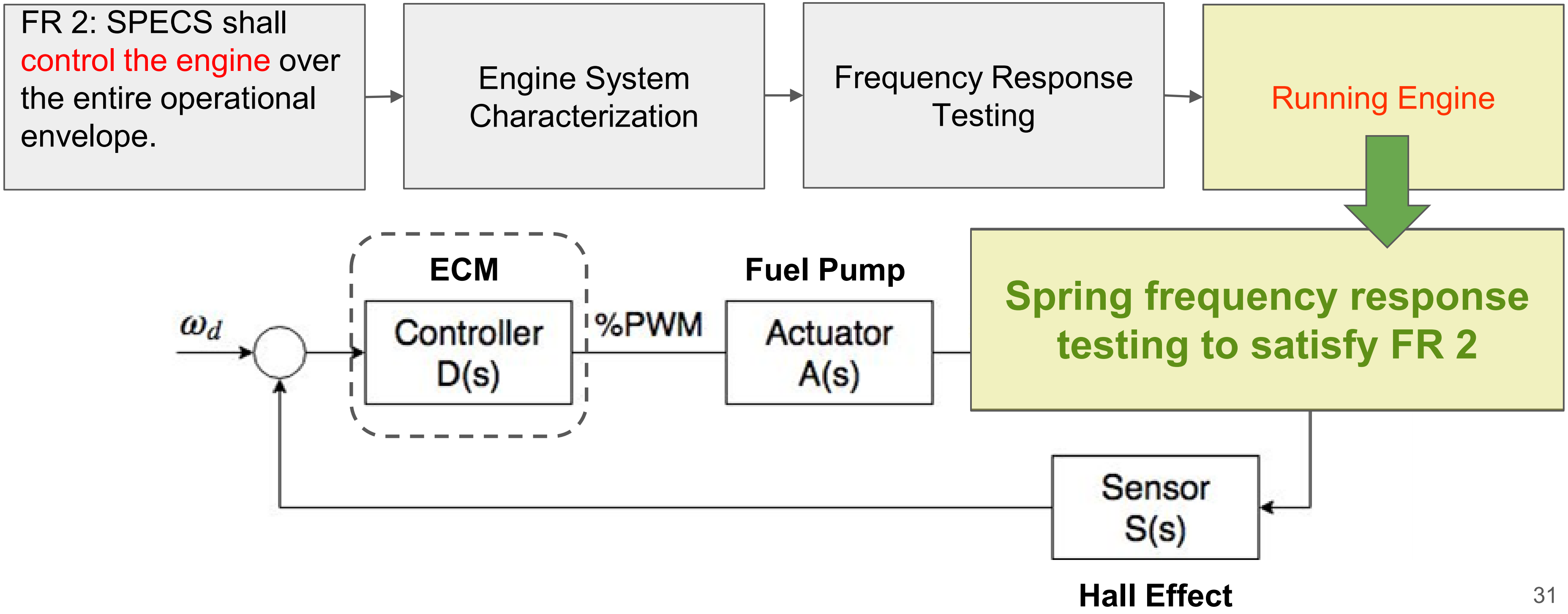

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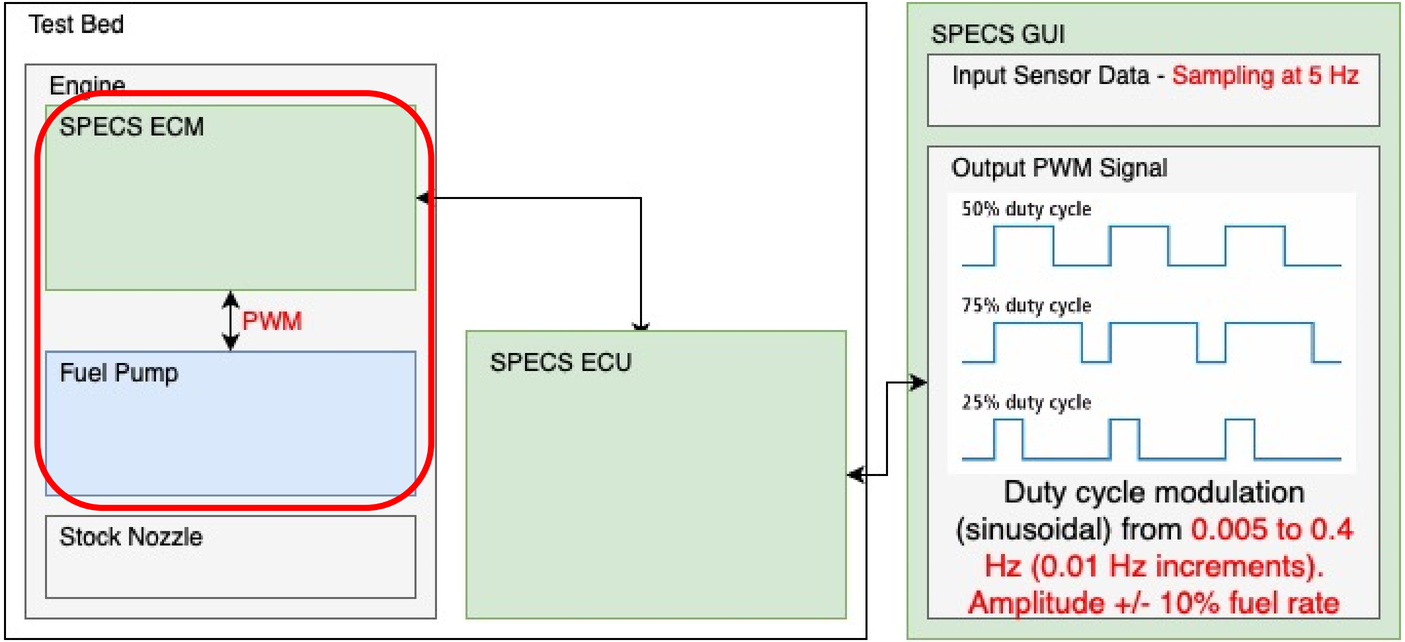

Test Details:
- Testing at several operating points from 55% to 90% max RPM.

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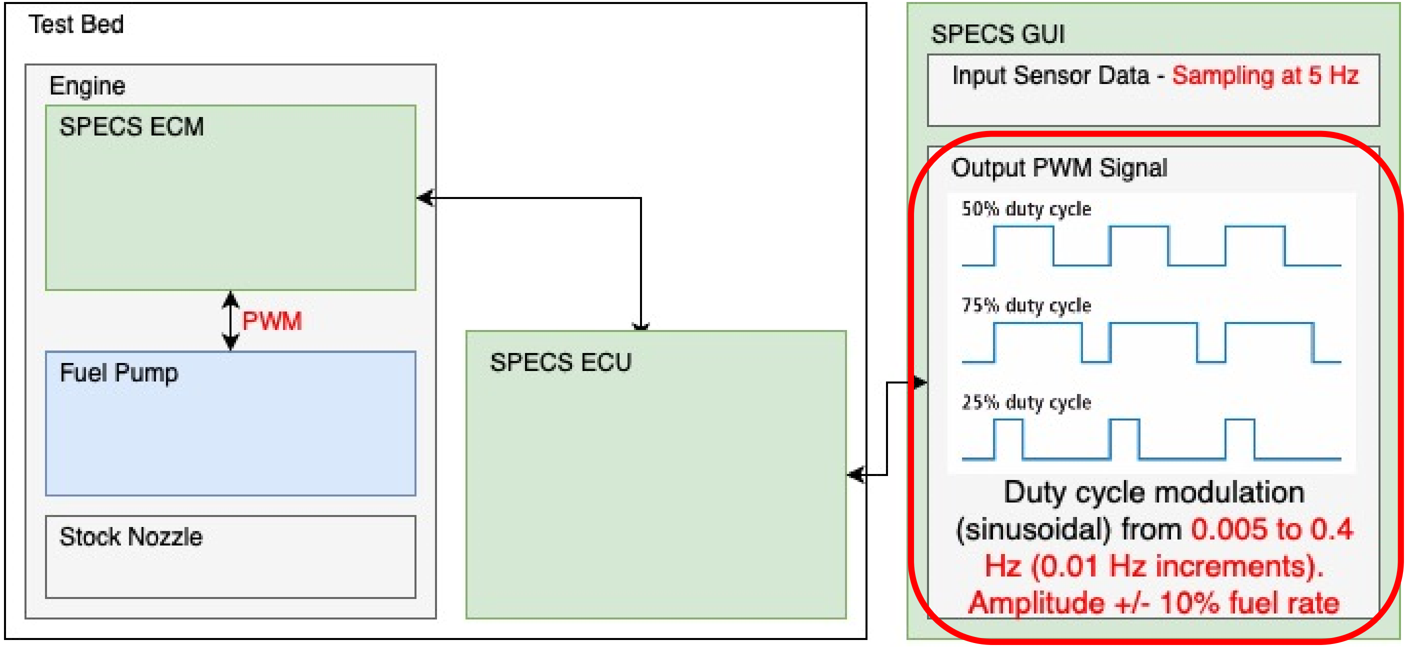

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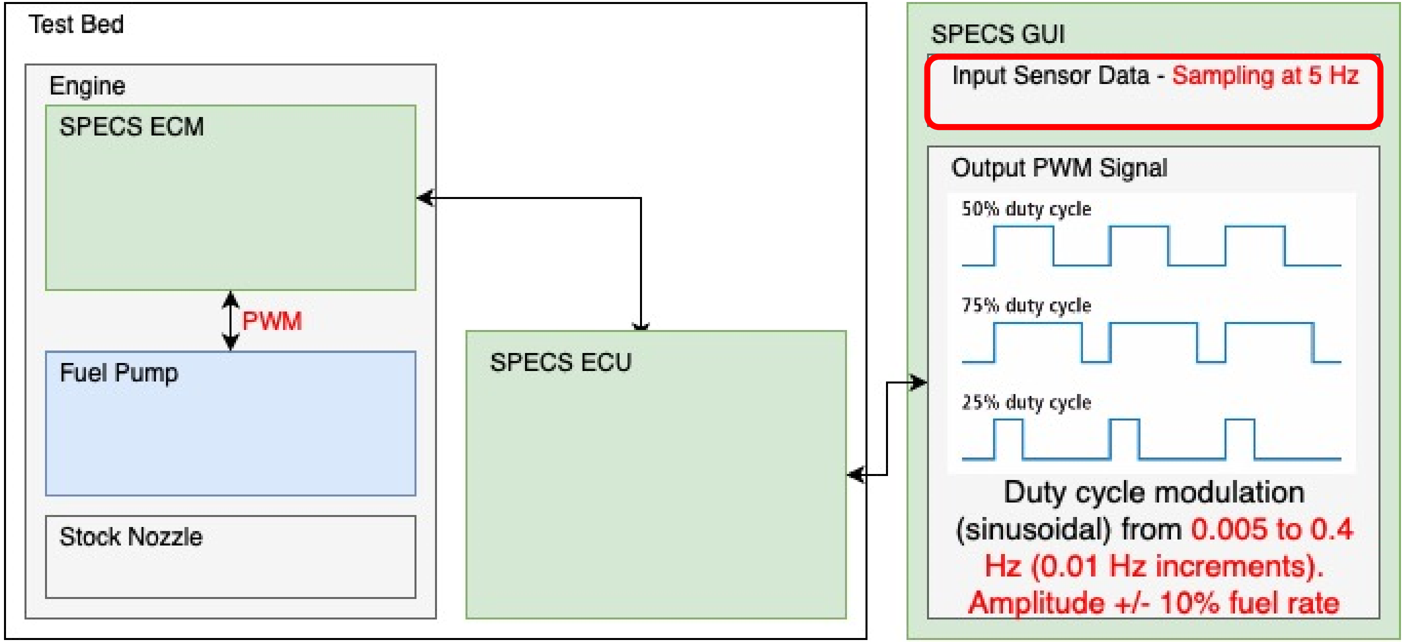


Test Details:
- Testing at several operating points from 55% to 90% max RPM.

Communication

Design Requirements & their satisfaction

CPE-3	Communication from User to Engine (ECU)	During initial testing and product development user oversight will **verify safe operation and monitor for anomalies.**

DR 4.1: The SPECS user interface **shall display** to the user the **EGT** (10°C increments), **RPM** (1000 RPM increments), **battery voltage** (0.1V increments), and **calculated fuel flow rate** (oz/min).

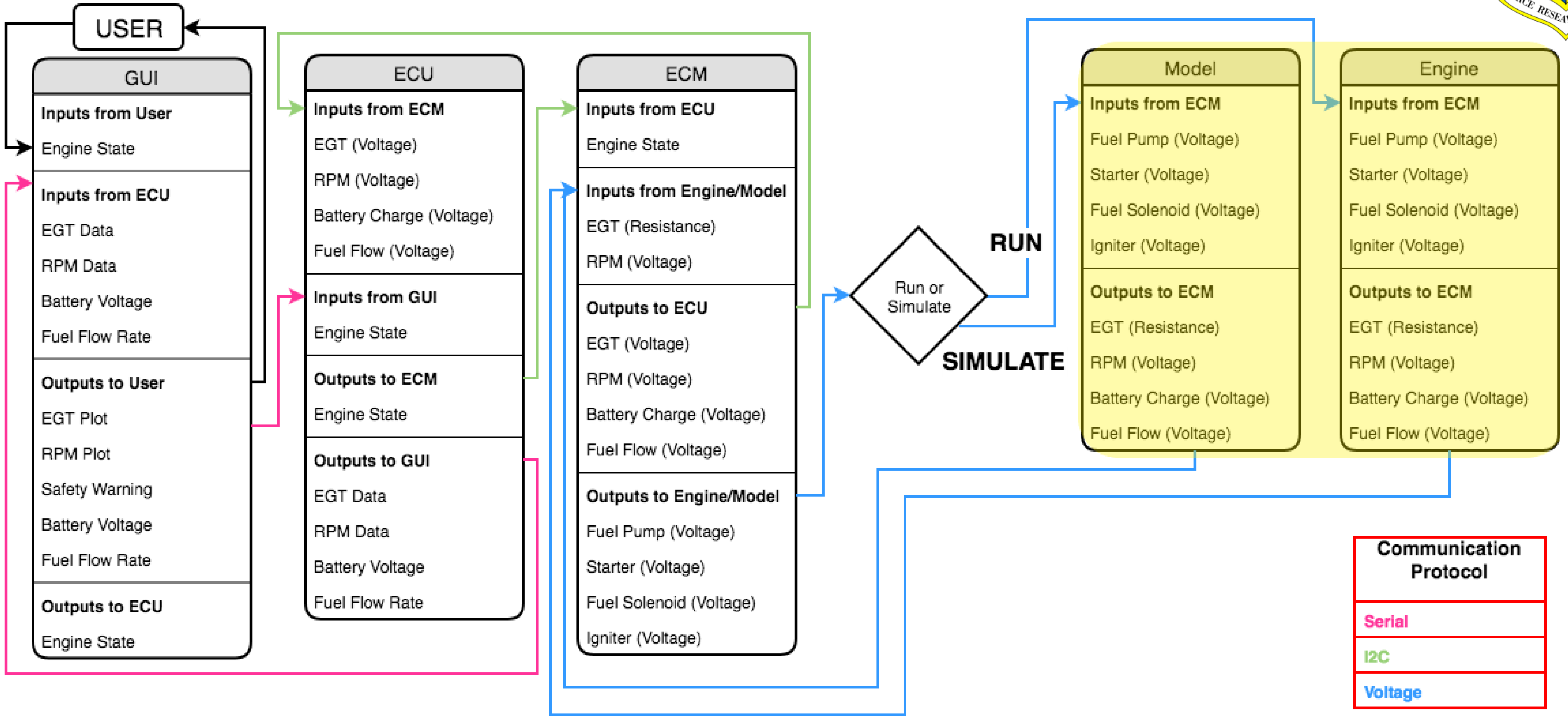
DR 4.2: The SPECS user interface shall **take user throttle inputs**.

DR 4.3: The SPECS user interface shall have the ability to **initiate the engine start up and shutdown sequences**.

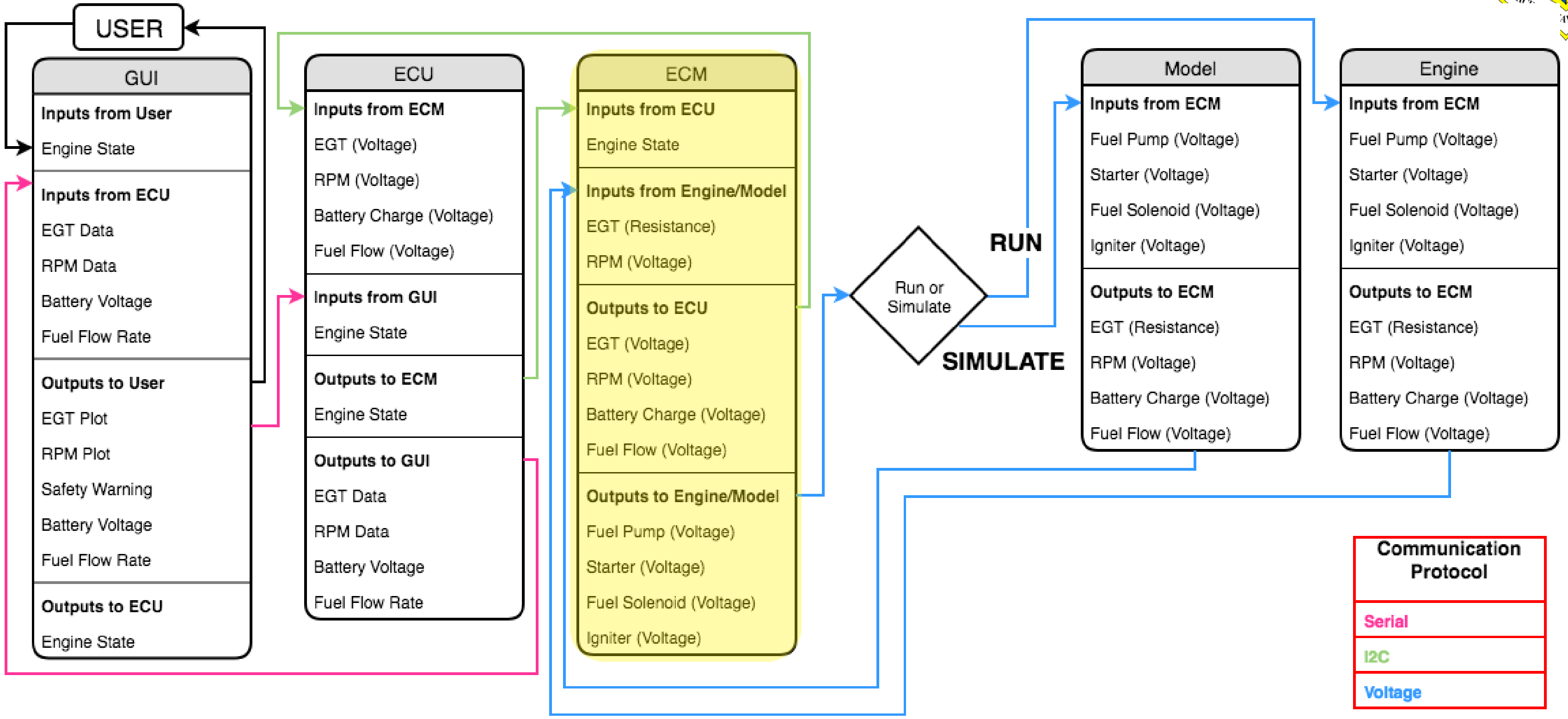
DR 4.4: The SPECS user interface shall **display warnings for operation** within 10% of safety limits to the operator.

DR 4.5: The SPECS user interface shall **have an Emergency Stop (E-Stop) function**.

Flowchart - Software



Flowchart - Software



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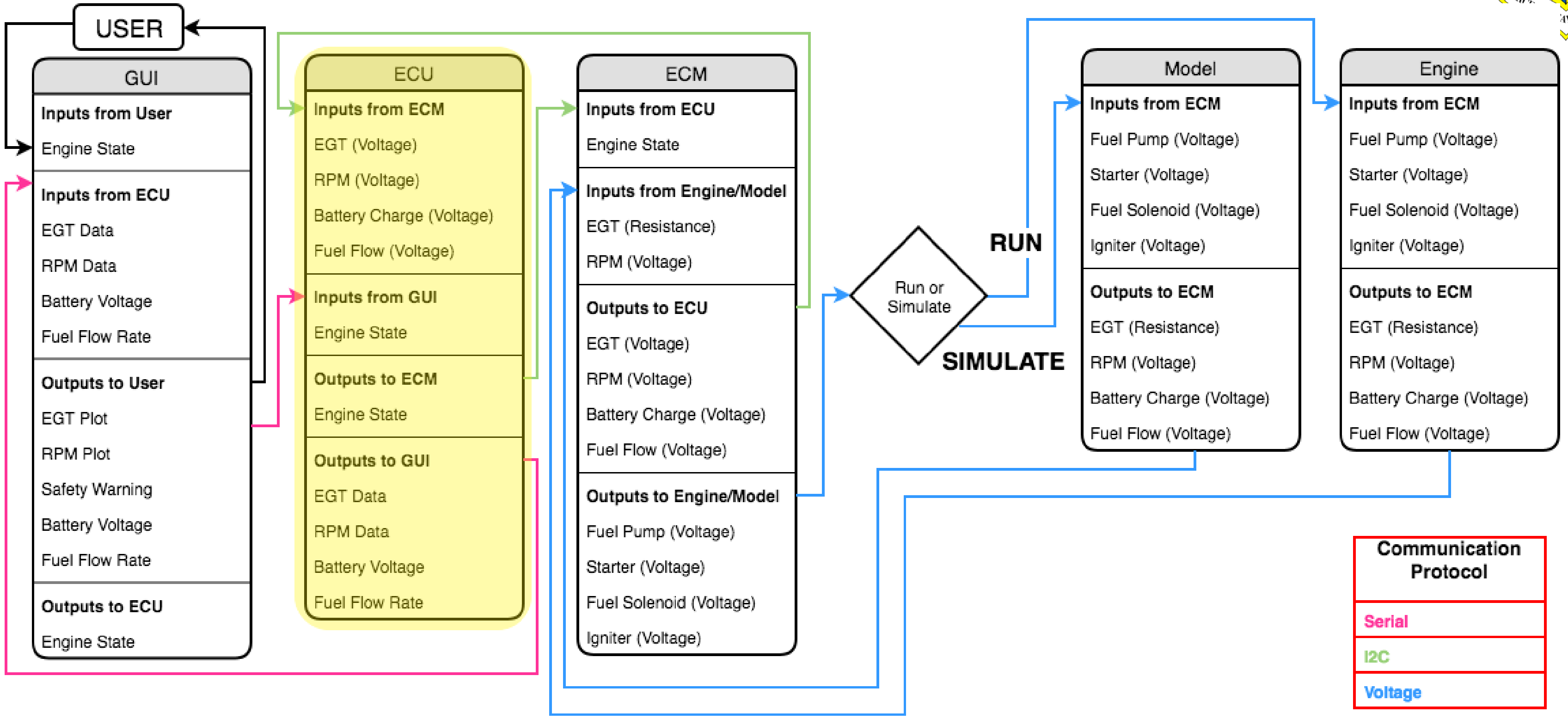

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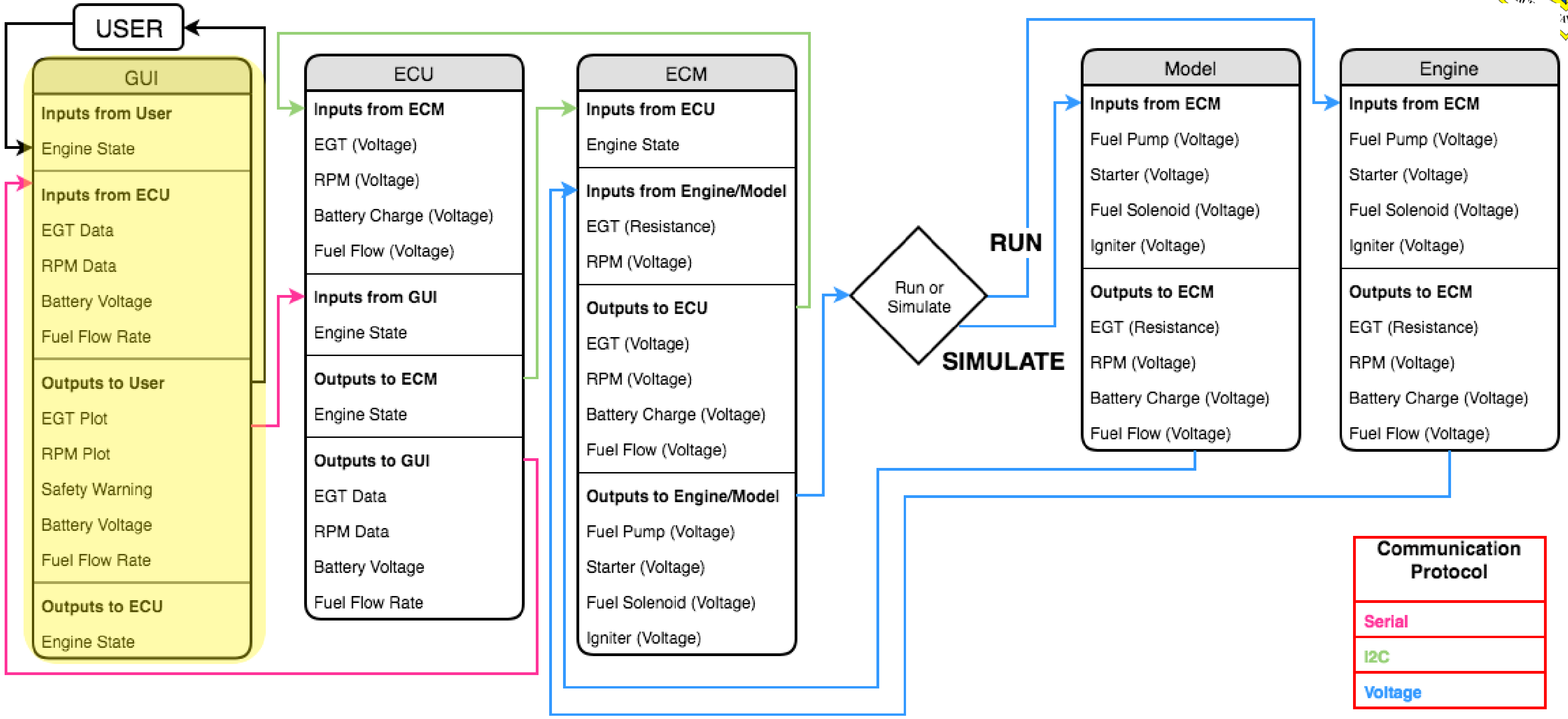
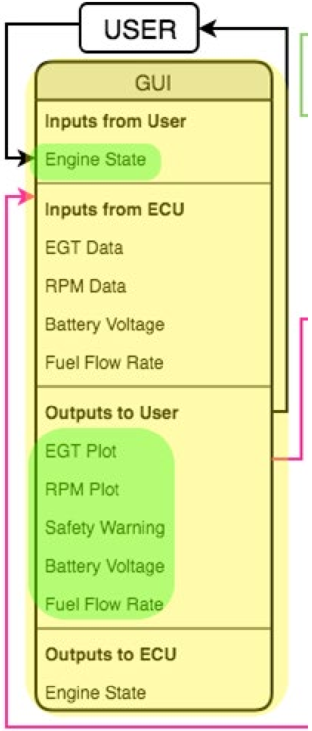


Flowchart - Software

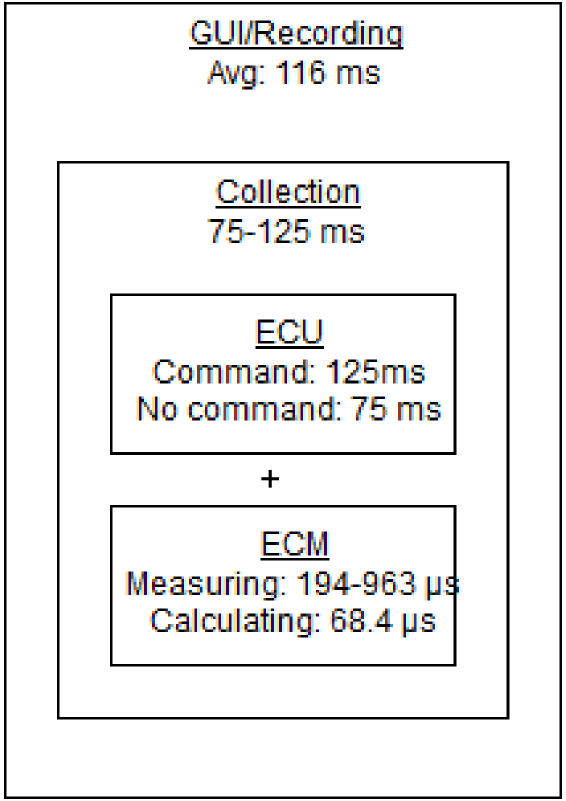


- User interface displays EGT, RPM, battery voltage, and fuel rate (DR 4.1).
- User interface displays safety warnings (DR 4.4).
- User interface allows changing engine state (start, stop, throttle, and emergency stops) (DR 4.2,4.3,4.5).

Software Timing of ECM/ECU

- Total Collection Time: 75 to 125 ms
  - Measured ECU Time:
    - Command: 125 ms
    - No command: 75 ms
  - Measured ECM Time: 267 to 1030 μs (3.81 to 0.97 kHz)
    - Measurement time dependent on engine RPM
      - 199μs at 130 kRPM
      - 963μs at 33 kRPM
    - Calculation time: 68.4μs
  - Sampling Delay: 50.0 ms
- Ultimate Average GUI Sampling Time: 116 ms

267μs < 462μs (130 kRPM) therefore communication is sufficiently fast



Design Requirements & Satisfaction

CPE-2.1 Engine Control Loop (ECM)	CPE-2.2 Engine Sensors (ECM)

DR 3.1: SPECS will maintain operation below 130,000 RPM **unless a new upper safety limit is determined** from the engine characterization.

*SPECS analysis found the new RPM limit to be 140,000. This will be measured by the Hall effect sensor and verified to be accurate by simulation and engine test run.

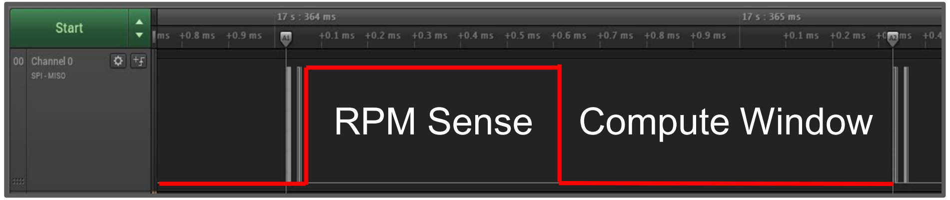
DR 3.2: SPECS will maintain EGT below 700° Celsius **unless a new upper safety limit is determined**.

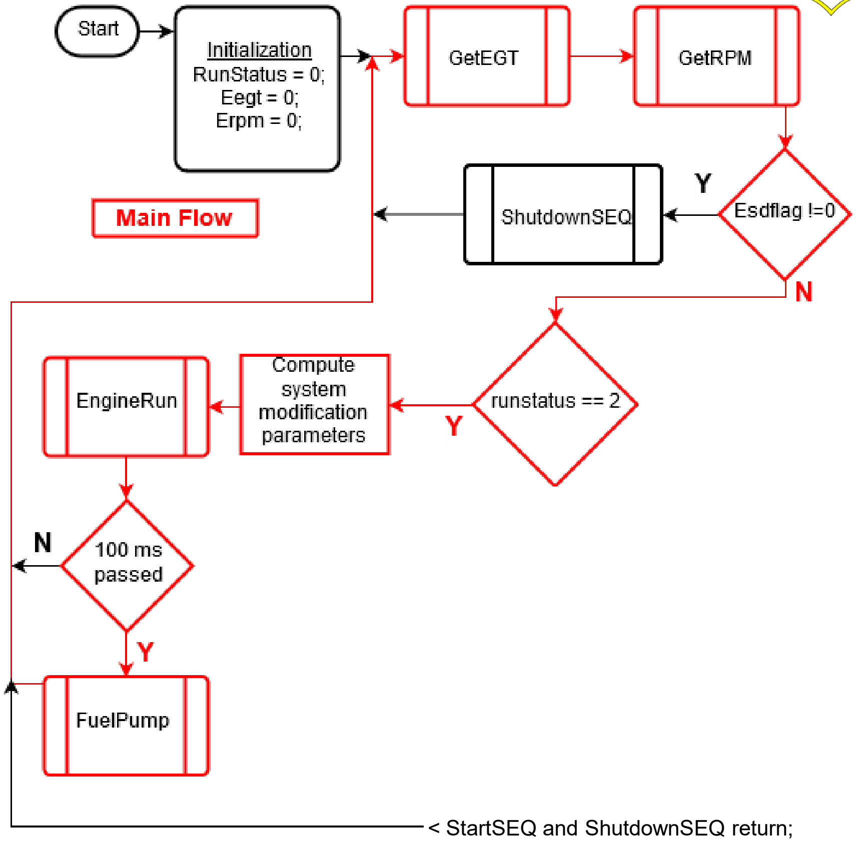
*SPECS analysis found new EGT upper safety limit is 730° C. This was determined through thermal analysis of engine materials.

ECM Compute Cycle Structure

Modular Programming

- Measure EGT
- Measure only the High pulse of RPM (Duty Cycle compensation)
- Compute system modification parameters
- Update “Engine Run” function
- Repeat





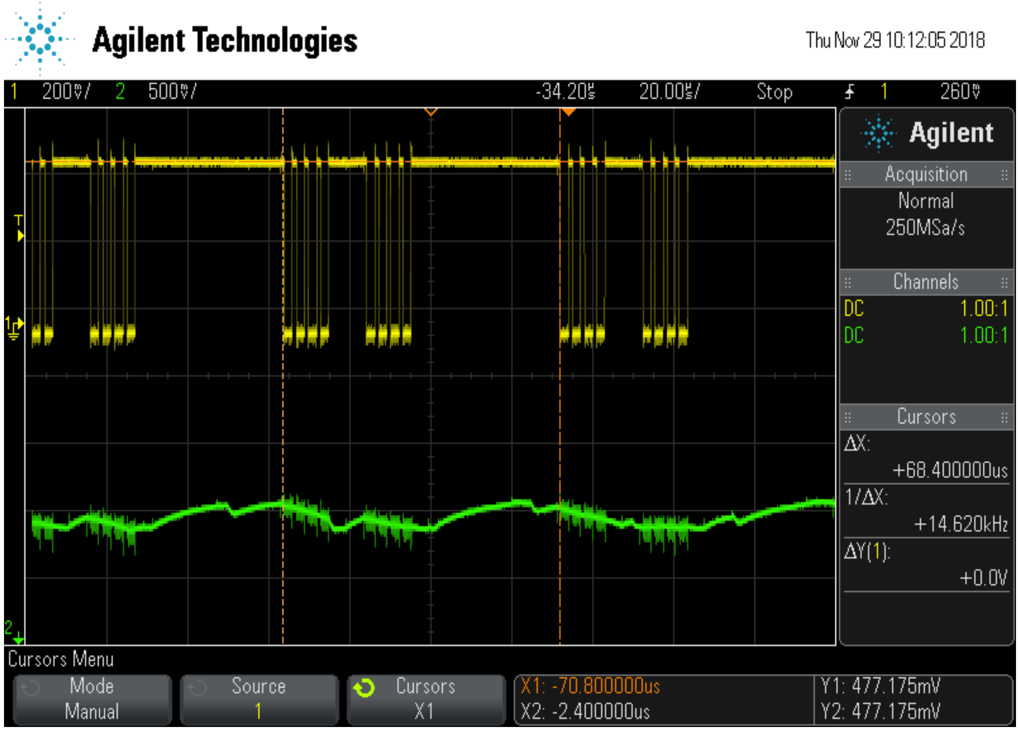
ECM Compute Cycle Timing

- Set simulation to “Engine Run”
- Disabled RPM Sense Function
- Measured Timing

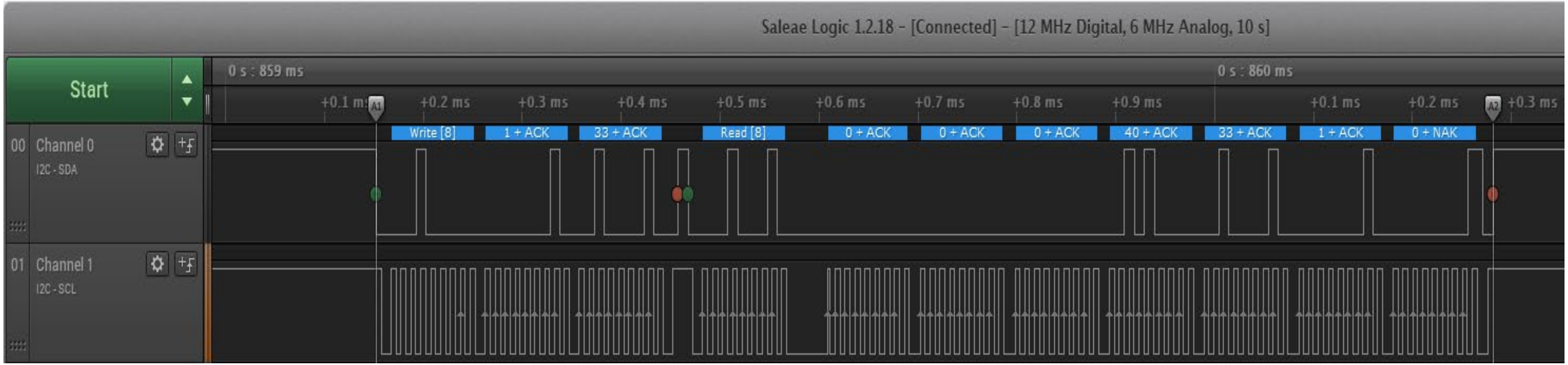
Total compute time 68.4μs

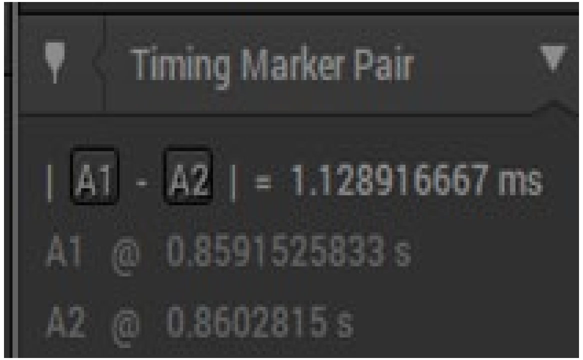
Compute Window @ 130k = 267μs

SPECS can measure RPM in excess of 130K, and maintain control of all engine systems simultaneously. (DR 3.1)

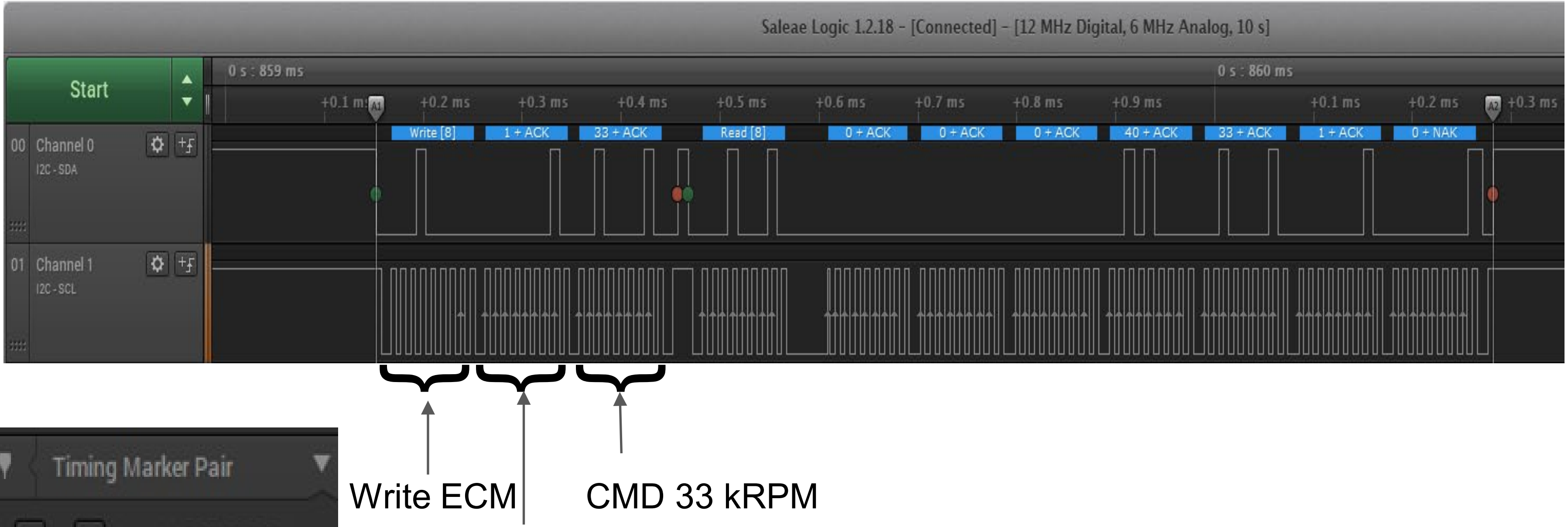


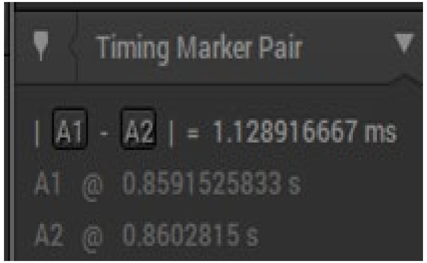
Communication Overview: ECM/ECU (I2C)



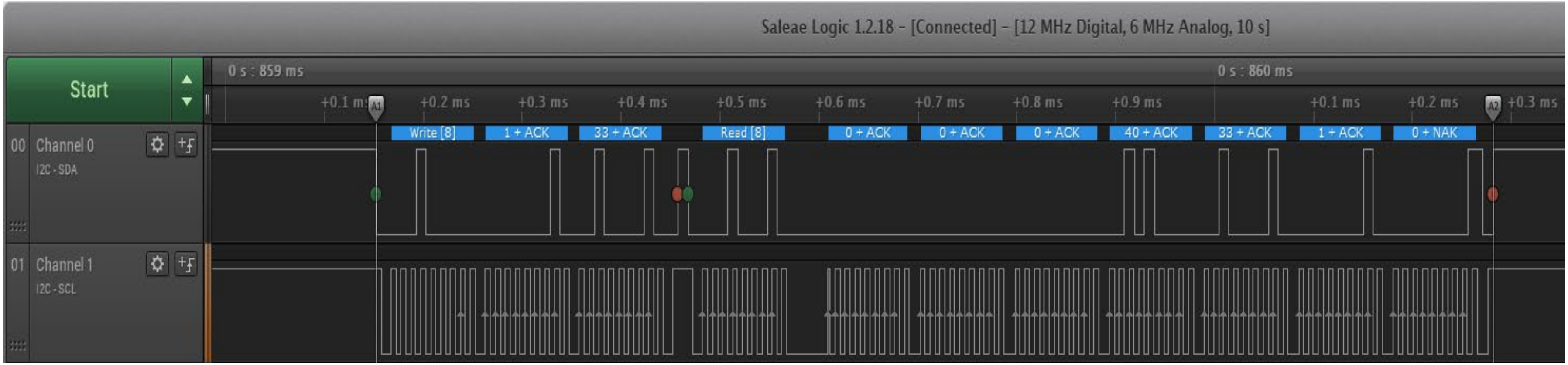


Communication Overview: ECM/ECU (I2C)

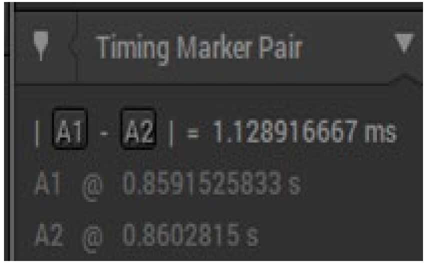




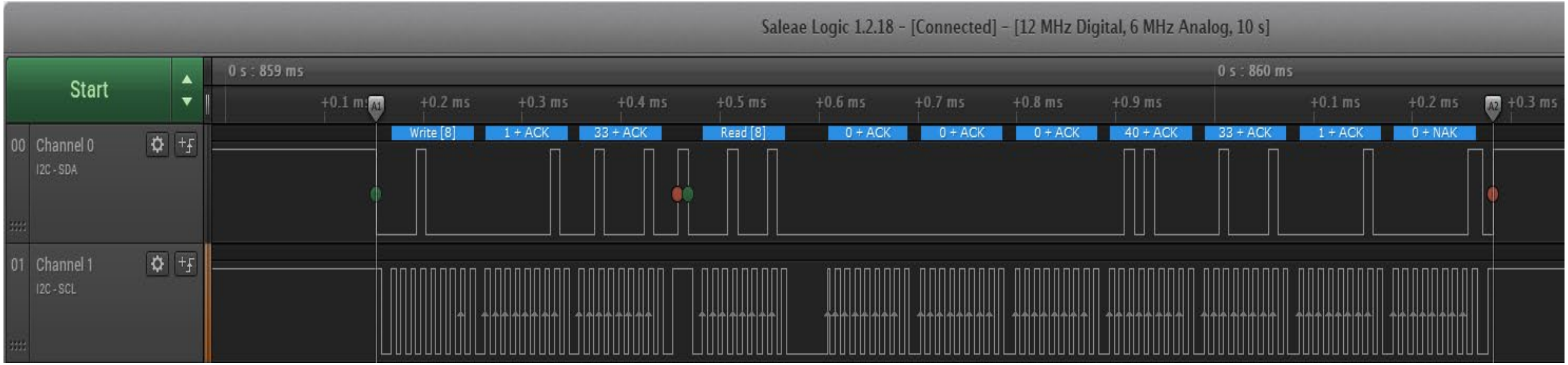
Communication Overview: ECM/ECU (I2C)



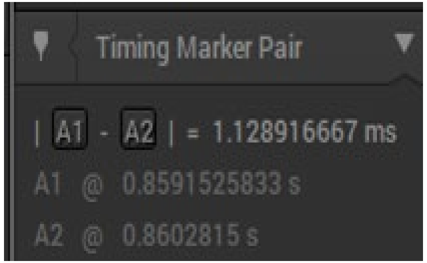
Read ECM



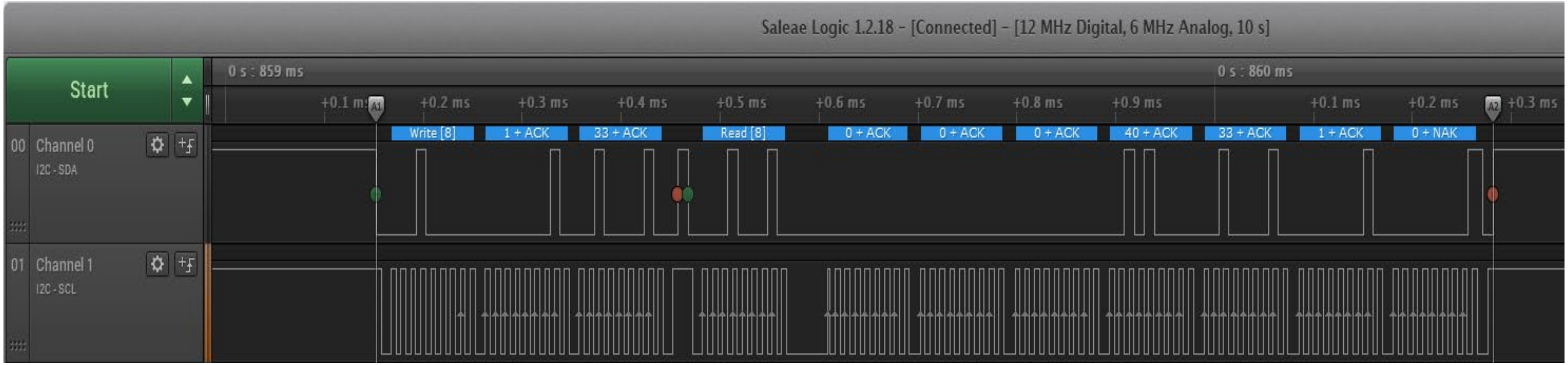
Communication Overview: ECM/ECU (I2C)

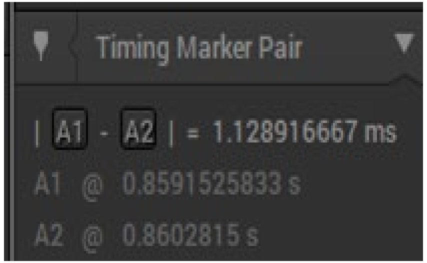


RPM Data Bytes



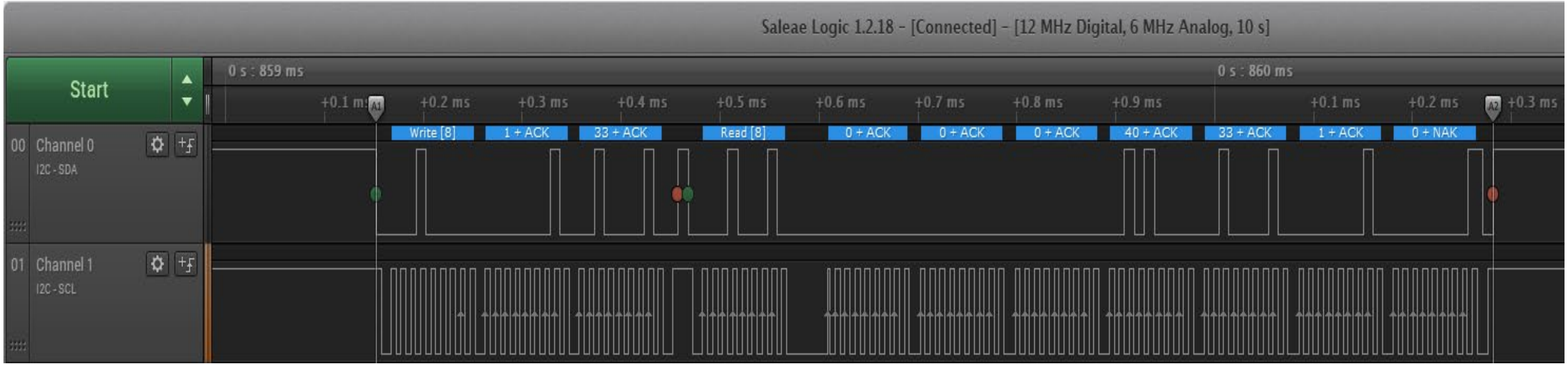
Communication Overview: ECM/ECU (I2C)



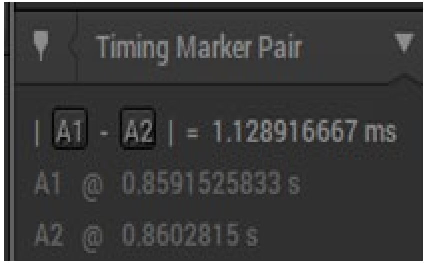


EGT Data Bytes

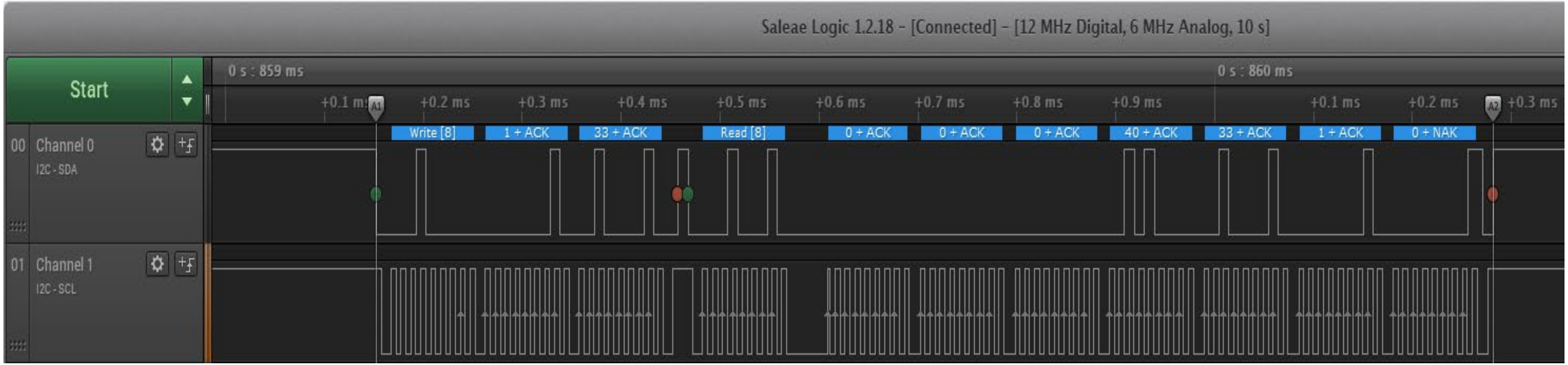
Communication Overview: ECM/ECU (I2C)



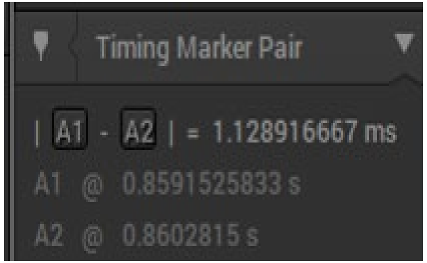
CMD Verify



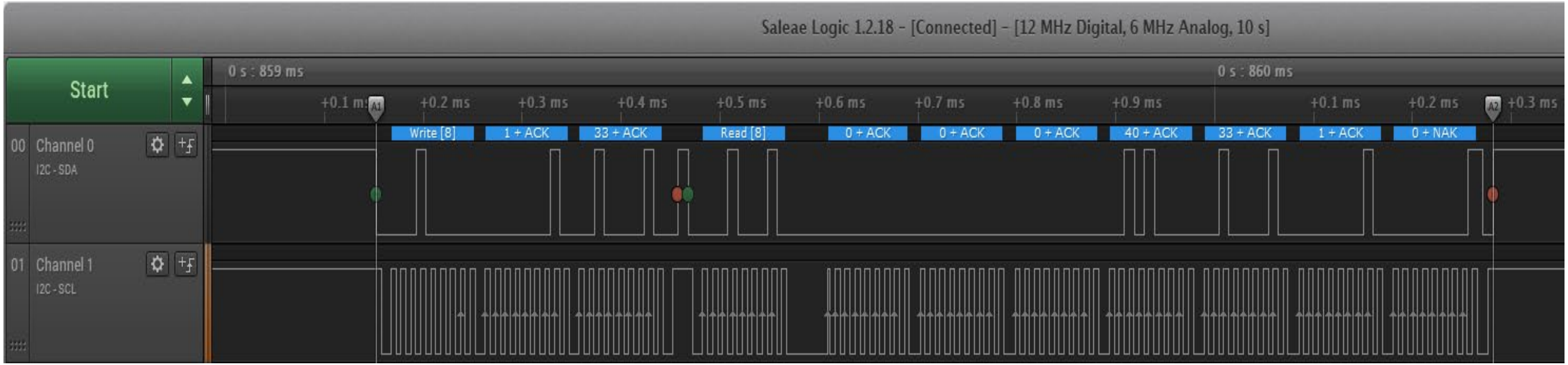
Communication Overview: ECM/ECU (I2C)

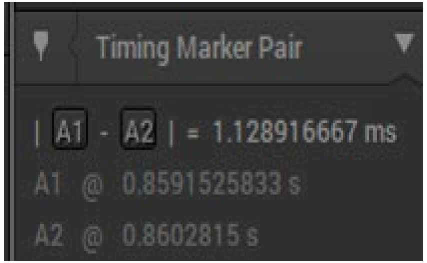


Start Verify



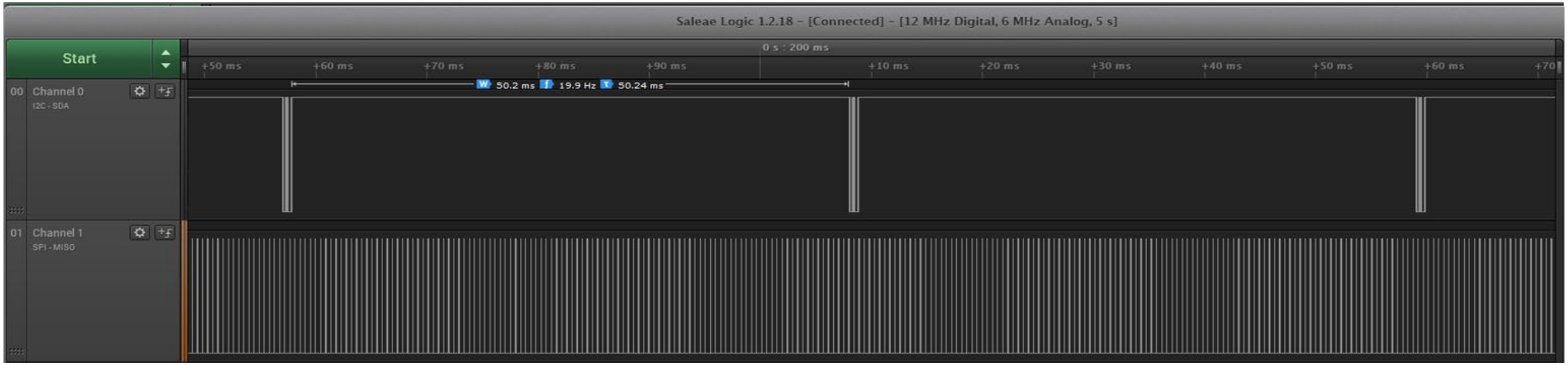
Communication Overview: ECM/ECU (I2C)





ERROR Flag

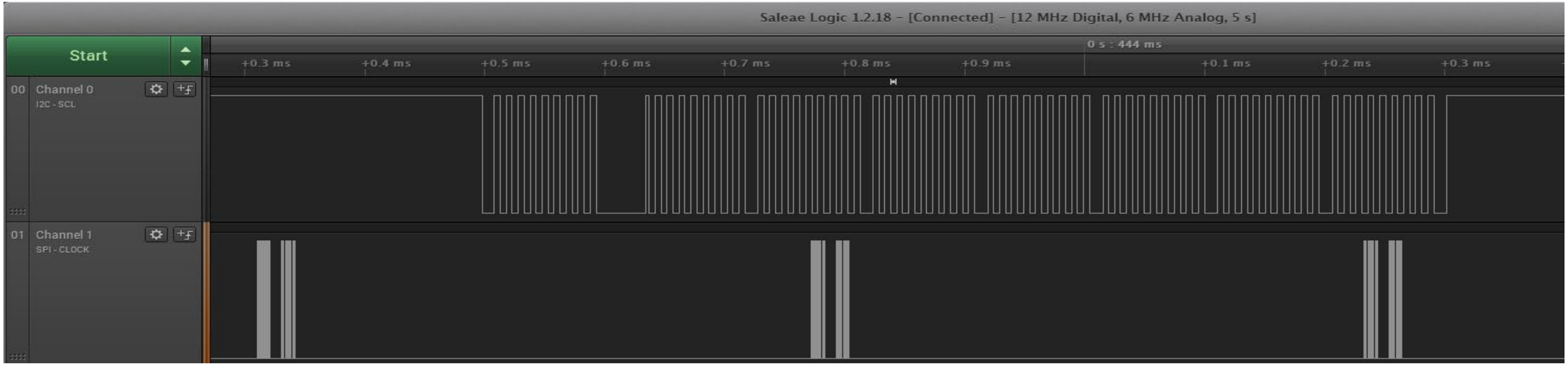
Communication Overview: I2C and SPI clock zoomed out



- Top: I2C clock signal
- Bottom: SPI clock signal

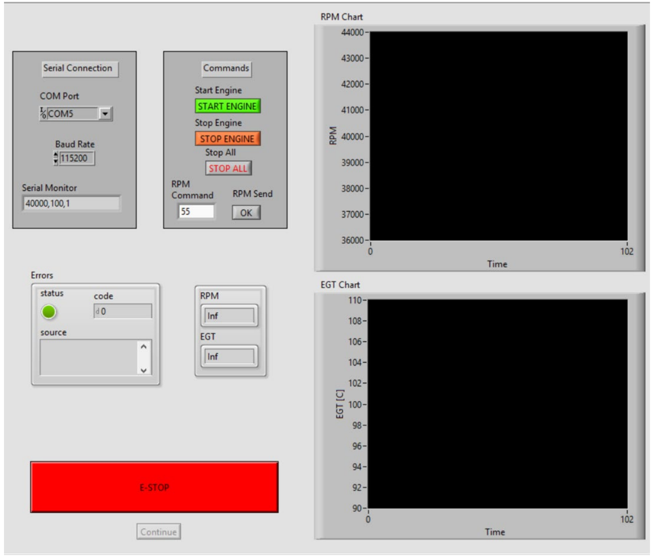
- 50 ms between each I2C communication
- Parameters are still measured while ECM is gathering and preparing data for transmission

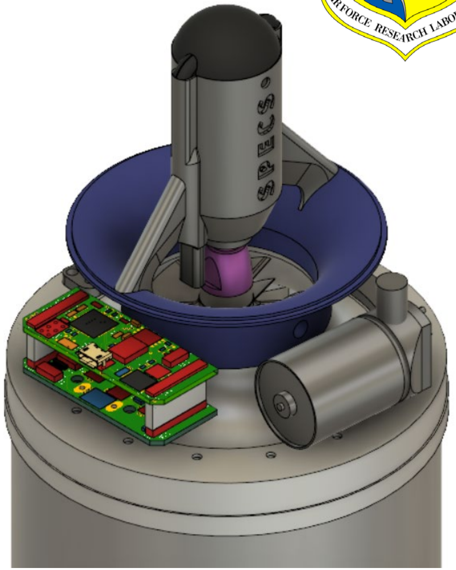
Communication Overview: I2C and SPI clock zoomed in



- Top: I2C clock signal
- Bottom: SPI clock signal
- No interference with clock signals when running I2C and SPI together

Safety Precautions





<u>E-Stop Button:</u> Disconnects all power. Last resort, no active cooling after use.

<u>GUI Manual:</u> User Emergency Stop, sends engine into shutdown.

<u>ECM Automatic:</u> Overspeed, Overtemp, Fuel Pump PWM to RPM Mismatch, Loss of ECU Communications.

SPECS user interface provides an Emergency Stop (E-Stop) function (DR 4.5)

CPE and DR Summary

CPE 2.1 - Engine Control Loop (ECM)

1) **DR 3.1:** SPECS will maintain operation below 140,000 RPM from the engine characterization.
2) **DR 3.2:** SPECS will maintain EGT below 730° Celsius

CPE 2.2 - Obtain accurate sensor data

1) **DR 4.1:** The SPECS user interface **shall display** to the user the **EGT** (10°C increments), **RPM** (1000 RPM increments), **battery voltage** (0.1V increments), and **calculated fuel flow rate** (oz/min).
2) **DR 4.2:** The SPECS user interface shall **take user throttle inputs**.
3) **DR 4.3:** The SPECS user interface shall have the ability to **initiate the engine start up and shutdown sequences**.
4) **DR 4.4:** The SPECS user interface shall **display warnings for operation** within 10% of safety limits to the operator.
5) **DR 4.5:** The SPECS user interface shall **have an Emergency Stop (E-Stop) function**.

Project Risks

Thrust Modification Risks and Mitigation

1) Engine Does Not Run
2) Turbine Failure
3) Other Engine Component Failure (Compressor, Shaft, etc.)
4) Foreign Object Damage

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY		1		2
LOW POSSIBILITY			4	3
NOT LIKELY				

Thrust Modification Risks and Mitigation

1) Engine Does Not Run
    a) Engine Simulator
    b) Spare Engine Purchase
2) Turbine Failure
3) Other Engine Component Failure (Compressor, Shaft, etc.)
4) Foreign Object Damage

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY				2
LOW POSSIBILITY	1		4	3
NOT LIKELY				

Thrust Modification Risks and Mitigation

1) Engine Does Not Run
   a) Engine Simulator
   b) Spare Engine Purchase
2) Turbine Failure
   a) Engine Model Validation
   b) Controller Safety Limits
3) Other Engine Component Failure (Compressor, Shaft, etc.)
4) Foreign Object Damage

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY				
LOW POSSIBILITY	1		4	2,3
NOT LIKELY				

Thrust Modification Risks and Mitigation

1) Engine Does Not Run
    a) Engine Simulator
    b) Spare Engine Purchase
2) Turbine Failure
    a) Engine Model Validation
    b) Controller Safety Limits
3) Other Engine Component Failure (Compressor, Shaft, etc.)
    a) Component FEA
4) Foreign Object Damage

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY				
LOW POSSIBILITY	1		4	2 ↓
NOT LIKELY				3

Thrust Modification Risks and Mitigation

1) Engine Does Not Run
   a) Engine Simulator
   b) Spare Engine Purchase
2) Turbine Failure
   a) Engine Model Validation
   b) Controller Safety Limits
3) Other Engine Component Failure (Compressor, Shaft, etc.)
   a) Component FEA
4) Foreign Object Damage
   a) Stock Inlet Filter

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY				
LOW POSSIBILITY	1			2
NOT LIKELY			4	3

Electronics Risk and Mitigation

1) Hall effect failure
2) Loss of engine control
3) Electrical component failure
4) Starter motor failure
5) Communication corruption

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY		3		
LOW POSSIBILITY		4	5	
NOT LIKELY			1	2

Electronics Risk and Mitigation

1) Hall effect failure
    a) Fuel to RPM check
2) Loss of engine control
3) Electrical component failure
4) Starter motor failure
5) Communication corruption

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY		3		
LOW POSSIBILITY		4	5	
NOT LIKELY		1		

Electronics Risk and Mitigation

1) Hall effect failure
    a) Fuel to RPM check
2) Loss of engine control
    a) Physical emergency stop
3) Electrical component failure
4) Starter motor failure
5) Communication corruption

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY		3		
LOW POSSIBILITY		4	5	
NOT LIKELY		1,2		

Electronics Risk and Mitigation

1) Hall effect failure
    a) Fuel to RPM check
2) Loss of engine control
    a) Physical emergency stop
3) Electrical component failure
    a) Simulation
    b) Testing/Redesign
4) Starter motor failure
5) Communication corruption

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY				
LOW POSSIBILITY		4	5	
NOT LIKELY		1,2,3		

Electronics Risk and Mitigation

1) Hall effect failure
    a) Fuel to RPM check
2) Loss of engine control
    a) Physical emergency stop
3) Electrical component failure
    a) Simulation
    b) Testing/Redesign
4) Starter motor failure
    a) Spare motors
5) Communication corruption

	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY				
LOW POSSIBILITY	4		5	
NOT LIKELY		1,2,3		

Electronics Risk and Mitigation

1) Hall effect failure
    a) Fuel to RPM check
2) Loss of engine control
    a) Physical emergency stop
3) Electrical component failure
    a) Simulation
    b) Testing/Redesign
4) Starter motor failure
    a) Spare motors
5) Communication corruption
    a) Message filtering

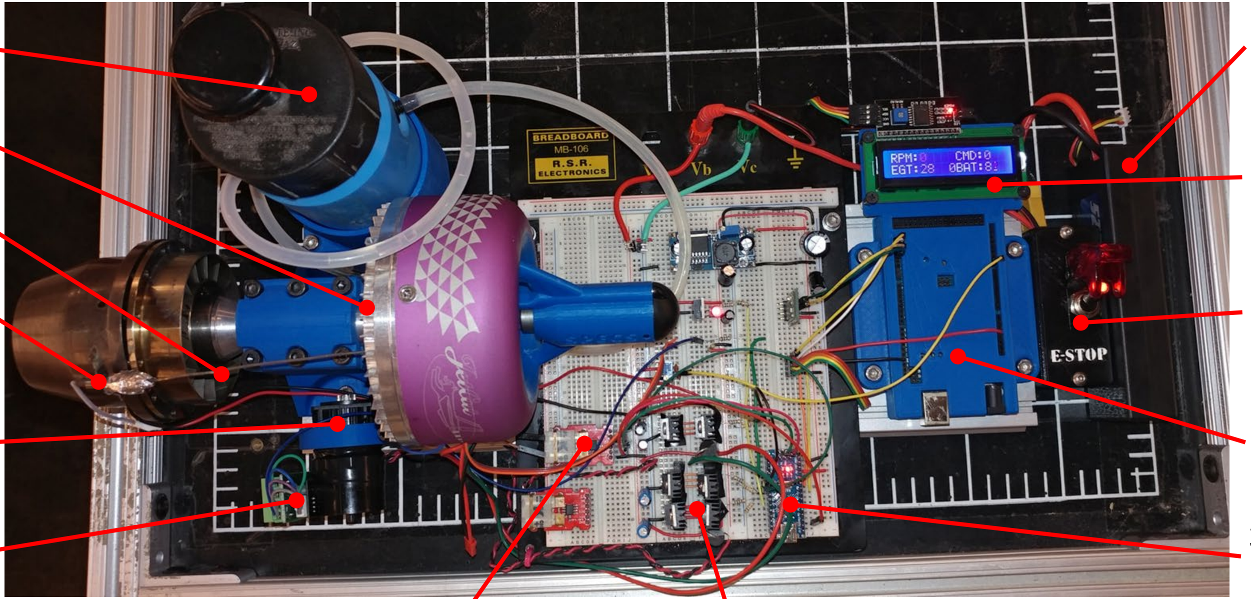
	ACCEPTABLE	MINOR ISSUE	MAJOR ISSUE	CATASTROPHIC
PROBABLE				
HIGH POSSIBILITY				
LOW POSSIBILITY	4			
NOT LIKELY		1,2,3	5	

Verification & Validation

Overview | Thrust Modification | Electronics | Comms | Risk | Verification & Validation | Plans

Electronics/Software Validation

Engine Test Rig Components



"Fuel" Tank
Engine Assembly
Thermocouple
Glow plug
Fuel Pump
RPM Simulation Rotary Encoder
Battery
LCD
Emergency Stop
ECU
328P Microprocessor
EGT Circuit
Motor Control Circuits

ECM Verification and Validation

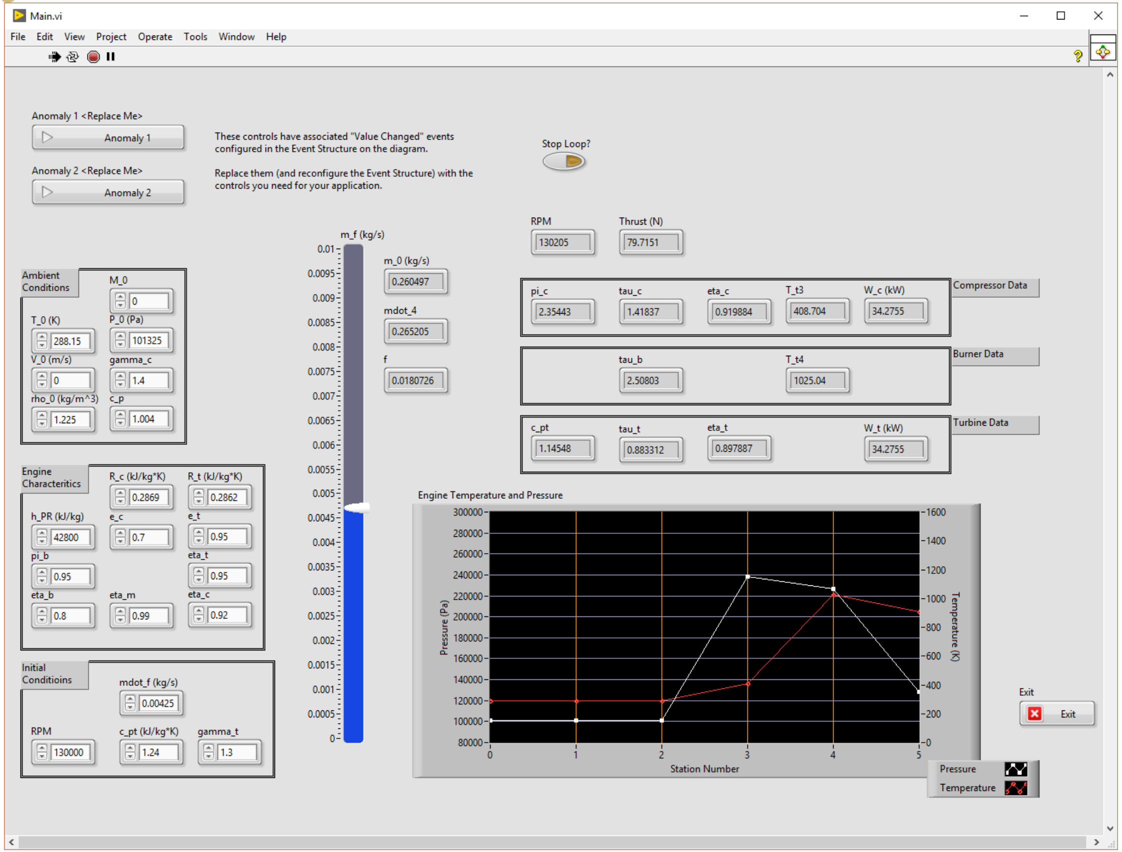
Testing Objective: Verify operation and control of all ECM circuits on breadboard and PCB.

Location: On assembled Test Rig

Method and Parameters:

1) Complete a startup, run and shutdown sequence on test rig.
2) Verify RPM measurements using oscilloscope.
3) Verify EGT measurement using infrared pyrometer.
4) Implement and test all emergency stop programming functions
    - GUI Command Emergency Stop
    - Engine Overspeed
    - Engine EGT Overtemp
    - Fuel command to measured RPM mismatch (Hall effect failure, max engine RPM)

JetCat Engine LabView Simulator



LabView Based JetCat Engine Simulator

Simulator Objectives:

- Verify entire SPECS electronics work as designed before integration with real JetCat engine.

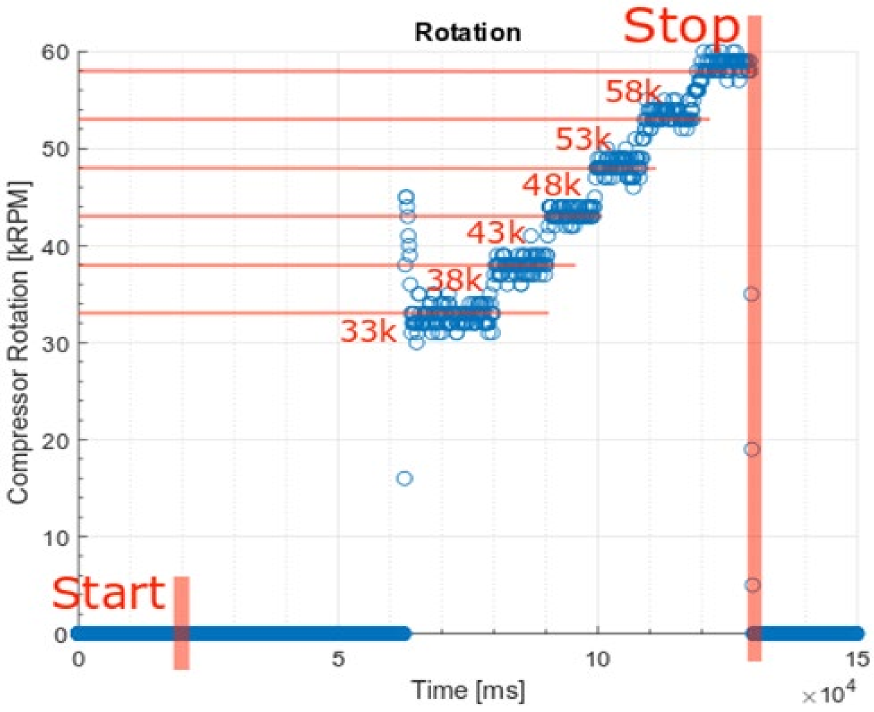
Items to Verified:

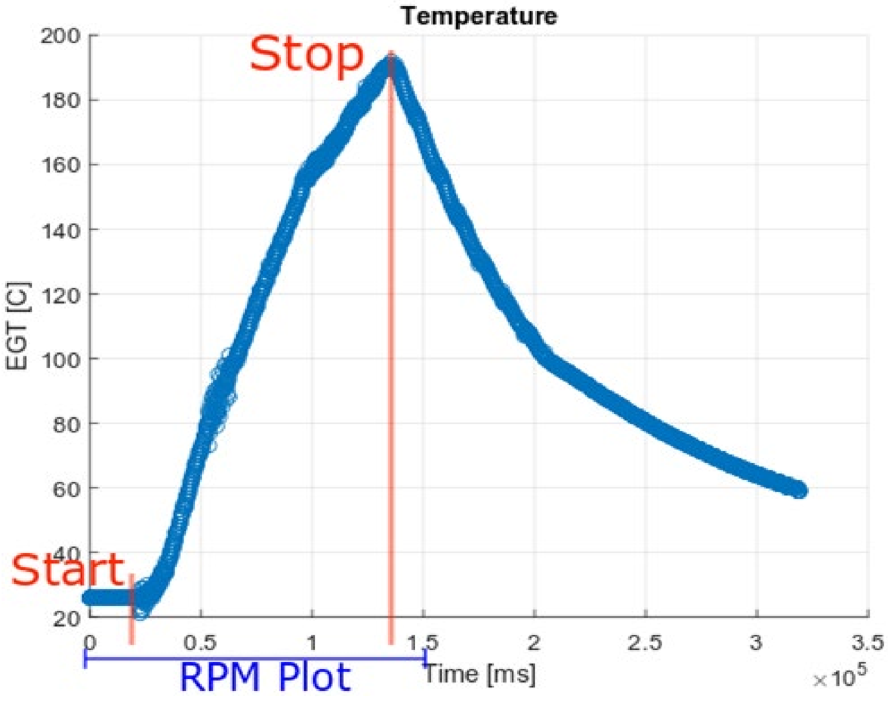
- Control
- Communication
- Electronics (Post PCB) operation
- Safety Limits
- Emergency Stop
- Anomaly Handling

Simulated Outputs:

- RPM
- EGT

Software Results Validated





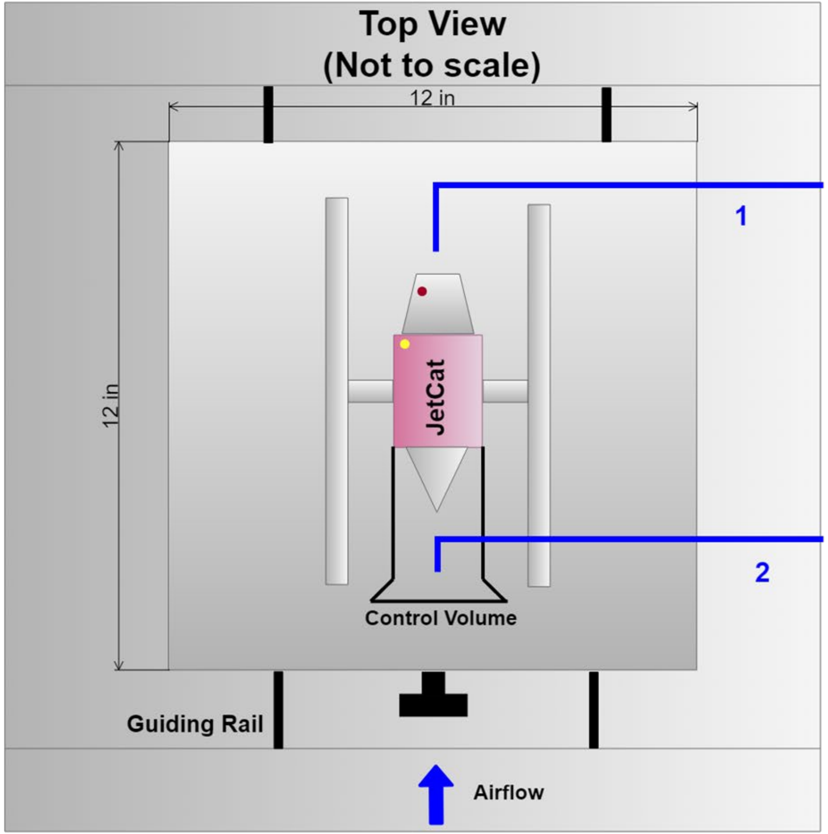
RPM and EGT collection successful

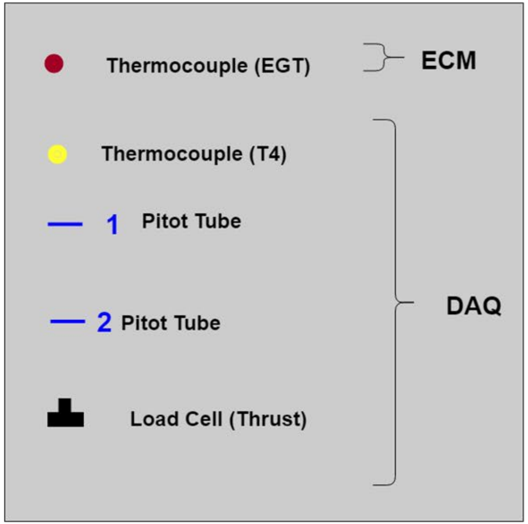
Engine Run SPECS Validation

JetCat Engine Run Validation Testing

Test Type	Engine RPM	Results Desired
Stock Engine Run	Idle - 130,000 RPM	Glow Plug, Fuel Pump PWM (Controls)
Stock Engine Run - Max Thrust	130,000 RPM	Max Thrust Statistical Data
Integrate SPECS with JetCat		
SPECS Engine Run (Stock Nozzle)	130,000 RPM	Verify Safety and Control of modified Eng.
SPECS Engine Run (Stock Nozzle)	140,000 RPM	New Max Thrust
SPECS Engine Run (SPECS Nozzle)	140,000 RPM	Modified Max Thrust, New Nozzle effectiveness

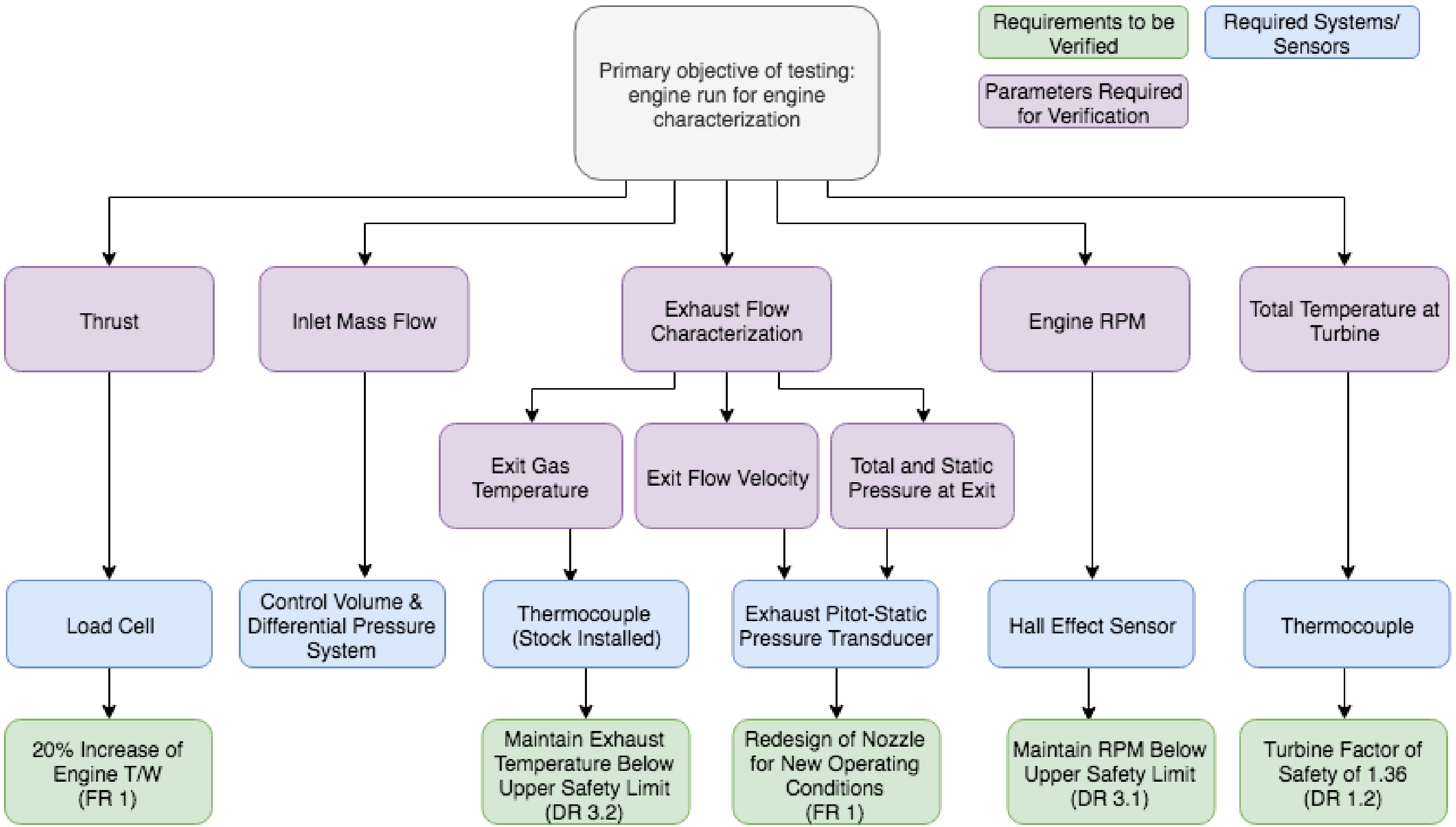
Engine Run Test Stand Setup



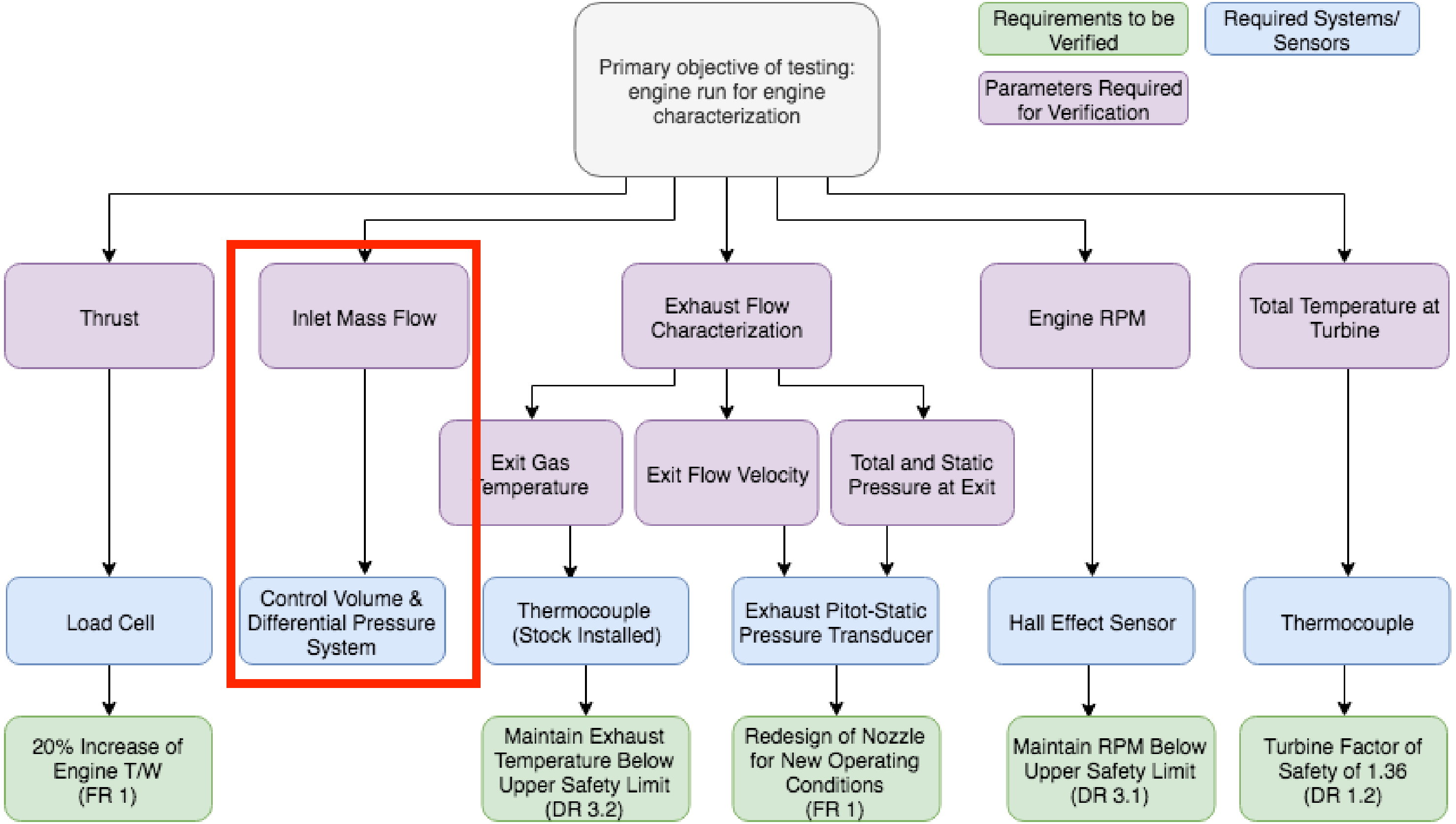


1) Main Objective of Testing is to verify all of the requirements, verify models.
2) Engine runs will be conducted at the CU East Power Plant
3) The test platform will measure EGT, Tt4, flow velocities and thrust

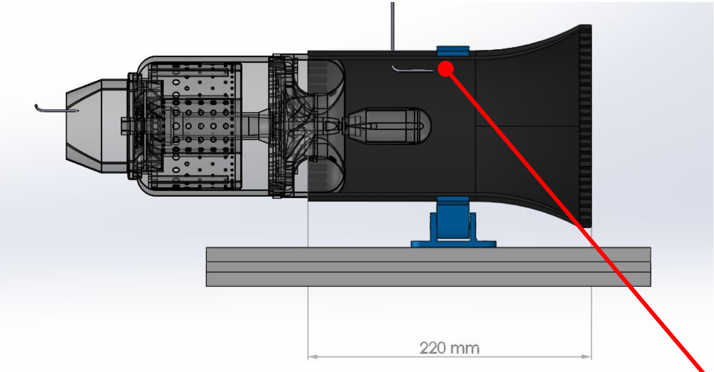
Full System Verification



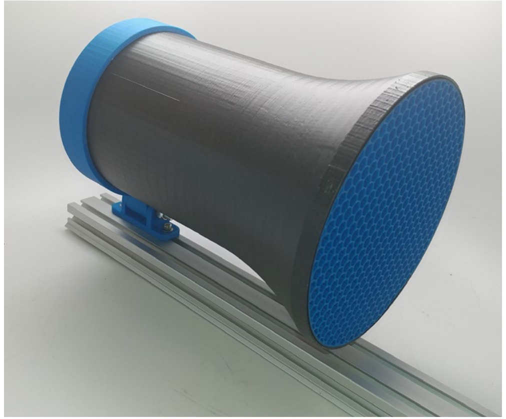
Mass Flow Characterization



Mass Flow Characterization



Pitot Tube



Mass Flow Inlet Design

Test Objectives:

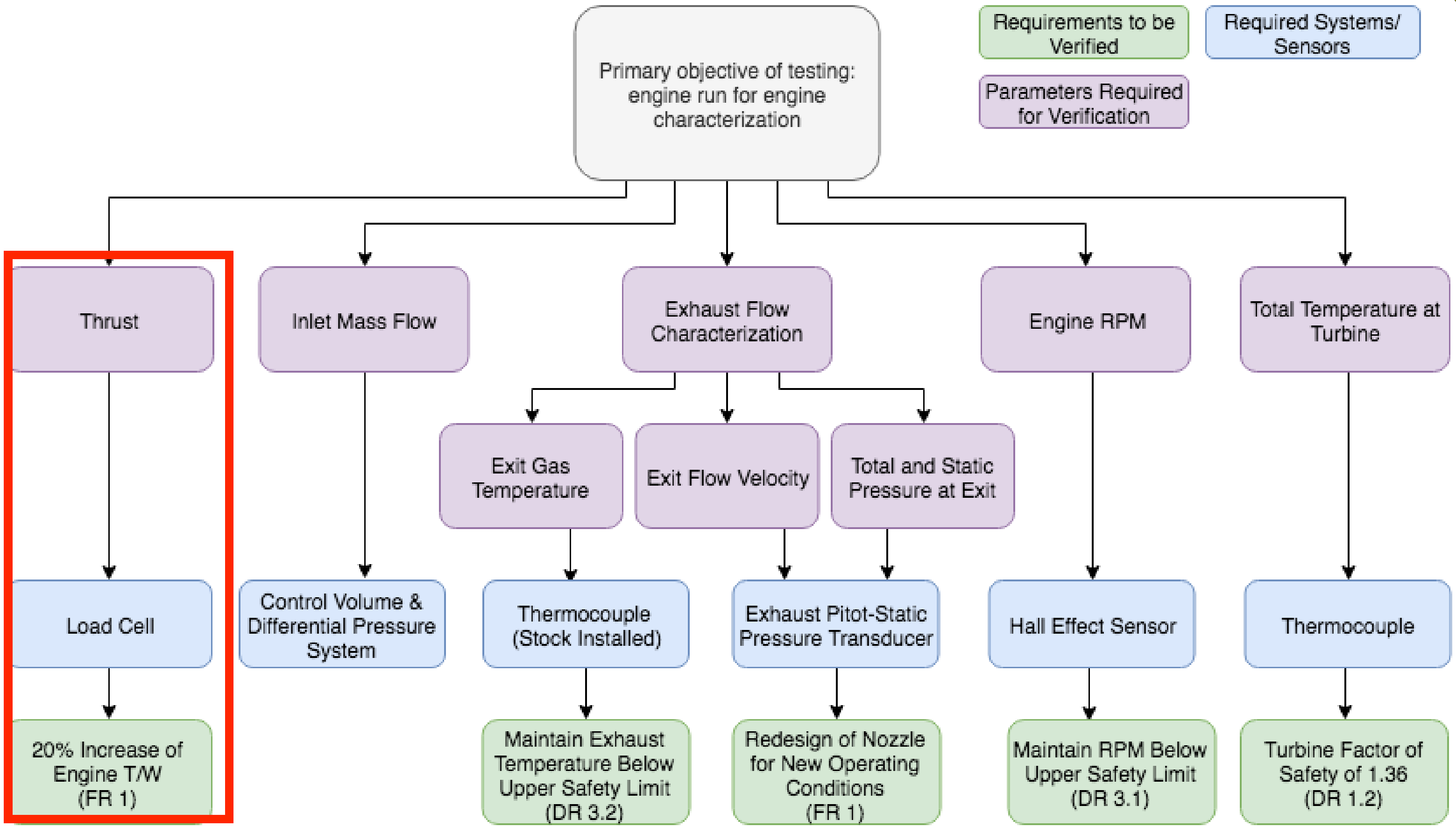
- Measure mass flow to verify simulation models
- Control volume created to measure inlet flow

Measurements:

- SPD1108R Differential Pressure sensor:
  - Range = 0 - 500 Pa ± 1%
  - Resolution = 0.0075 mV/Pa

SPD1108R Differential Pressure sensor

Thrust Modification Validation



Thrust Improvement Verification

Load Cell FC22

<u>Test Objectives</u>:

- Measure thrust and verify proper expansion of flow by nozzle.
- Engine Run 140,000 RPM Stock Nozzle
- Engine Run 140,000 RPM SPECS Nozzle

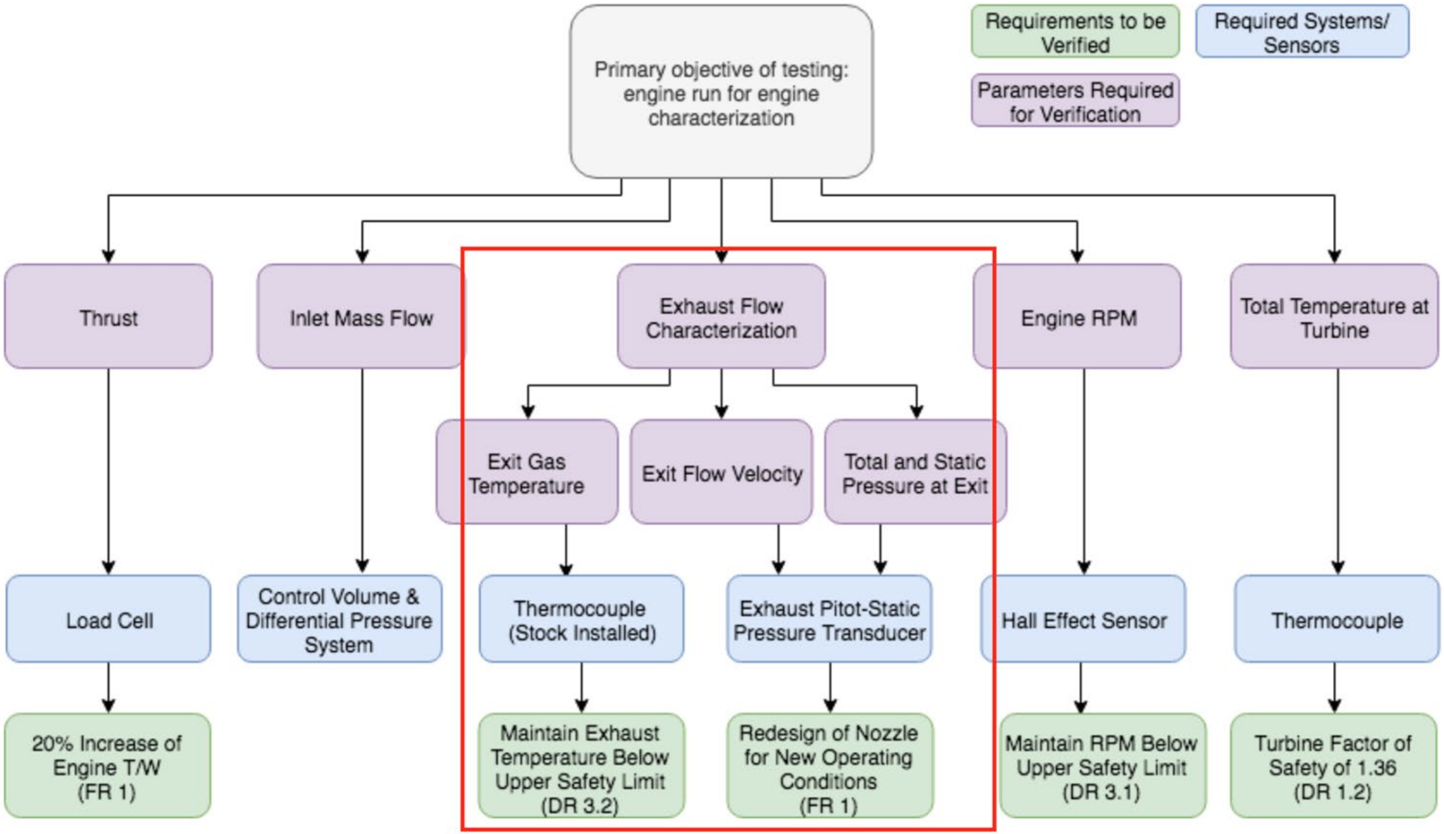
<u>Requirements Verified</u>:

- FR 1: 20% increase of T/W.

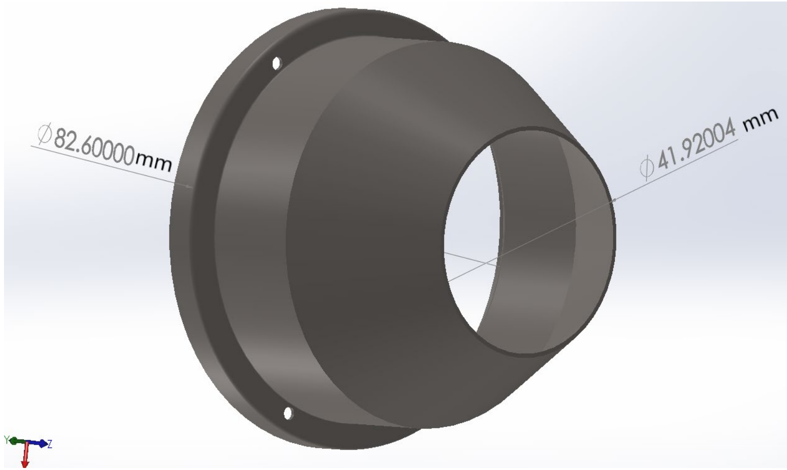
<u>Measurements</u>:

- Load Cell FC22:
  Range = 44.5 - 444.8 N ± 1%
  Resolution = 0.00125 mV/N

Exit Flow Validation



Exit Temperature Characterization



Re-designed Nozzle

Inconel Sheathed Thermocouple

<u>Test Objectives</u>:

- Measure the exit gas temperature

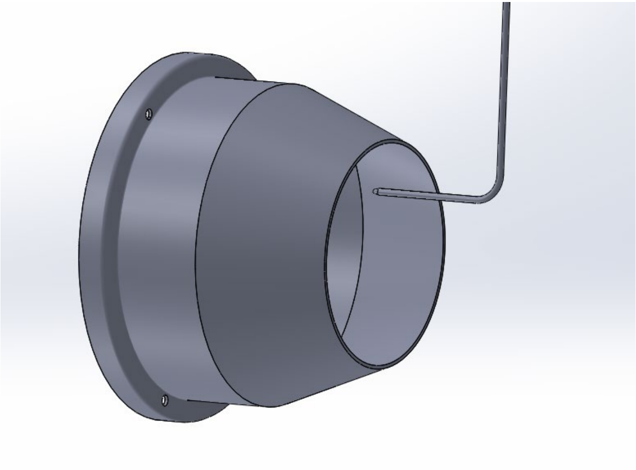
<u>Requirements Verified</u>:

- DR 3.2: SPECS will maintain EGT below 700° Celsius unless a new upper safety limit is determined.
- New safety limit was determined to be 730° Celsius

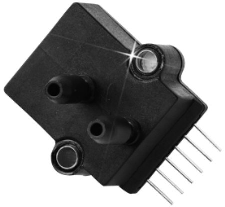
<u>Measurements</u>:

- JetCat Stock Thermocouple:
  Range = -100 to 1300°C ±1.1°C

Exit Flow Characterization



Nozzle Pitot Probe



Differential Pressure Transducer PX137-015DV

Test Objectives:

- Measure exit pressure differential to verify flow is properly expanded by modified nozzle

Requirements Verified:

- Model validation & thrust improvement

Measurements:

- Differential Pressure Transducer PX137-015DV:
  Range = 0-206.84 kPa ± 1.5%
  Resolution = 0.43 mV/kPa

DAQ Selection

National Instruments USB 6009 DAQ

- Selected USB 6009 for data acquisition
- 8 analog inputs for data collection
- Input Resolution: 13 bits
- Maximum Sampling Rate: 48 kS/s
- 500 Hz Square Wave on software timed digital I/O, sufficient for 150000 RPM simulation

Project Plans

Organizational Chart

- **AFRL**
  POC: Lt. Carol Bryant
  - **SPECS**
    - **Project Advisor** — *Prof. John Mah*
    - **Course Coordinator** — *Dr. Jelliffe Jackson*
    - **Project Manager** — *Greg Frank*
      - **Financial Lead** — *Daniel Castillo Oropeza*
      - **Systems Engineer** — *Sam Piper*
        - **Electrical** — *Dan Harthan*
          - **Electrical** — *Cedric Camacho*
        - **Mechanical** — *Markus Fuernkranz*
          - **Mechanical** — *Yuzhang Chen*, *Dan Harthan*
        - **Software** — *Madison Junker*
          - **Software** — *Preston Fitzrandolph*
        - **Simulation** — *Preston FitzRandolph*
          - **Simulation** — *Sam Piper*
        - **Testing** — *John Cutler*
          - **Testing** — *Daniel Castillo Oropeza*
        - **Thermo-Fluid** — *Matt Knickerbocker*
          - **Thermo-Fluid** — *Greg Frank*
        - **Manufacturing** — *Yuzhang Chen*
          - **Manufacturing** — *Markus Fuernkranz*
      - **Safety Lead** — *Cedric Camacho*

Work Breakdown Structure

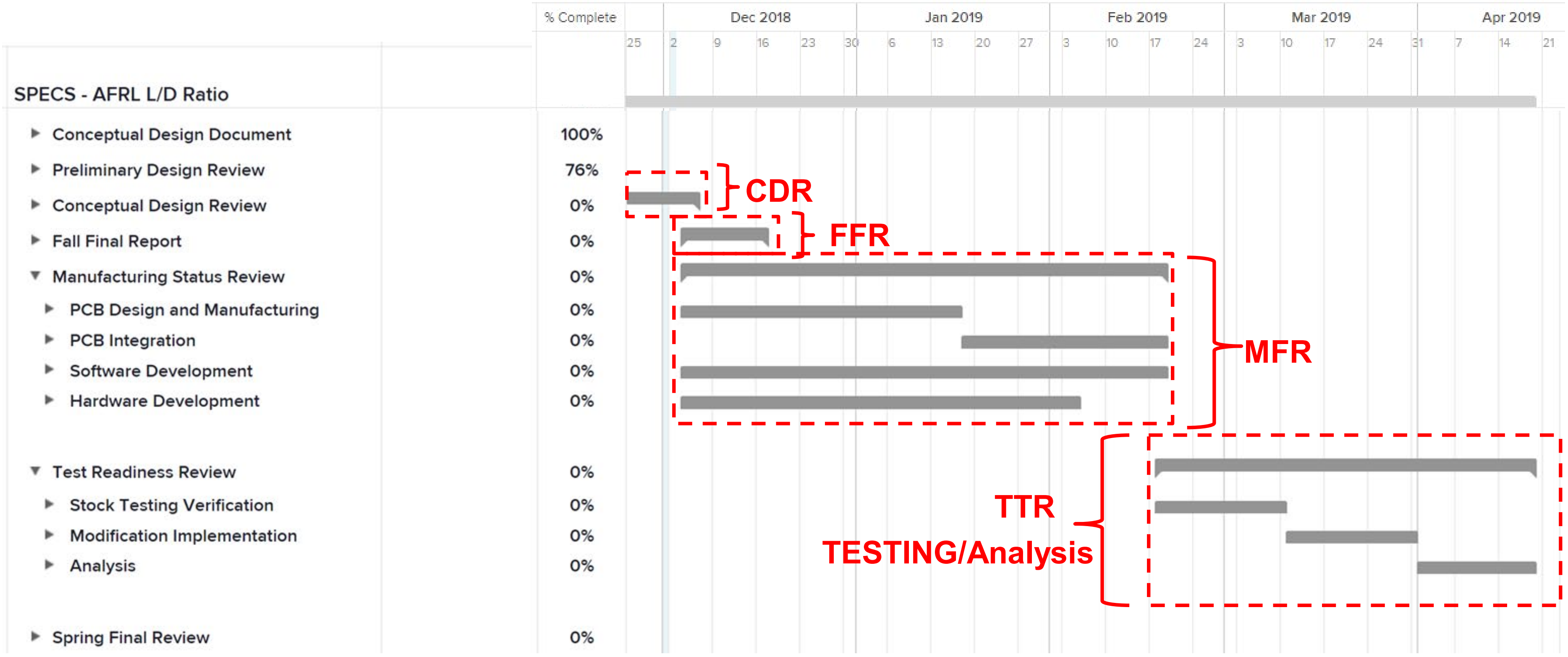
SPECS

- **Course Deliverables**
  - CDR
  - FFR
  - MSR
  - TTR
  - AIAA Paper
  - SFR
  - PFR
  - AFRL Competition
- **Management**
  - Schedule
  - Assess Risk
  - WBS
  - Budget
  - Part Procurement
  - Design Req. Satisfaction
- **Electrical**
  - PCB Design
  - PCB Sim.
  - Test Bed Development
  - Manufacture
    - PCB ECM
    - PCB ECU
  - Test Rig Integration
  - Engine Integration
- **Software & Simulation**
  - GUI Dev.
  - E-Stop
  - Engine Simulation
  - Controller - Simulation Interface
  - Control Algorithms
  - Anomaly - Safe Design
  - Refine Control
  - User Manual
- **Thermal - Mechanical**
  - Nozzle CAD
  - Spectroscopy Analysis
  - Data Based Model Refinement
  - Manufacture
    - Nozzle Al.
    - Nozzle Ti.
- **Testing**
  - Test Stand Design
  - Procedures
  - Safety Plan
  - Stock Eng. Run Data
    - Mass Flow
    - EGT
    - Glow Plug
    - RPM
    - Thrust
  - Modified Eng. Run

Legend

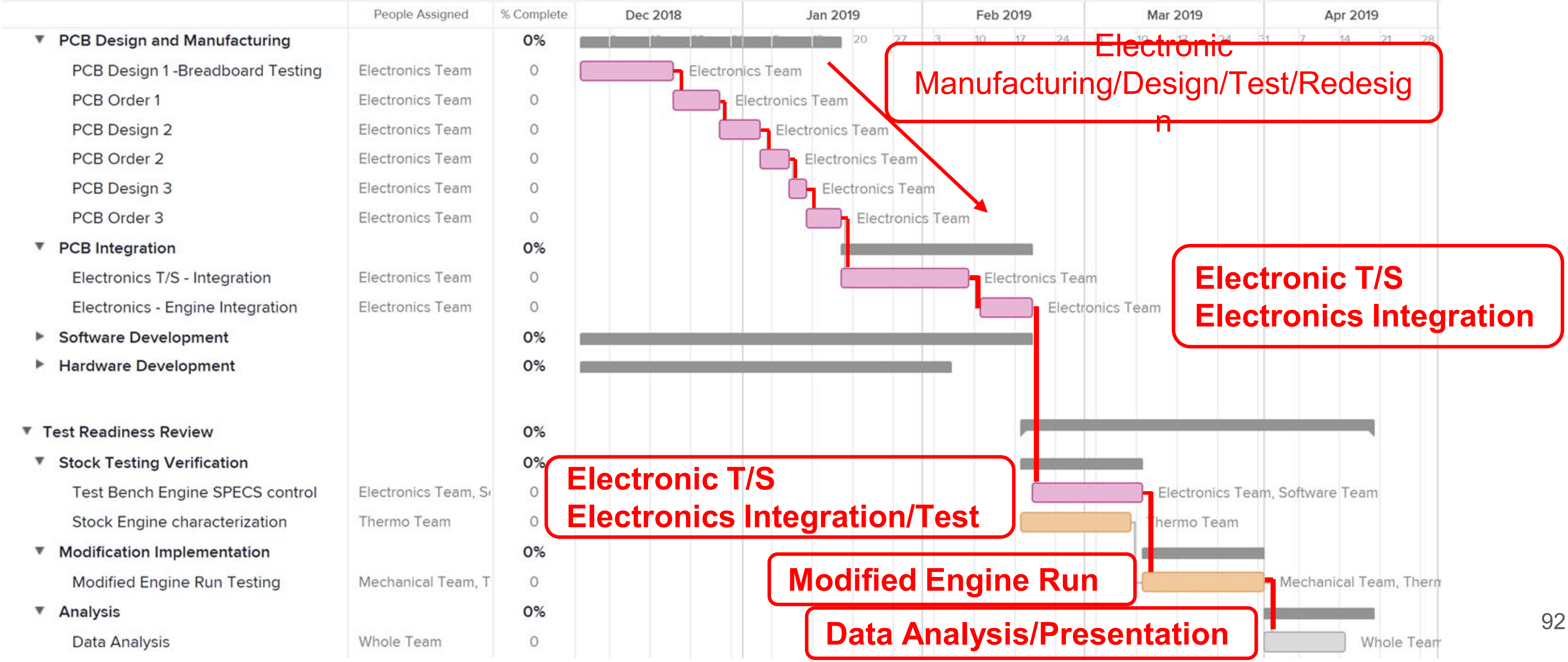
Completed	gray
Future Work	yellow

Project Planning



Project Planning

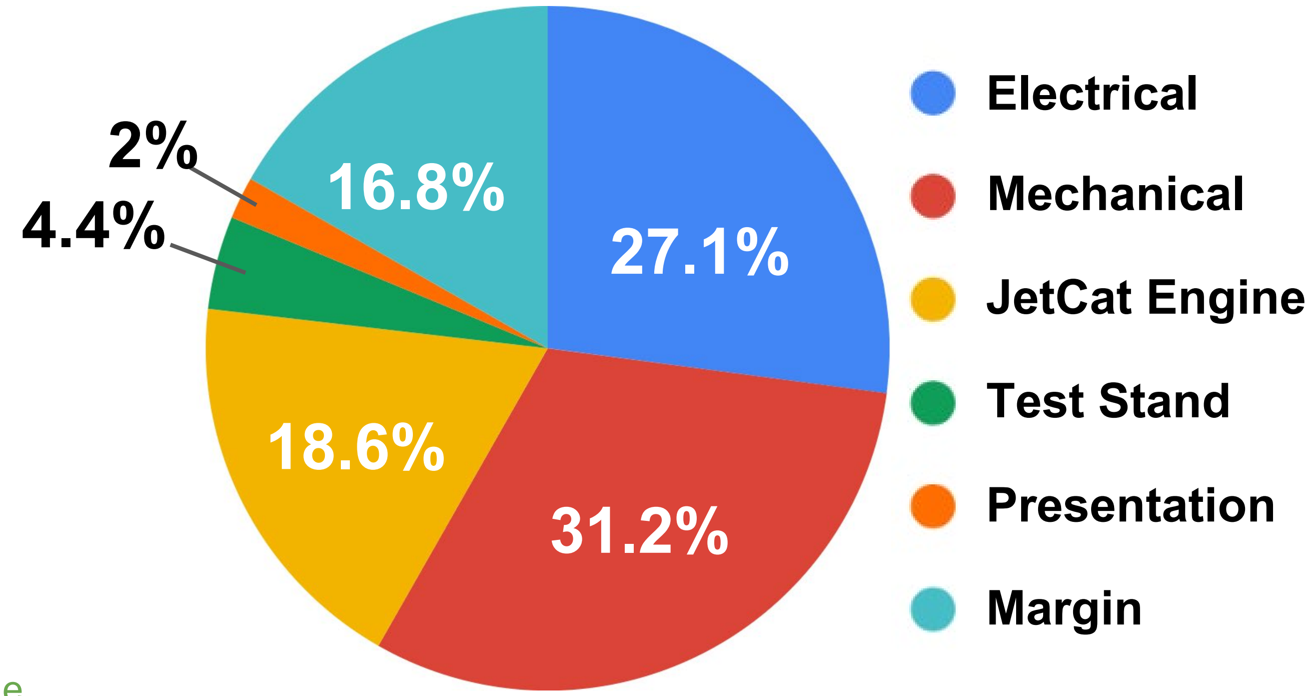
Thermo
Mechanical
Electronics
Critical Path
Critical Events



Cost Plan

	Costs
Electrical	$ 1354.70
Mechanical	$ 1557.55
Engine	$ 930.00
Test Bed	$ 220.00
Presentation	$ 100.00
Total	$ 4162.25
Budget	$ 5000.00
Margin	$ 837.75

- Margin is positive, therefore the project is financially feasible



Cost Plan Major Items + EEF

High Cost Items	Cost
Titanium Round Bar 3.75” x 10”	$1307.55
Custom PCB (ECU/ECM) 3 Iterations	$792.00
JetCat V.10 ECU	$500.00
JetCat Refurbishment	$400.00

Requested EEF Fund

- New JetCat P90-Rxi Engine: $2195.00
- JetCat V.10 ECU: $500.00
- Test Stand Refurbishment: $200.00
- Differential Pressure Transducer: $100.00

Total: $2995.00

Upcoming Testing Schedule

Test to be Conducted	Date Scheduled	Test Plan	Materials	Facility	Test Completed
Test Rig "Engine Run" 1	28 DEC	✓	● PCB 1.0	ITLL/EC	●
Test Rig "Engine Run" 2	07 JAN	✓	● PCB 2.0	ITLL/EC	●
Test Rig "Engine Run" 3	16 JAN	✓	● PCB 3.0	ITLL/EC	●
Test Rig Anomaly Simulation Interface	11 FEB	✓	● PCB 3.0	ITLL/EC	●
Stock Engine Run Start	18 FEB	✓	●	* CU Boulder E. Power Plant	●
SPECS Engine Run Start	11 MAR	✓	●	* CU Boulder E. Power Plant	●

Completed	✓
In-Progress	●

* 1 week notice + test plan required for engine run at CU Boulder E. Power Plant

Questions?

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[11] Evans, Ceri & Rees, David & Hill, Dave. (1998). Frequency-domain identification of gas turbine dynamics. Control Systems Technology, IEEE Transactions on. 6. 651 - 662. 10.1109/87.709500.

[12] Daniel Alonzo, Alex Crocker, Eric James, John Kingston III, “Design and Manufacturing of a Miniature Turbojet Engine”, Worchester Polytechnic Institute, March 23, 2018, retrieved 20 October 2018

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[13] Robert Canfield, Craig Woolsey, “Development and Implementation of a Flight Test Program for a Geometrically Scaled Joined Wing SensorCraft Remotely Piloted Vehicle”, Virginia Polytechnic Institute, October 5, 2011, retrieved 20 October 2018

[14] Jason A. Widegreen and Thomas J. Bruno, “Thermal Decomposition Kinetics of the Aviation Turbine Fuel Jet A”, NIST, 2008, retrieved 28 October 2018

Backup Slides

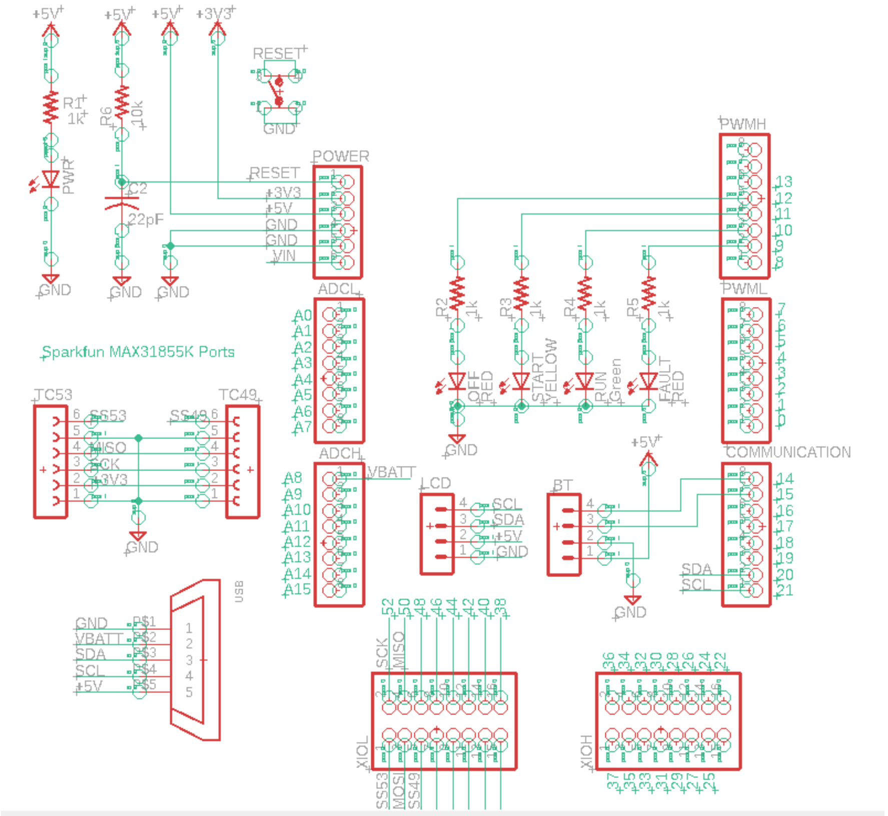
Electronics

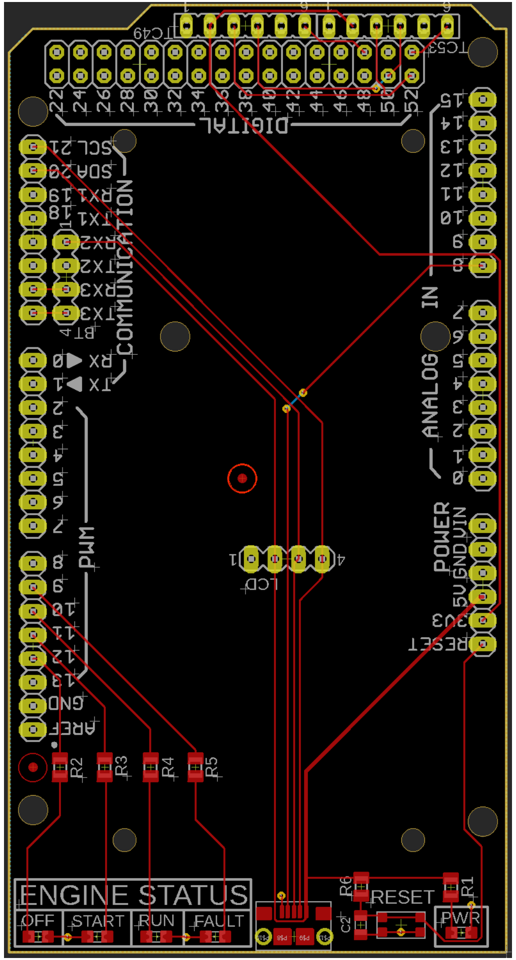
I2C vs. SPI & Why

GUI ← SPI → ECU ← I2C → ECM ← SPI → EGT

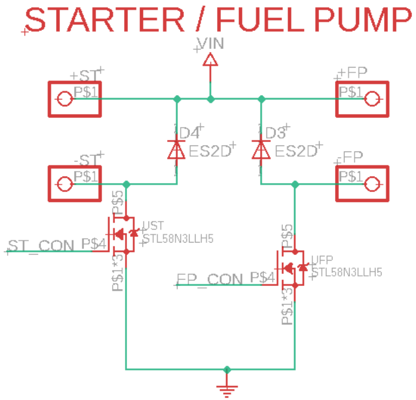
- Problem: ECM has master emergency control of engine. With SPI only one master device, Master initiates communications.
- If ECM is SPI master, cannot guarantee that E-Stop from GUI would be read in an emergency, internal interrupts would overwrite incoming commands.
- If ECU is SPI master, EGT is a native SPI device, EGT monitoring could not occur on ECM. Adds complexity, EGT required for sequence and monitoring resulting in multiple transmissions between devices.
- Solution: Use both
    - ECM as SPI master and ECU as I2C master.

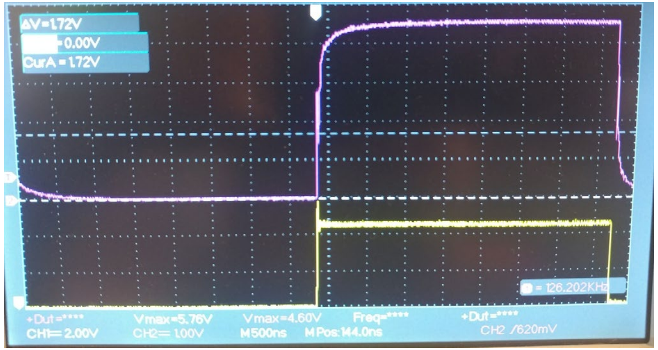
ECU Shield PCB

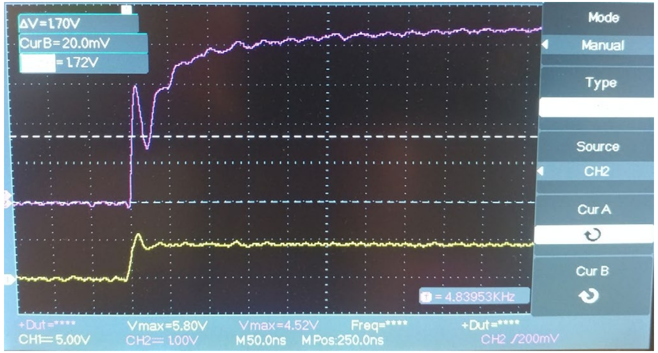




Motor Control Circuit (Starter / Fuel Pump)







PWM frequency must be greater than 5τ for stable operation, higher PWM results in smooth operation with less noise.

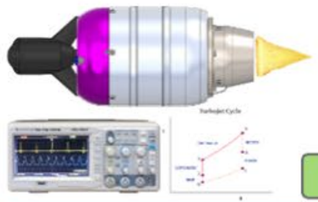
$$V_L(t) = Ve^{-t\frac{R}{L}}$$

$$V_R(t) = V(1 - e^{-t\frac{R}{L}})$$

Calculated optimal PWM = 1.138kHz
Setpoint = 976.56 Hz (Closest Prescale > 5τ)

$$\tau = \frac{L}{R}$$

Concept of Operations (SPECS)



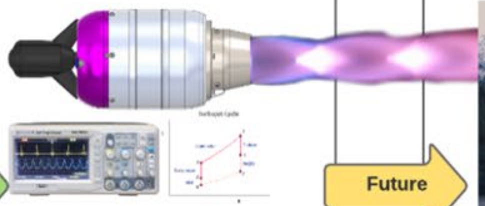
Using JetCAT electronics test engine performance. Identify control methods and develop baseline.

Remove all JetCAT electronic control components. Starter, fuel pump, temp sensors ignition system remain.

PROJECT SPECS

Specialized Propulsion Elecectonic Control System

Install SPECS ECU/ECM control system onto JetCAT turbojet engine. Install additional sensors.



Tune system performance to approach new safe operation limits to improve thrust to weight ratio.

Future

SPECS controller will allow future engine modification beyond stock system capabilities.

Effect of Thermal Expansion on Nozzle Area

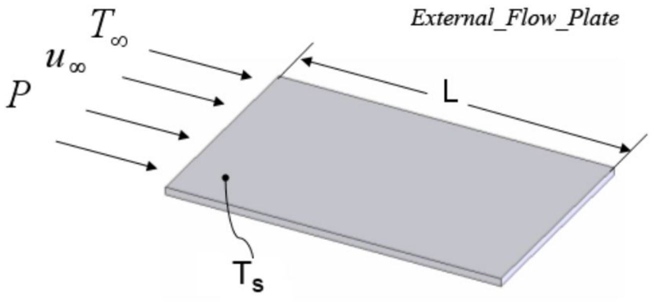
Material	Thermal Coefficient	Area After Expansion	Percentage Change
Ti 6AL-4V	$7x10^{-6}$ in/in/F	498.8226 mm^2	1.6193 %
Inconel 718	$11x10^{-6}$ in/in/F	503.3934 mm^2	2.5505 %
Cobalt Chrome	$8.4x10^{-6}$ in/in/F	500.4152 mm^2	1.9439 %
N60 Stainless Steel	$10.3x10^{-6}$ in/in/F	502.5904 mm^2	2.3869 %

Thermomechanical Calculations

Modeling the heat transfer into the turbine blades due to the combustion gases with a Convective heat flux on a flat plate:

$$h = \frac{k}{L}\left(0.037Re^{0.8}Pr^{1/3}\right)$$

$$Pr = \frac{\mu c_p}{k} \quad Re = \frac{\rho V L}{\mu}$$

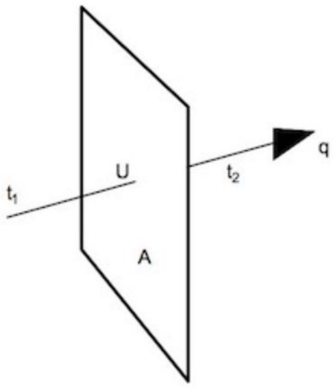


Thermomechanical Calculations

Modeling the heat transfer out of the turbine blades due to the cooling oil with a surface heat flux on a flat plate:

$$\Delta h = m c_p \Delta T$$

$$q = \dot{m} \Delta h c_p$$

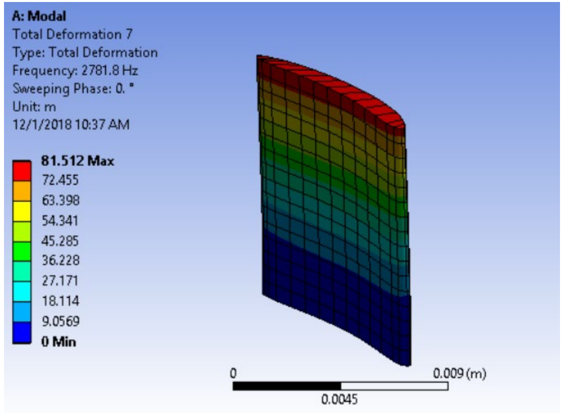


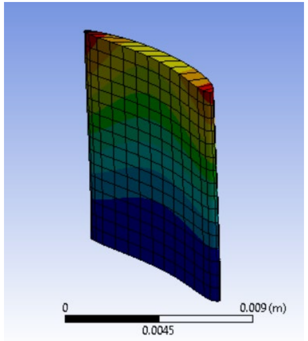
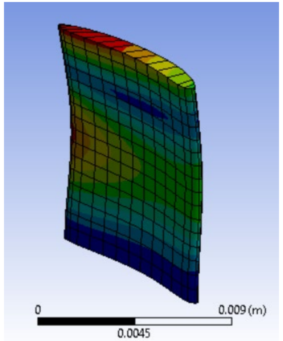
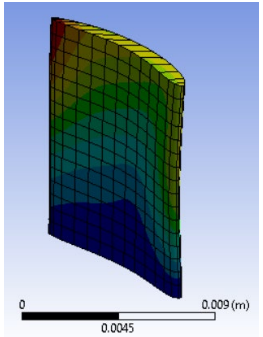
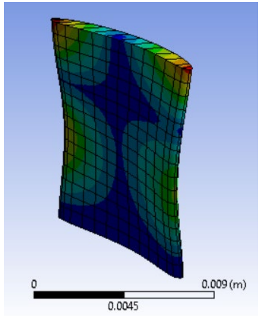
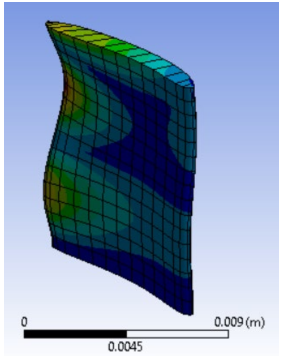
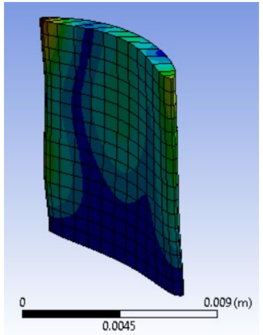
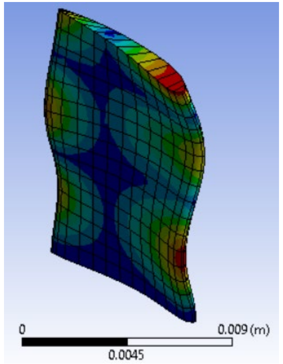
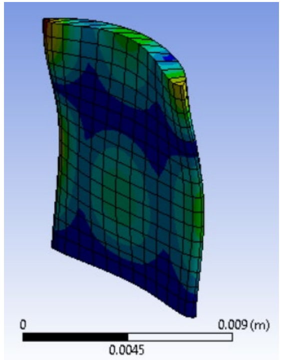
Shaft Assembly FEA Results

Component (Stock)	MATERIAL	YIELD STRENGTH OF MATERIAL	Maximum Stress	S.F.
COMPRESSOR	Al 7075	440.57 MPa	223.5 MPa	1.97
SHAFT	AISI 301	2123.60 MPa	279 MPa	7.61

- Component materials were determined from Alibaba, a vendor of JetCat replacement parts
- All material properties were found in
  - Military Handbook-5H --- Metallic Materials and Elements for Aerospace Vehicle Structures

Modal Blade FEA



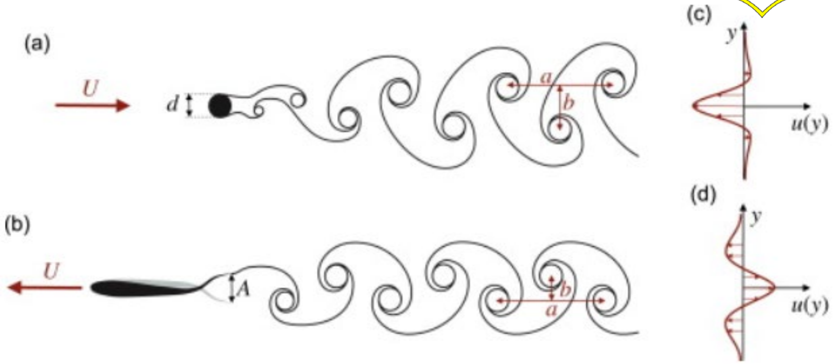
Vibration

- Strouhal Number:

$$St = \frac{fL}{V}$$

- Blade Passing Frequency:

$$BPF = \frac{nt}{60}$$



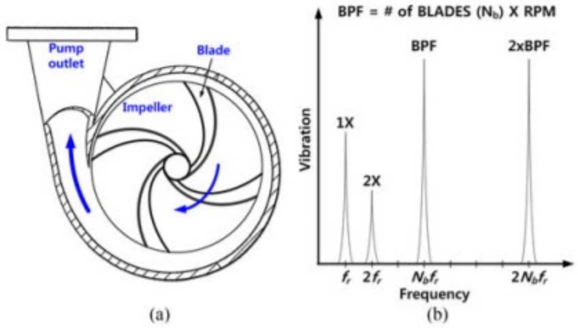


Fig. 1. (a) Centrifugal pump with a 4-blade impeller ($N_b = 4$), and (b) vibration spectrum for pump/fan/compressor with four blades/cylinders.

Fatigue

- Marin Factors:

$$S_e = K_a K_b K_c K_d K_e K_f S_e'$$

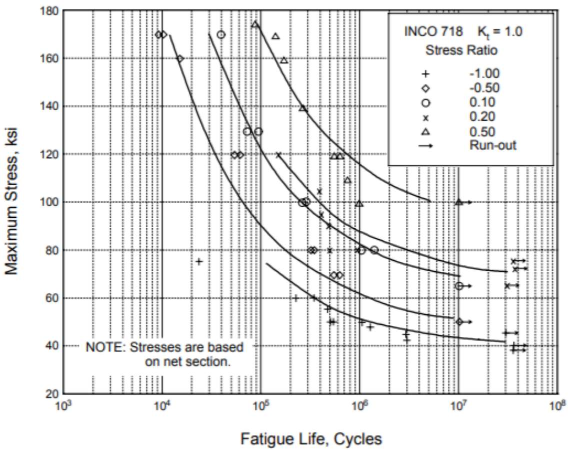


Figure 6.3.5.1.8(a). Best-fit S/N curves for unnotched Inconel 718 sheet at room temperature, long transverse direction.

Creep

- Arrhenius Equation:

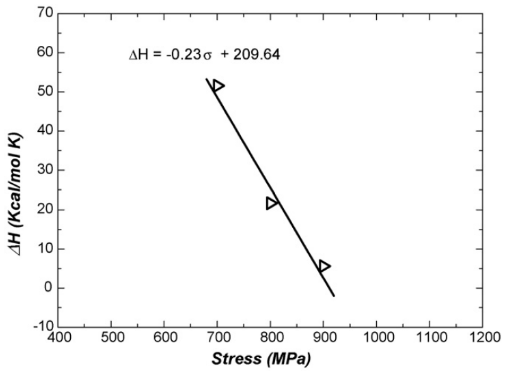
$$\dot{\epsilon}_s = Ce^{-Q/RT}$$

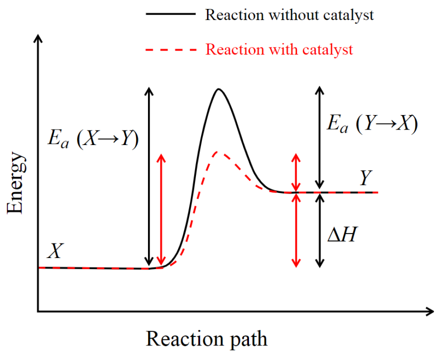
  - Activation Energy Approximation:

$$\Delta H = -0.23\sigma + 209.64$$

- Power Relation:

$$\dot{\epsilon}_s = (\frac{\sigma}{E})^n$$





Creep

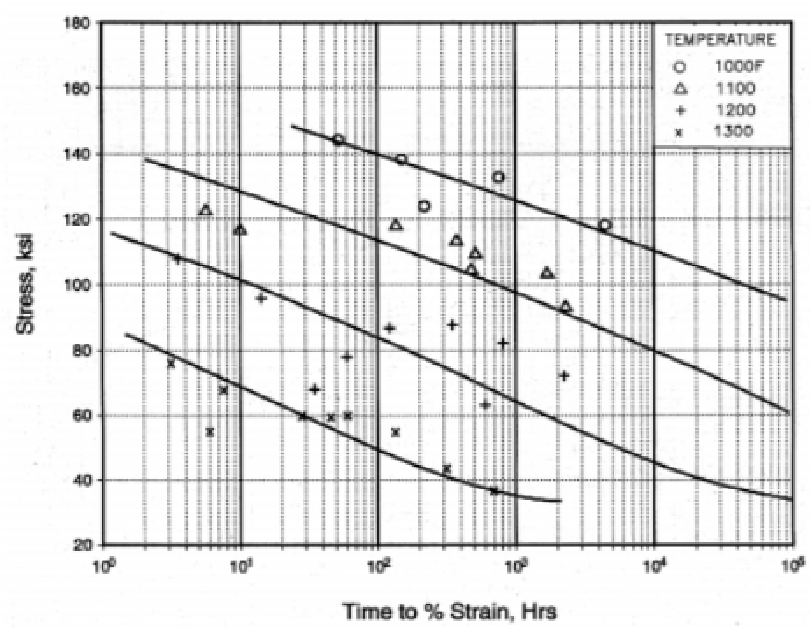
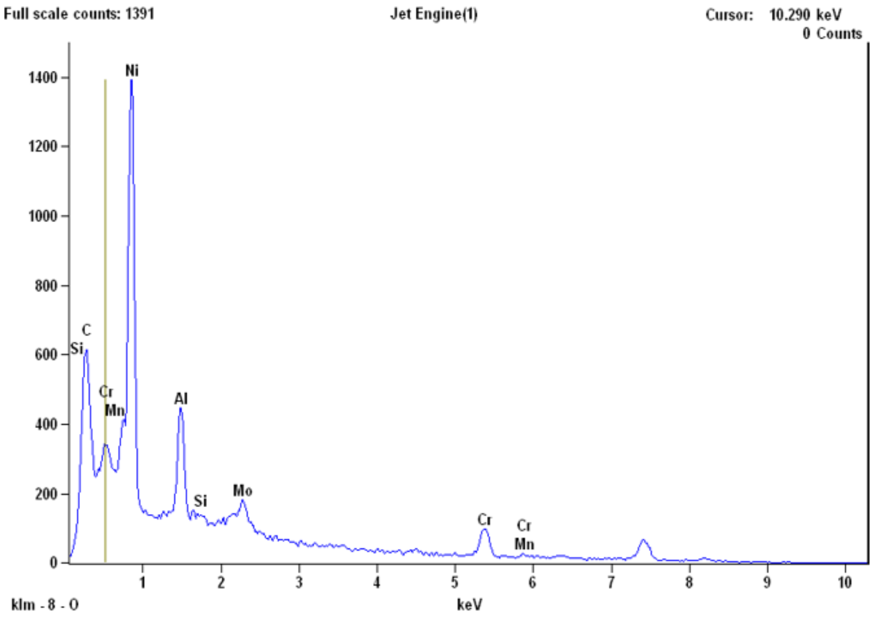


Figure 6.3.5.1.7(a). Average isothermal 0.10% creep curves for Inconel 718 forging.

EDS Spectroscopy Results



EDS spectral of jet engine material sample at point #1.

Net Counts

	C-K	Al-K	Si-K	Cr-K	Mn-K	Ni-L	Mo-L	Ta-M
Jet Engine(5)	5549	2535	156	755	100	7770		
jet engine(1)	5644	2662	174	1064	0	11861	957	
jet engine(2)	6023	2498	73	803		8880		
jet engine(3)	5516	2294	126	888		7989		
jet engine(4)	5879	2088	0	795		8711	751	160

Summary of EDS signals tested at 5 different locations. C, Ai, Si, Cr, Ni are found in all of 5 locations. Mn, Mo, and Ta are found in several points.

WARNING: DO NO PUBLISH THIS SLIDE

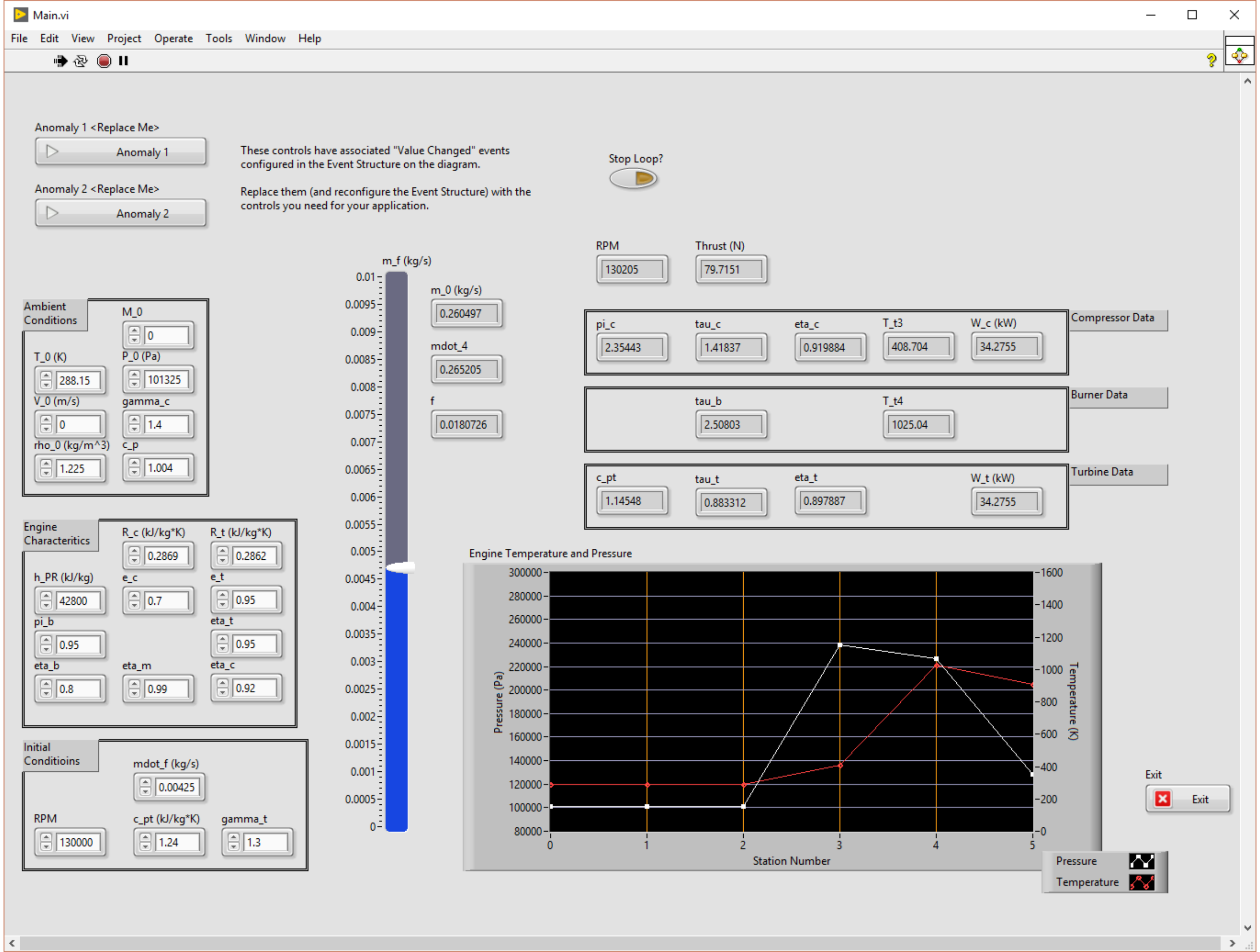
FAILURE MODE AND EFFECTS ANALYSIS

Item: JetCat P90-Rxi
Model: Current
Core Team: S. P.(Systems), G. F. (PM), M. F. (Mech), M. K. (Therm), D. H. (Electr)
Responsibility: S. Piper
Prepared by: S. Piper
FMEA number: 1
Page : 1 of 1
FMEA Date (Orig): 11/2/2018 Rev: 3

Process Function/Part	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results: Actions Taken	Sev	Occ	Det	RPN
Turbine Blades	High-Cycle Fracture	Damage Engine/ Personnel Harm	4		Torsional Resonance/ Design Factors	3	Design Criteria	4	48	None						0
	Low-Cycle Fracture	Damage Engine/ Personnel Harm	4		Improper Heat Treatment	2	Design Criteria	4	32	None						0
	Intragranular Fracture	Damage Engine/ Personnel Harm	4		Blade Over Heating	3	Thermo Analysis	3	36	Refine Thermo Analysis	M.F. (Nov 2018)		4	2	3	24
	Creep	Damage Engine/ Personnel Harm	4		Local Recrystallization from Heat	2	Thermo Analysis	3	24	Refine Thermo Analysis	M.F. (Nov 2018)		4	1	3	12
	Fatigue	Damage Engine/ Personnel Harm	4		Thermal/ Centrifugal Stress	3	Thermo Analysis	3	36	Refine Thermo Analysis	M.F. (Nov 2018)		4	2	3	24
	Cracking	Damage Engine/ Personnel Harm	4		Thermal Stress/ Fatigue and Corrosion	2	Thermo Analysis	3	24	Refine Thermo Analysis	M.F. (Nov 2018)		4	1	3	12
	Corrosion	Damage Engine/ Personnel Harm	2		Fuel Impurities	1	Fuel Filter	1	2	None						0

	Deformation	Damage Engine/ Personnel Harm	4		Overspeed and Low Yield Strength	4	Manual Fuel Limiting	1	16	Implement automatic controls	D.H. (Jan 2019)					0
Compressor Blades	FOD Damage	Replace Compressor	3		FOD Inhalation	2	Operating Procedures	2	12	Implement safety protocols during testing	S.P. (Jan 2019)					0
	Cracking	Replace Compressor	3		FOD Inhalation, Corrosion	2	Operating Procedures	2	12	Implement safety protocols during testing	S.P. (Jan 2019)					0
	Corrosion	Replace Compressor	2		Operating Environment, Surface Imperfections	1	Operating Procedures	3	6	None						0
	Deformation	Replace Compressor	2		Overspeed and Low Yield Strength	2	Manual Fuel Limiting	1	4	Implement automatic controls	D.H. (Jan 2019)					0
	Fracture	Damage Engine/ Personnel Harm	3		Improper Materials, Corrosion	1	Design Criteria	3	9							0
	Blade Tip Wear	Replace Compressor	2		Engine Wear	2	Regular Maintenance	3	12	Contact Manufacturer to Schedule maintenance as needed	M.F. (Jan 2019)					0
Bearings	Housing Fracture	Replace Core	2		Fatigue, Excessive Loading	2	Regular Maintenance	3	12	Contact Manufacturer to Schedule maintenance as needed	M.F. (Jan 2019)					0
	Excessive Outer Race Wear	Replace Core or Bearing	1		Contamination	2	Fuel Filter	1	2	None						0

	Bearing Siezure	Replace Core or Bearing	1		Contamination, Excessive Loading	1	Fuel Filter	1	1	Assess Bearing Radial Loading Capability	M.F. (Nov 2019)					0
	Outer Race Interface Wear	Replace Core or Bearing	1		Excessive Thrust Loading	2	Loading Limits	3	6	Assess Bearing Axial Loading Capability	M.F. (Nov 2019)					0
	Bearing Outer Race Fracture	Replace Core or Bearing	2		Fatigue, Excessive Loading	1	Loading Limits	3	6	Assess Bearing Radial Loading Capability	M.F. (Nov 2019)					0
	Bearing Fracture	Replace Core or Bearing	2		Fatigue, Excessive Loading	1	Loading Limits	3	6	Assess Bearing Radial Loading Capability	M.F. (Nov 2019)					0
	Flow Channel Blockage	Clean Channels or Replace Core	1		Contamination	1	Fuel Filter	1	1	None						0
	Corrosion	Replace Bearing	2		Contamination	1	Fuel Filter	1	2	None						0
Shaft	Torsion Fracture	Replace Shaft	2		Excessive Loading	1	Operating Limits	2	4	Assess Shaft Loading Capability	M.F. (Nov 2019)					0
	Thread Wear	Replace Shaft	1		Vibration	1	Design Criteria	3	3	None						0
	Shaft Twisting Deformation	Replace Shaft	1		Stress	1	Operating Limits	3	3	Assess Shaft Loading Capability	M.F. (Nov 2019)					0
	Excessive Inner Race Wear	Replace Shaft	2		Contamination	2	Fuel Filter	1	4	None						0
	Inner Race Interface Wear	Replace Shaft	1		Excessive Thrust Loading	1	Loading Limits	3	3	Assess Bearing Axial Loading Capability	M.F. (Nov 2019)					0
	Bearing Siezure	Replace Shaft or Bearing	2		Contamination, Excessive Loading	1	Fuel Filter	1	2	Assess Bearing Radial Loading Capability	M.F. (Nov 2019)					0
	Bearing Inner Race Fracture	Replace Shaft	2		Fatigue, Excessive Loading	1	Loading Limits	3	6	Assess Bearing Radial Loading Capability	M.F. (Nov 2019)					0
Pressure Vessel	Nozzle/Inlet Interface Leakage	Condition Interface	1		Surface Scoring/Excessive Pressure	2	Operating Limits	3	6	None						0
	Vessel Rupture	Replace Pressure Vessel	3		Excessive Pressure/Heat	2	Operating Limits	3	18	Assess Hoop Stress Limits	M.F. (Oct 2019)					0



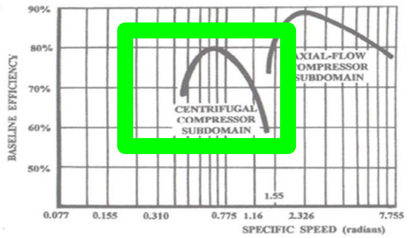
Main.vi
File Edit View Project Operate Tools Window Help
Anomaly 1 <Replace Me>
Anomaly 1
Anomaly 2 <Replace Me>
Anomaly 2
These controls have associated "Value Changed" events configured in the Event Structure on the diagram.
Replace them (and reconfigure the Event Structure) with the controls you need for your application.
Stop Loop?
Ambient Conditions
M_0 0
T_0 (K) 288.15
P_0 (Pa) 101325
V_0 (m/s) 0
gamma_c 1.4
rho_0 (kg/m^3) 1.225
c_p 1.004
Engine Characteritics
R_c (kJ/kg*K) 0.2869
R_t (kJ/kg*K) 0.2862
h_PR (kJ/kg) 42800
e_c 0.7
e_t 0.95
pi_b 0.95
eta_t 0.95
eta_b 0.8
eta_m 0.99
eta_c 0.92
Initial Conditioins
mdot_f (kg/s) 0.00425
RPM 130000
c_pt (kJ/kg*K) 1.24
gamma_t 1.3
m_f (kg/s)
m_0 (kg/s) 0.260497
mdot_4 0.265205
f 0.0180726
RPM 130205
Thrust (N) 79.7151
Compressor Data
pi_c 2.35443
tau_c 1.41837
eta_c 0.919884
T_t3 408.704
W_c (kW) 34.2755
Burner Data
tau_b 2.50803
T_t4 1025.04
Turbine Data
c_pt 1.14548
tau_t 0.883312
eta_t 0.897887
W_t (kW) 34.2755
Engine Temperature and Pressure
Pressure (Pa)
Temperature (K)
Station Number
Pressure
Temperature
Exit

Predictive Model

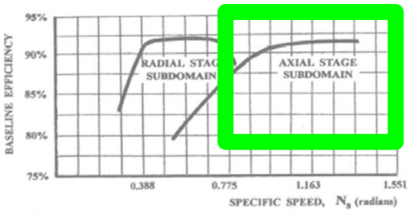
Advanced engine model required to test ECU/ECM prior to installation on hardware

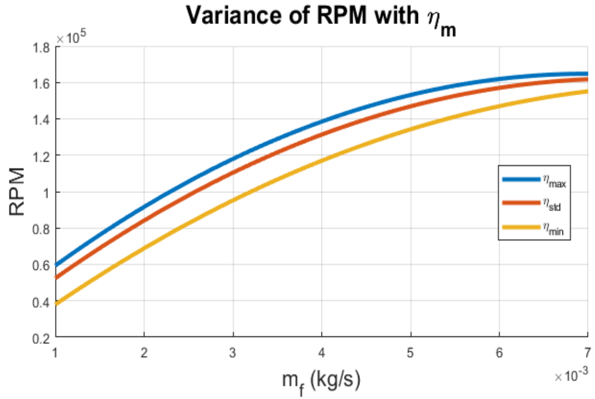
Incorporation of component efficiencies provides more accurate results (<2% error on test/manufacturer data)

Compressors



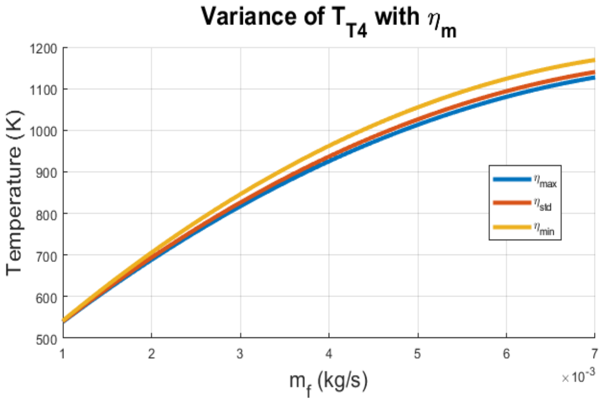
Turbines





Verifies Model

...with manufacturer/ past test data

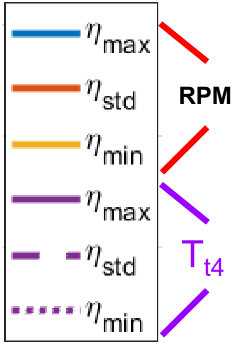


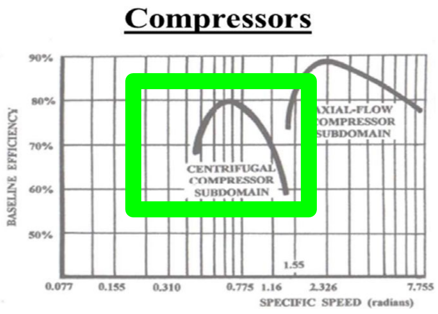
...with theoretical model and future T_t4 test data

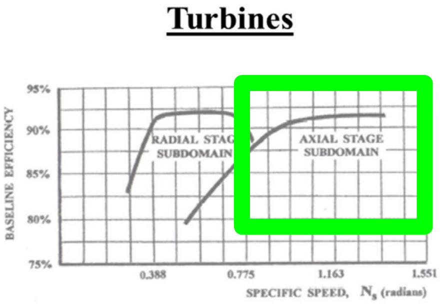
Simulation

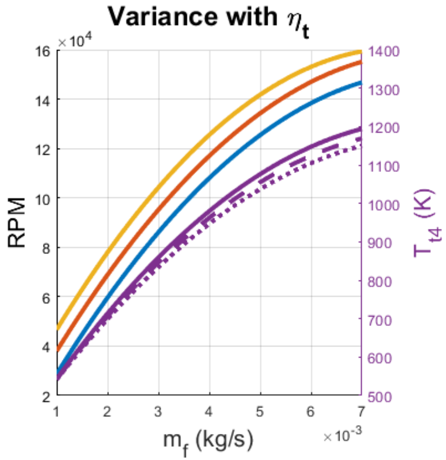
Thermodynamic analysis necessitates a more advanced model

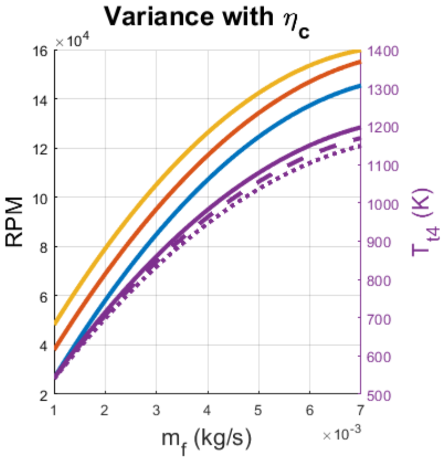
Incorporation of component efficiencies provides more accurate results (<2% error from engine data)

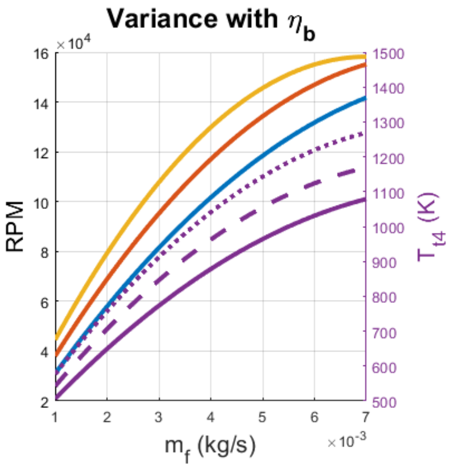


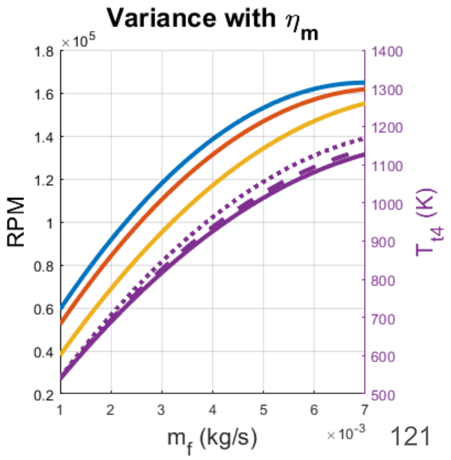


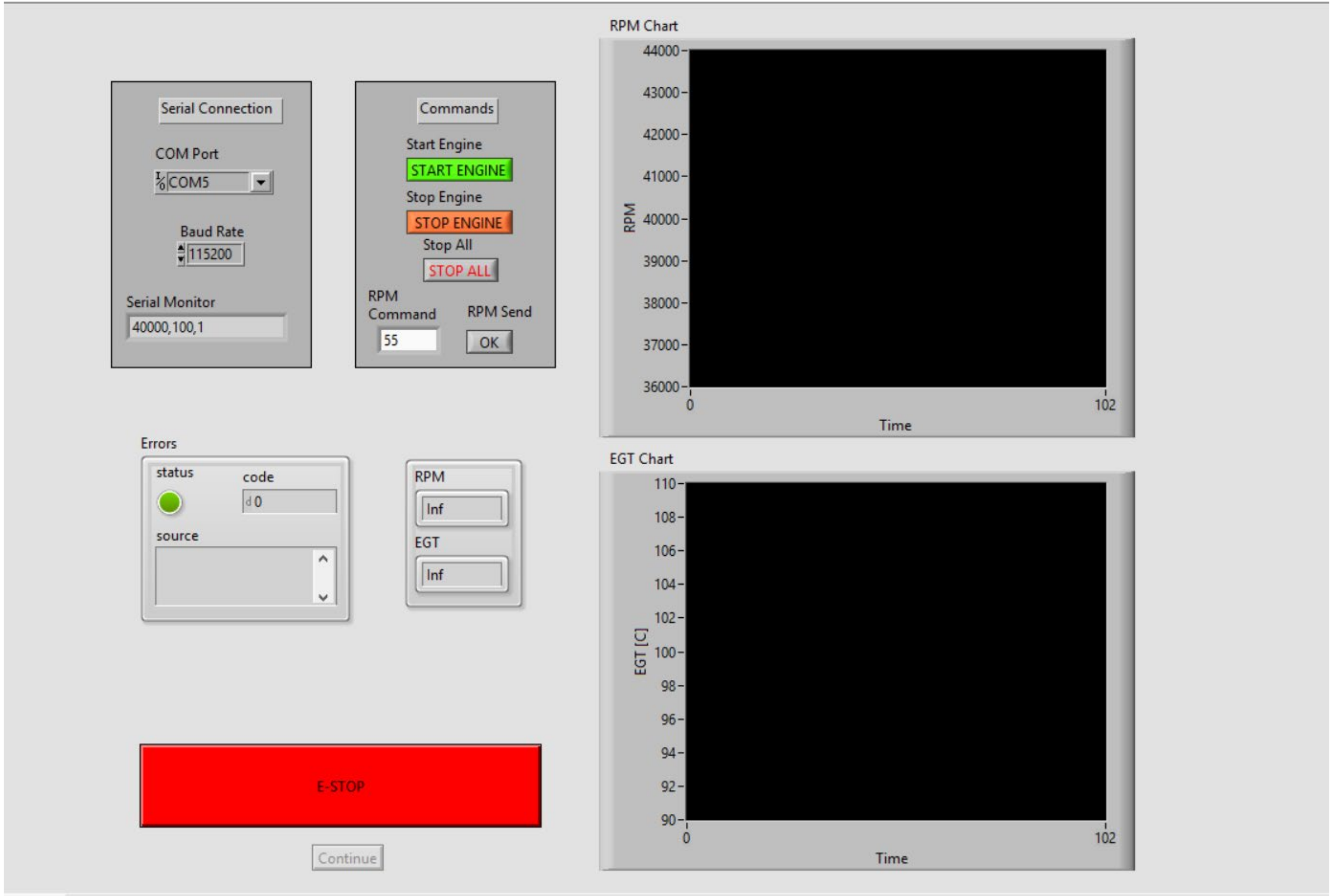




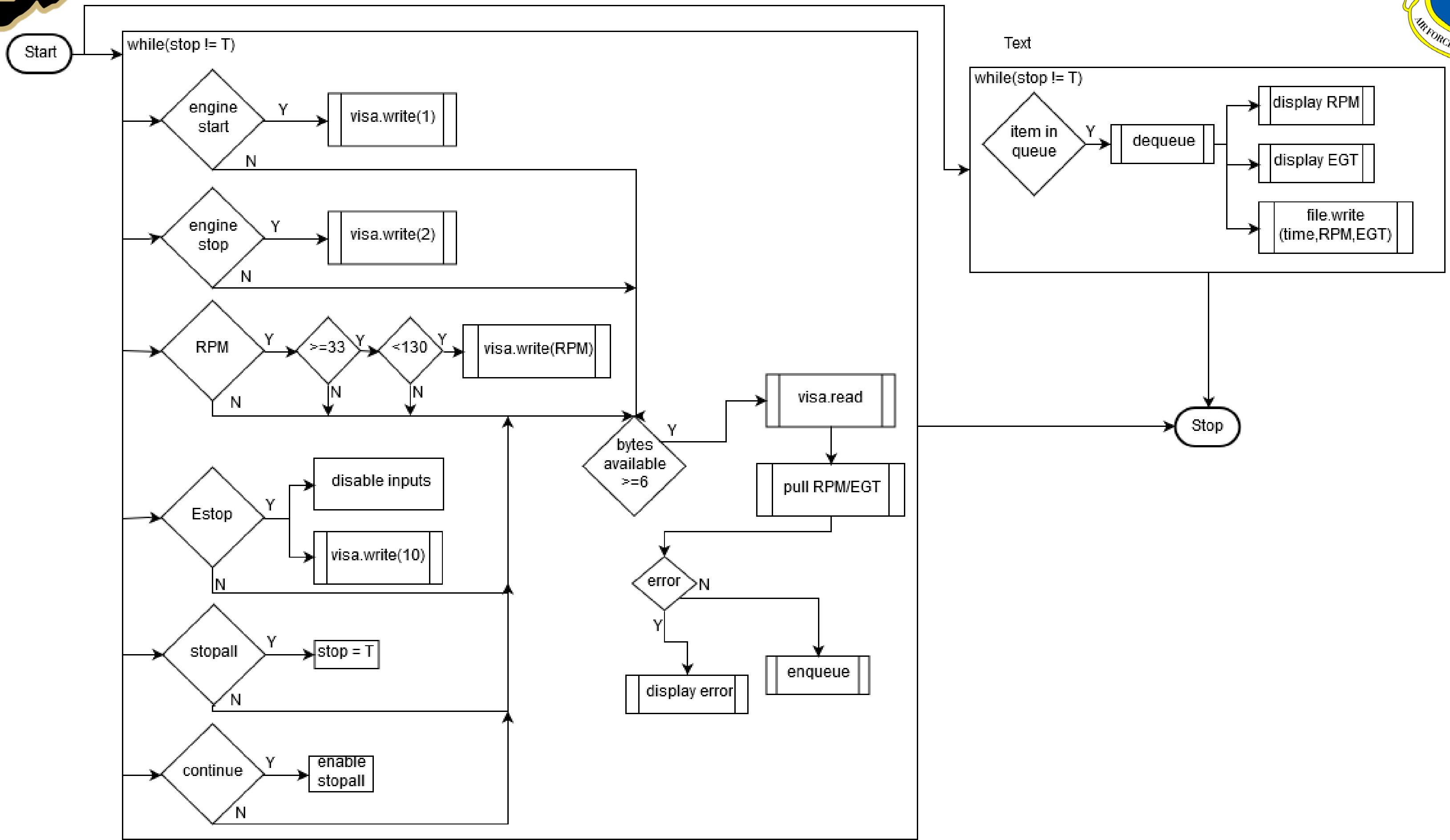




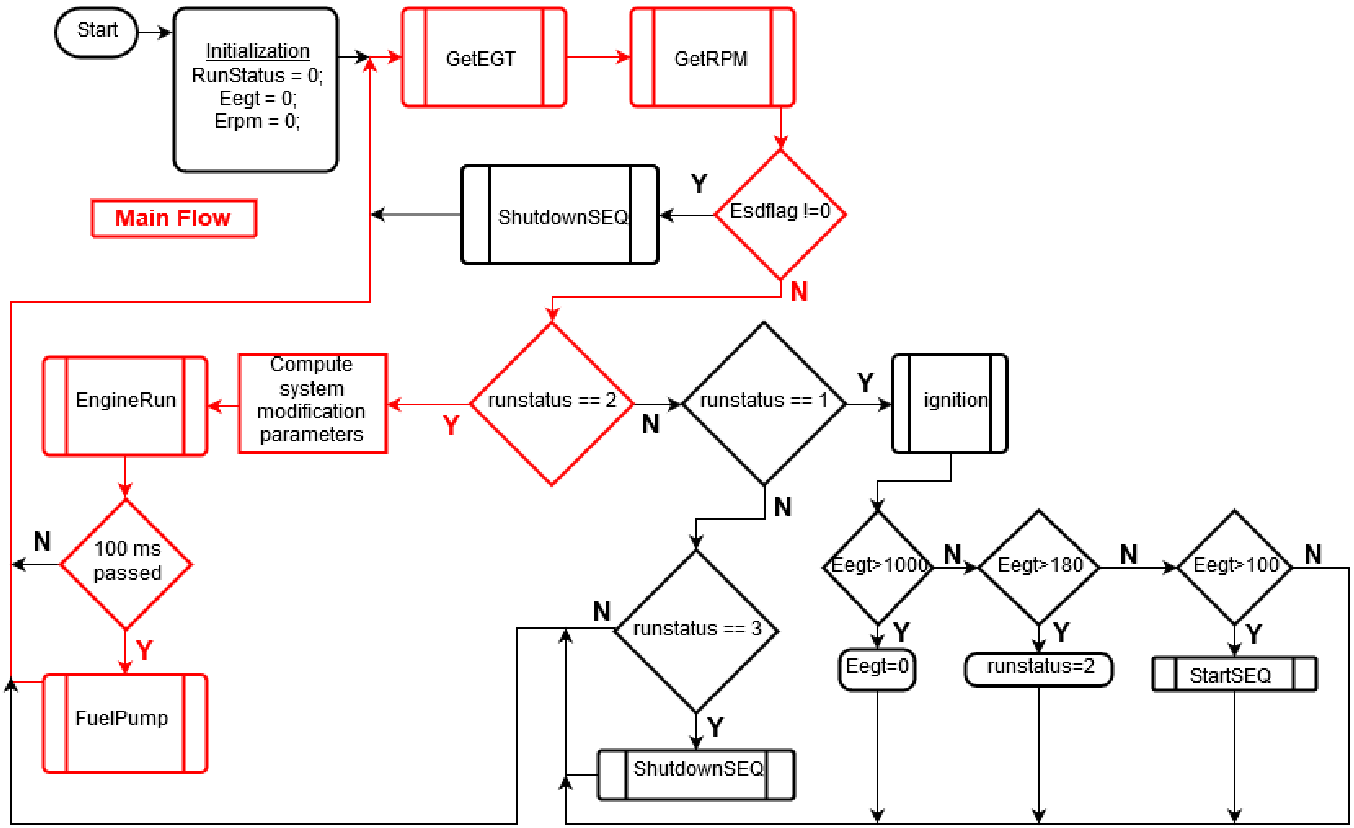



Serial Connection
COM Port
COM5
Baud Rate
115200
Serial Monitor
40000,100,1
Commands
Start Engine
START ENGINE
Stop Engine
STOP ENGINE
Stop All
STOP ALL
RPM Command
55
RPM Send
OK
Errors
status
code
0
source
RPM
Inf
EGT
Inf
E-STOP
Continue
RPM Chart
RPM
44000
43000
42000
41000
40000
39000
38000
37000
36000
0
102
Time
EGT Chart
EGT [C]
110
108
106
104
102
100
98
96
94
92
90
0
102
Time

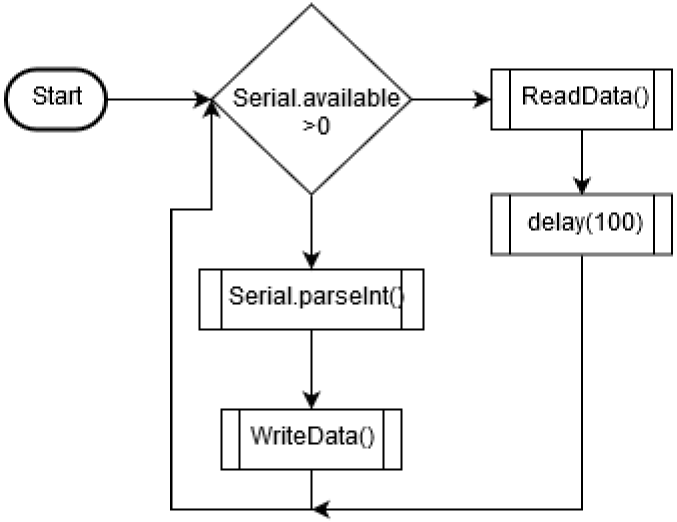
GUI Flowchart



ECM Flowchart



ECU Flowchart



Testing Backup Slides

Differential Pressure Sensor Selection Process I

- Assumed model mass flow:

$$\dot{m} = (4.26 * 10^{-6})(kRPM)^2 + (1.77 * 10^{-4})(kRPM) + 0.16523$$

- Flow velocity:

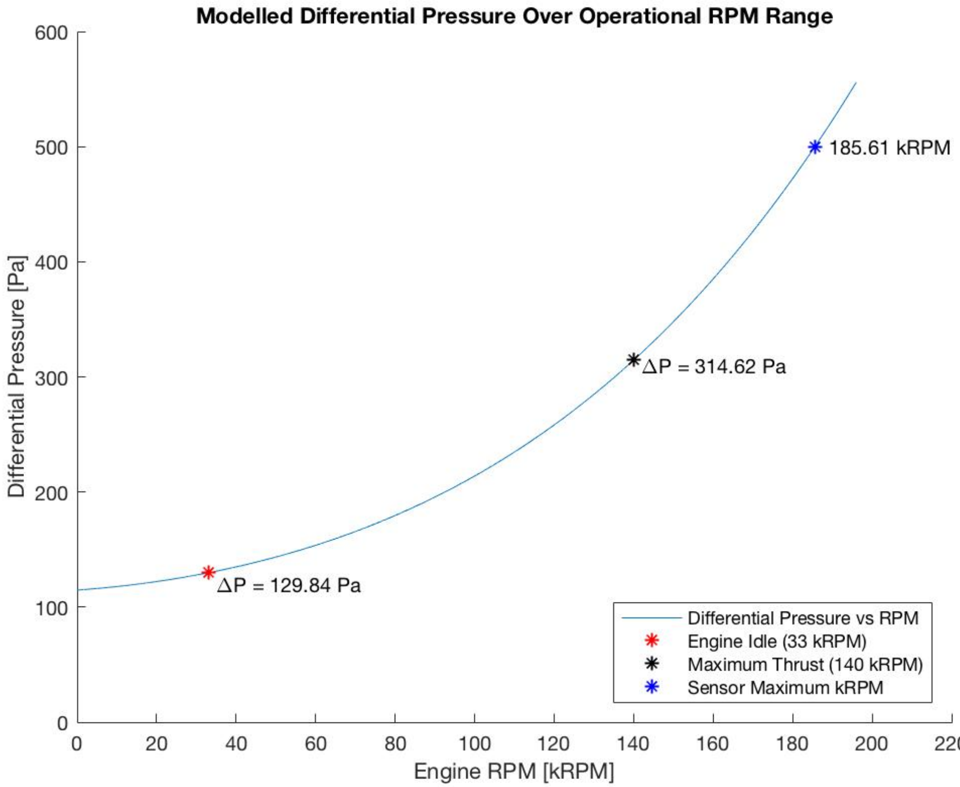
$$V = \frac{\dot{m}}{\rho A}$$

- Differential pressure:

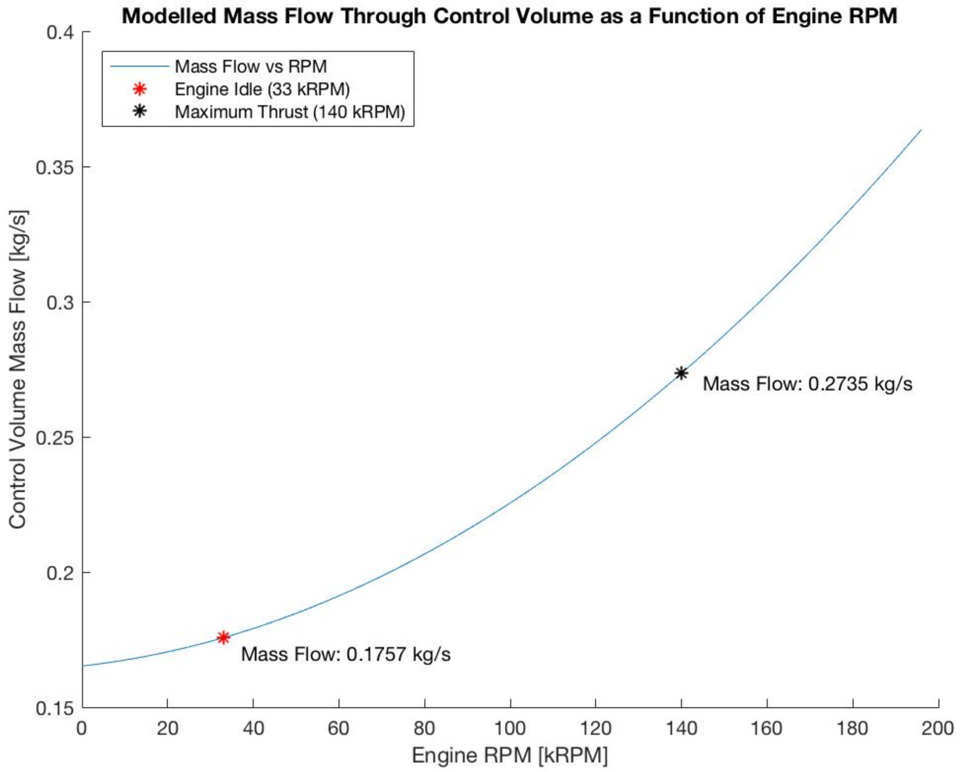
$$\Delta P = \frac{V^2 * \rho}{2}$$

- Mass flow had been modelled across entire operational range of RPM
- Used model to find flow velocity assuming constant density
- Found differential pressure using flow velocity

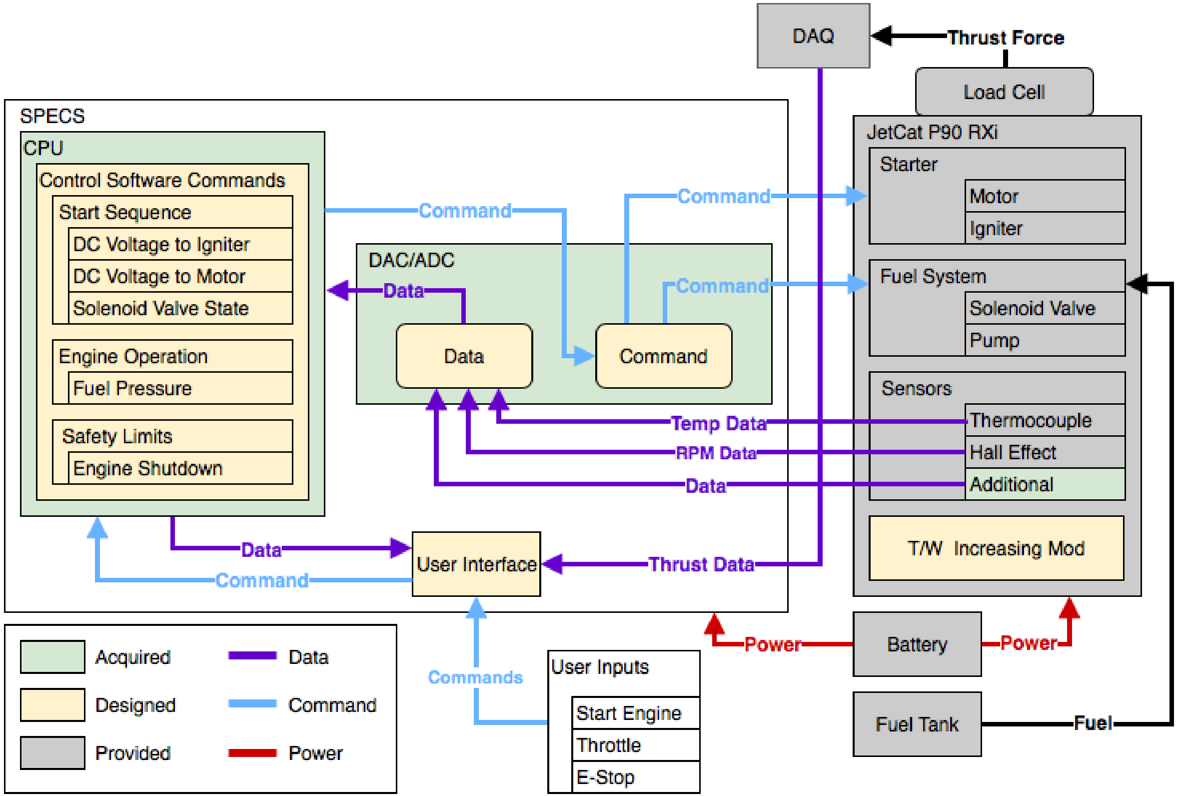
Differential Pressure Sensor Selection Process II



Modelled Mass Flow Rate



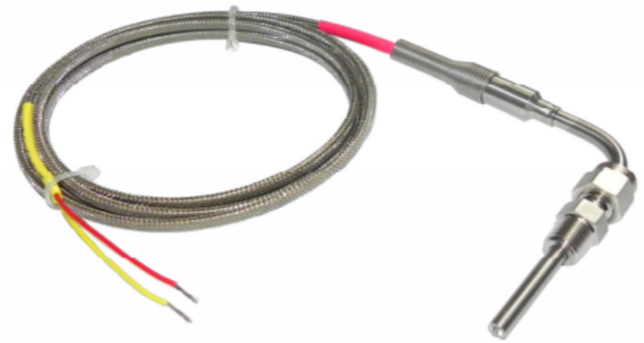
Functional Block Diagram



EGT probe data sheet

Fast Response EGT Temperature Probe

- Type K thermocouple probe
- Exposed sensing junction for fastest response
- Includes 316 SS adjustable compression fitting
- Stainless steel protected wires
- Designed for engine test & racing environments



Specifications

Thermocouple type:	K
Range:	-148 to 2372°F (-100 to 1300°C)
Accuracy:	+/-0.4% of reading or about +/- 1.1°C (Special Limits of Error)
Probe diameter:	3/16 inch (0.187 inch) (4.75 mm)
Sensing Junction:	Exposed, Ungrounded
Response Time*:	250 mS
*Time Constant:	Defined as the time required to reach 63.2% of an instantaneous temperature change Five time constants are required to approach 100% of the step change value
Outer Sheath Material:	Inconel, melting point 2550°F (1400°C)
Cable:	Stainless steel overbraiding over Teflon™ insulated, stranded wires, 20 gage
Compression Fitting:	316 stainless steel, double ferrule, adjustable, 1/8 inch –27 NPT male thread
Wiring:	+ = Yellow - = Red

Thrust Modification Risk Analysis

1) Nozzle Inefficiencies
2) Bearing Wear
3) Compressor Fatigue
4) Fuel System Failure
5) Sensor Failure
6) FOD
7) Compressor Failure
8) Bearing Failure
9) Shaft Failure
10) Pressure Vessel Failure
11) Turbine Failure

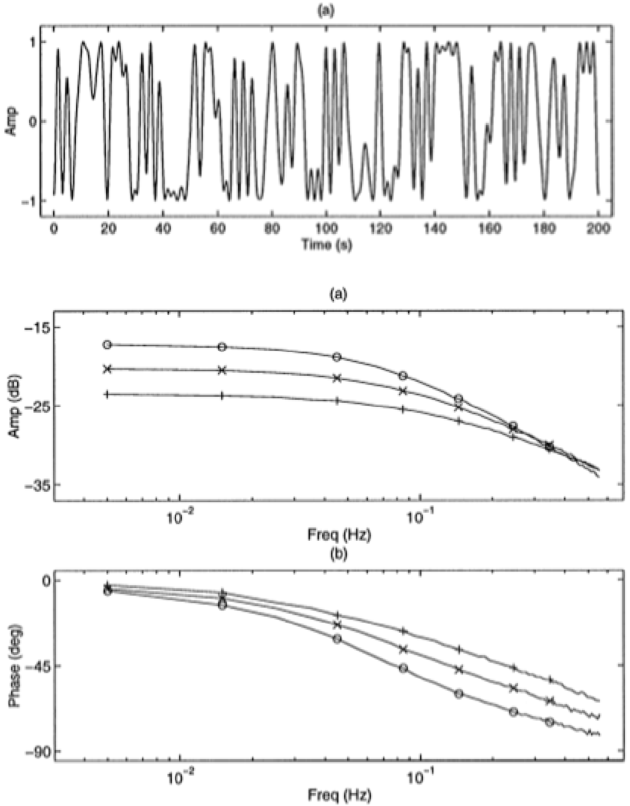
	ACCEPTABLE	MINOR ISSUE	JETCAT REPAIR REQUIRED	JETCAT BEYOND REPAIR
PROBABLE				
HIGH POSSIBILITY				
LOW POSSIBILITY				
NOT LIKELY				

Controls Backup Slides

Frequency Domain Testing

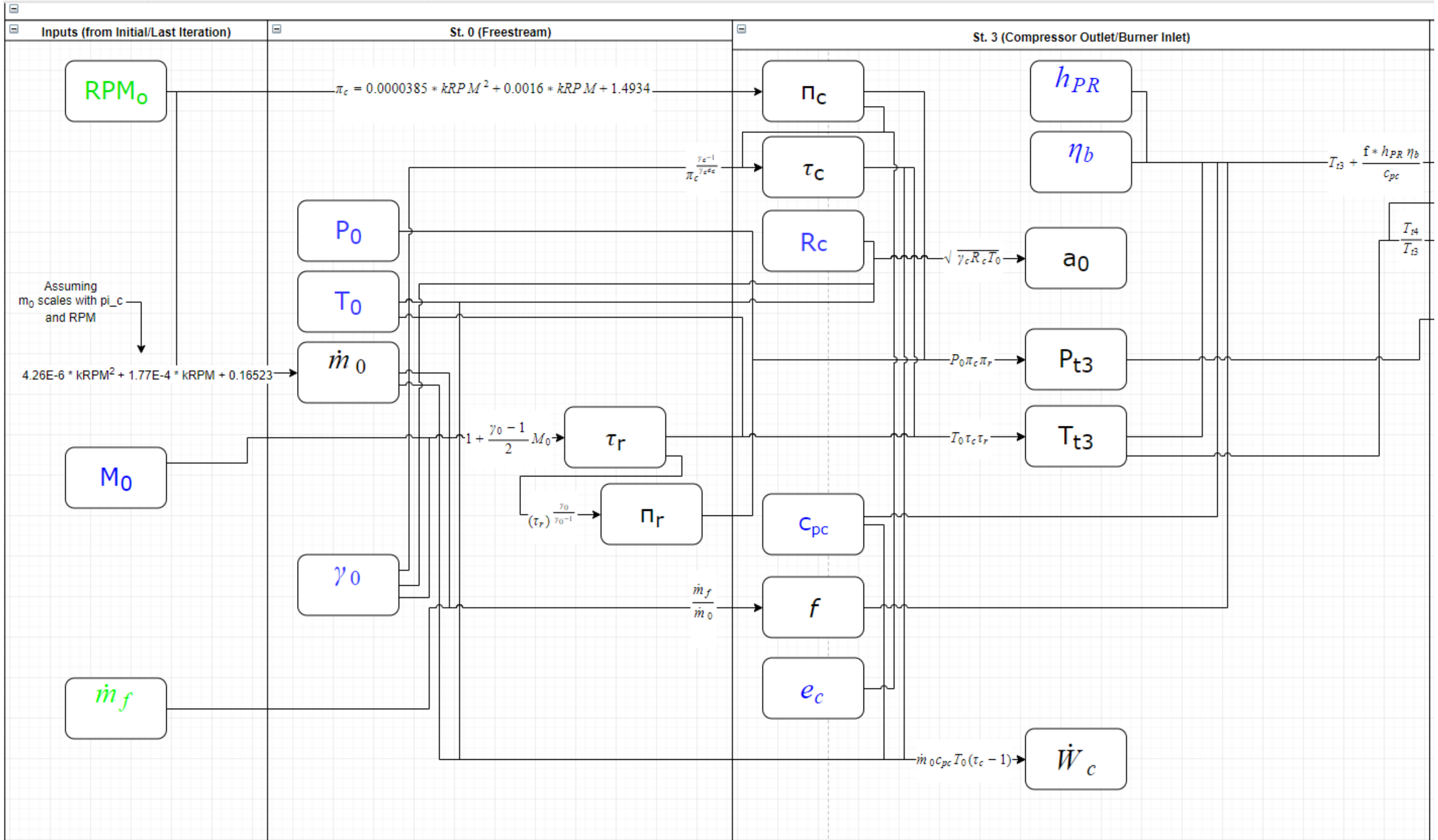
Test details:

- 0.005 to 0.4 Hz multisine with 0.01 Hz increments covering turbine dynamics[11]
- Testing at several operating points from 55% to 90% max RPM.
- 5 Hz sampling frequency
- amplitude +/- 10% fuel rate

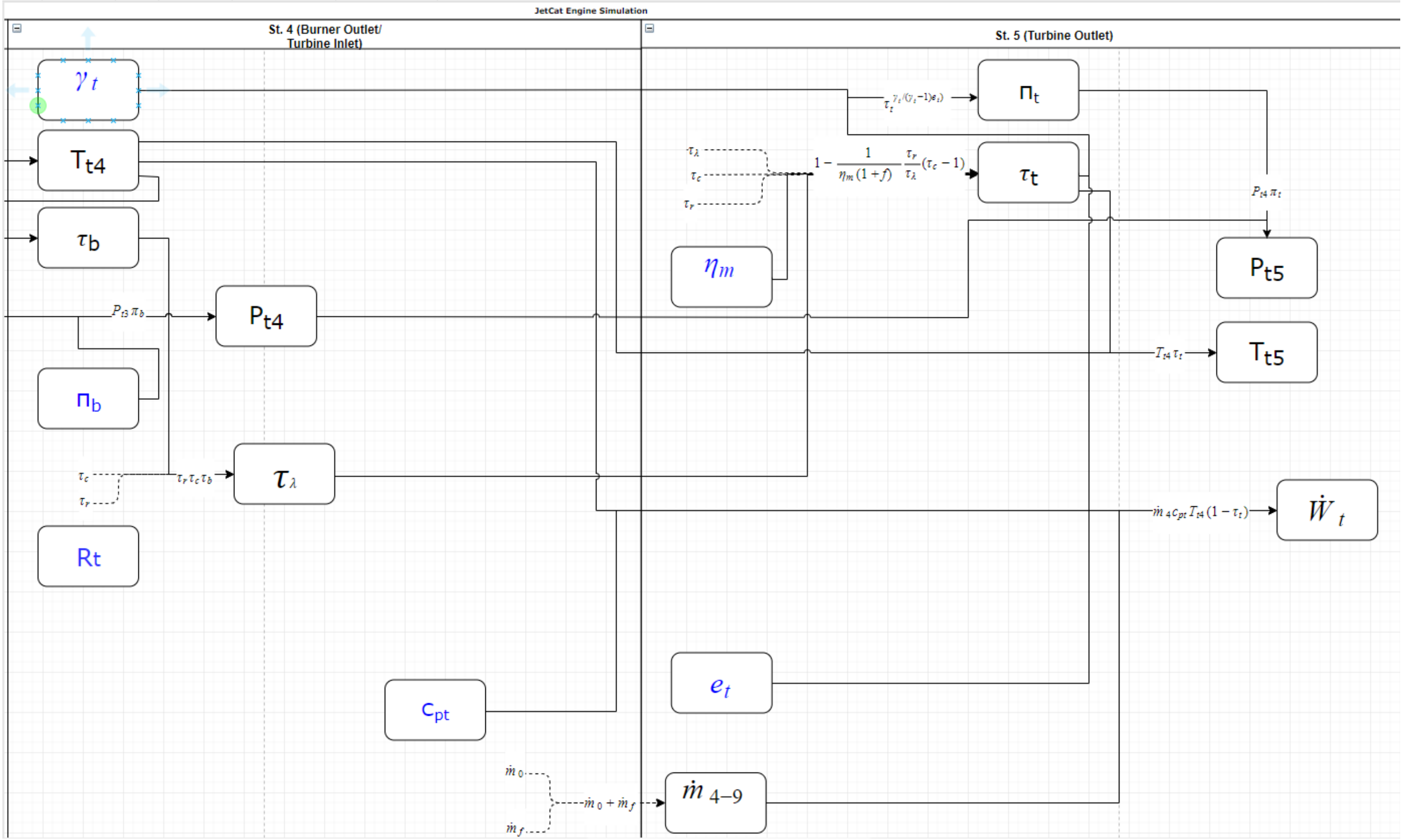


System	Item	Price (EA) $	Quantity (EA)	Total	Sub-Total	Budget %
Electrical	PCB	88	9	792		
	Processor ATmega 328P	1.3	12	15.6		
	PCB Components	50	6	300		
	Arduino Mega	28	2	56		
	Arduinio Nano	19	2	38		
	Hall Effect Sensor	0.11	10	1.1		
	LCD Screen	3	1	3		
	Battery	33	3	99		
	Battery Charger	50	1	50	1354.7	27.094
Mechanical						
	Titanium Round Bar	1307.55	1	1307.55		
	Tooling	250	1	250		
					1557.55	31.151
Engine	Refurbishment	400	1	400		
	New ECU	500	1	500		
	Fuel	20	1	20		
	Fuel Line	10	1	10	930	18.6
Test Bed	Pitot-Static	20	1	20		
	Pressure Transducer	100	1	100		
	DAQ	100	1	100	220	4.4
Presentation	Presentation Poster	100	1	100	100	2
			Total:	4162.25		83.245
			Margin	837.75		16.755

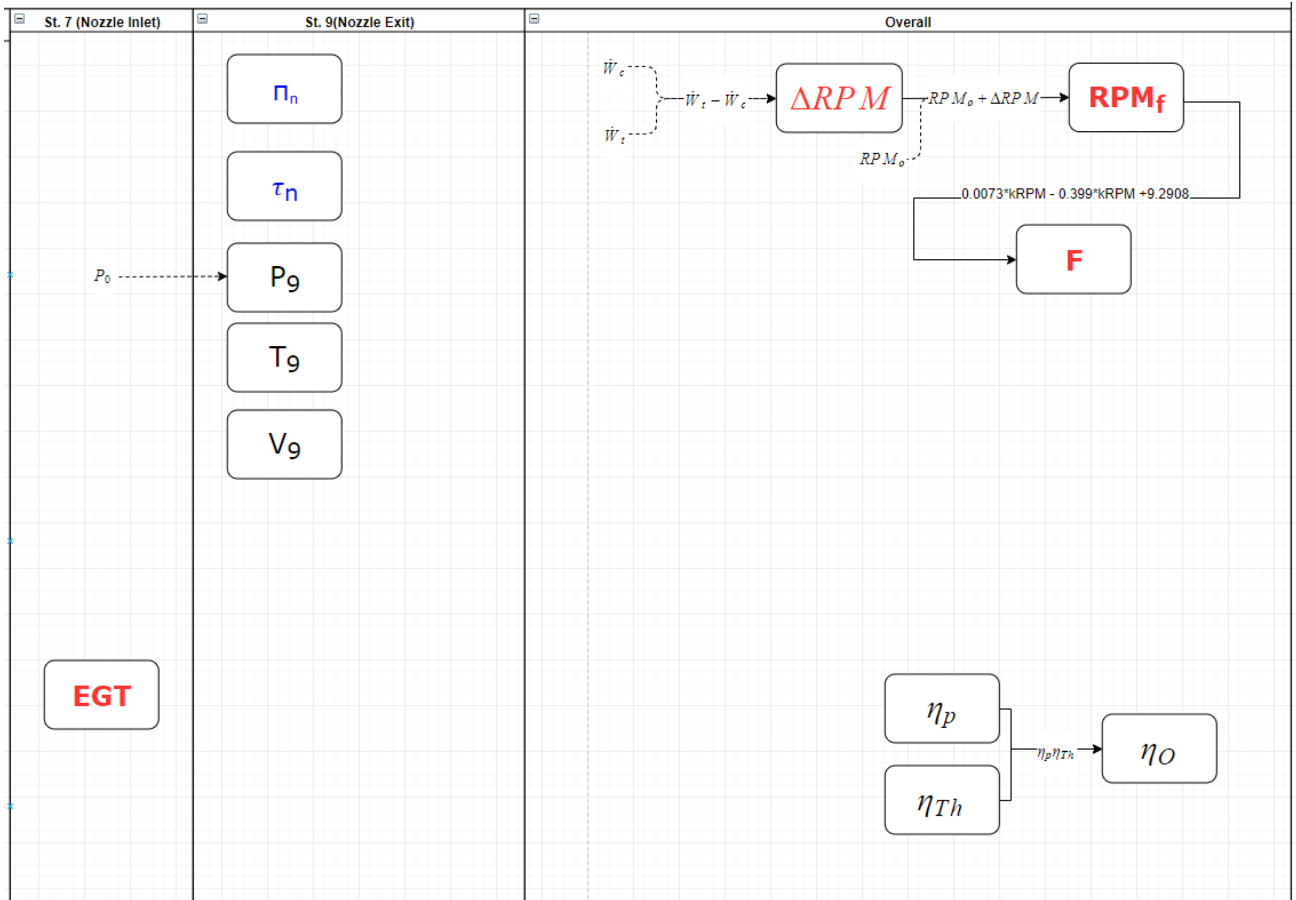
Engine Simulation Flowchart (1)



Engine Simulation Flowchart (2)



Engine Simulation Flowchart (3)



PDR Backup Slides

BASELINE DESIGN - ECU

Purpose: Offboard communication device between ECM and user interface. Performs computation of system parameters to output to GUI

Needs:

- Send engine state requirements to ECM
- Send engine throttle commands from user to ECM
- Receive sensor data from ECM for processing

Capabilities: (Arduino Mega)

- I2C communication
- 54 Digital I/O pins
- 256 kB Flash Memory (store program and data)
- 4 x 16 bit timers (control complex timing sequence)
- 4 UART (connect many devices)

Arduino Mega

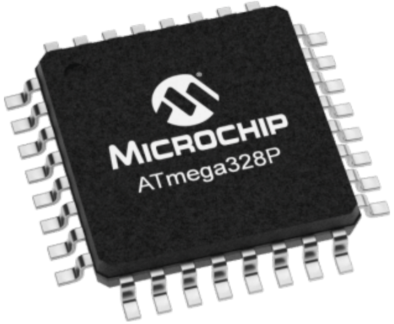
BASELINE DESIGN - ECM

Purpose:

- Control engine sequence operation: Start, Run, Shutdown.
- Control engine to commanded throttle setting from ECU

Needs:

- Read RPM and temperature data from Hall effect and thermocouple respectively
- Perform DAC/ADC
- PWM motor control
- I2C & SPI communication



ATmega 328P

Capabilities: (ATmega 328P)

- 6 PWM channels
- 20 MHz oscillator
- 32 kBytes flash memory
- 8-channel 10-bit ADC
- I2C and SPI capable
- 500 kHz internal sampling rate for digital inputs

BASELINE DESIGN - ECM (HALL EFFECT SENSOR)

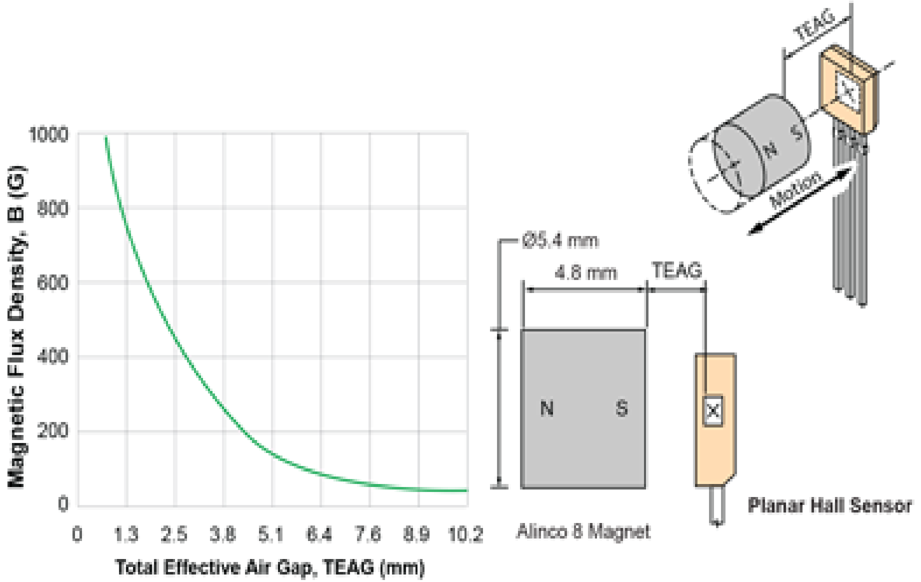
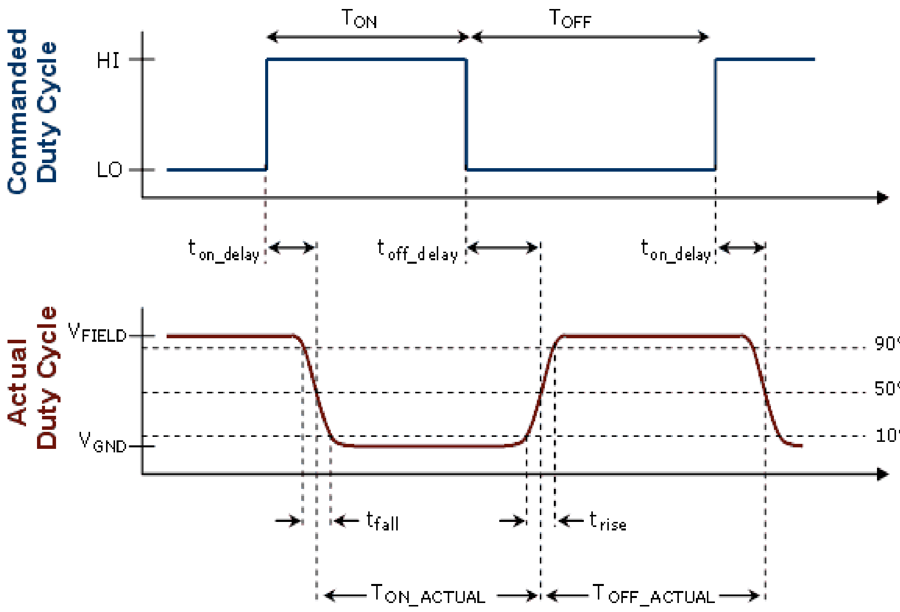


Figure 12B. Demonstration of head-on mode of operation

Output Waveform Timing Diagram



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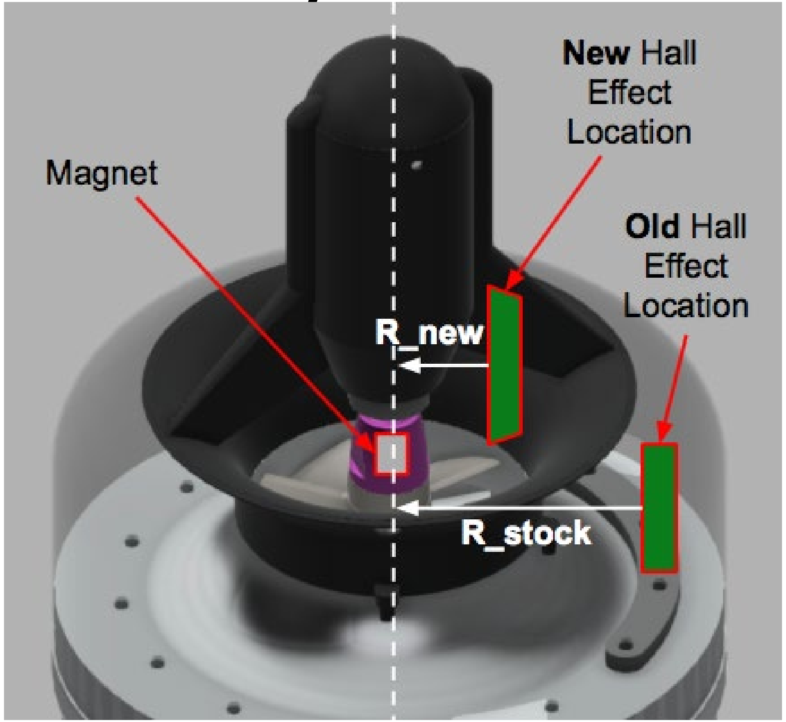
BASELINE DESIGN - ECM (HALL EFFECT SENSOR)

Purpose: Sense RPM, output square wave for engine control

Needs: Sense RPM >130 kRPM, output to microprocessor, read pulse width to calculate RPM

Capabilities: Hall effect Honeywell SS40A - Measured pulse width duty cycle at 42.5% for 5 kRPM. Pulse width at 130 kRPM is 197.5 μs; 13 μs minimum pulse width for rise / fall and response time of Hall effect sensor

Application Note: Starter assembly - redesign and 3D print to capture Hall effect sensor and route wire to ECM without inlet obstruction



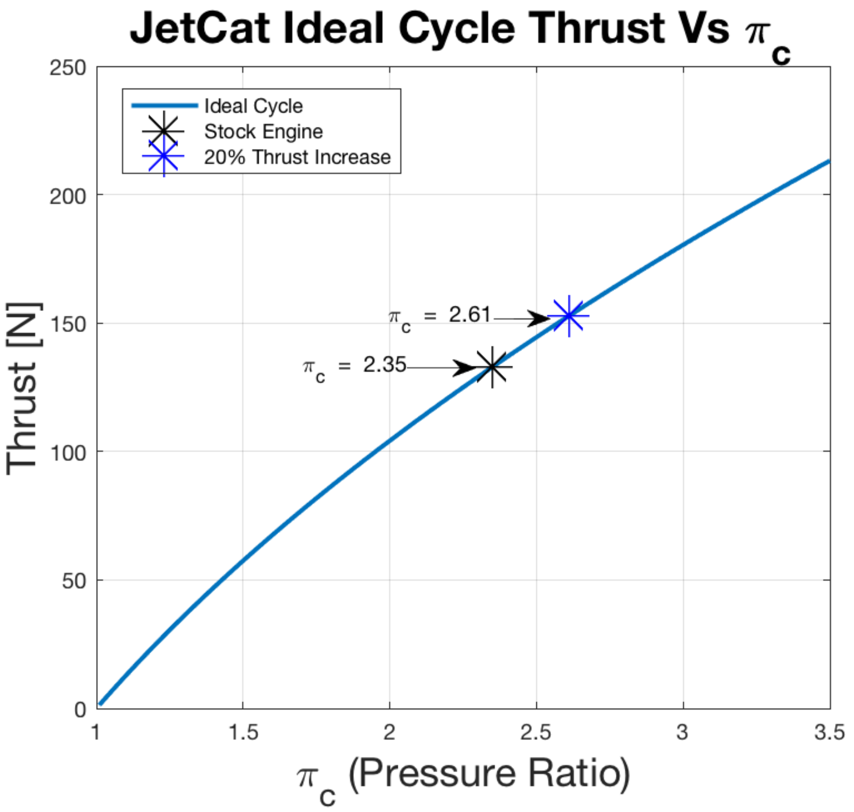
MODIFICATION FEASIBILITY PROCESS

- Increase engine thrust by 20%
  - What π_C is required?
    - SABRE data correlates π_C to RPM
    - Ideal cycle calculations verify
  - Is the engine physically capable of new P, T and RPM?
    - Energy balance for W_c to W_t
      - Work capability of turbine
      - Work requirements of compressor
    - Engine component properties

IDEAL COMPRESSOR PRESSURE RATIO

Pressure ratio (π_C) calculation for 20% increase in thrust assuming:

Model results: Ideal Brayton cycle requires π_C = 2.61 to feasibly obtain 20% thrust increase

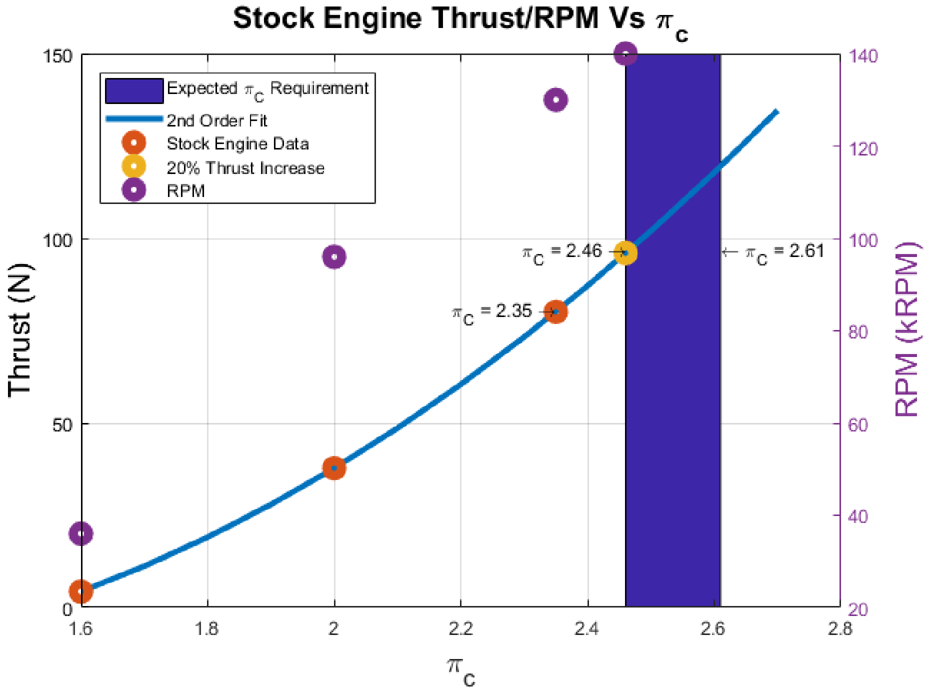


STOCK ENGINE COMPRESSOR PRESSURE RATIO

Pressure ratio observation for 20% increase in thrust:

- Observed in SABRE data
  - Provides a lower bound for expected value of π_C
- Required π_C therefore expected to fall between:
  - 2.46 (real) - 2.61 (ideal)

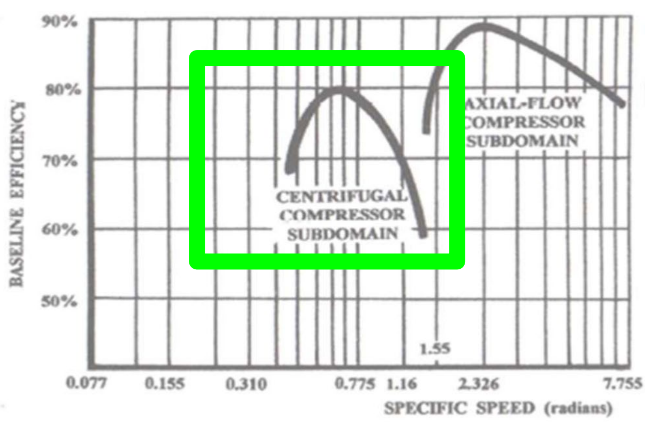
Model results: Increased thrust with π_C = 2.46 is feasible to obtain with ~10,000 RPM increase



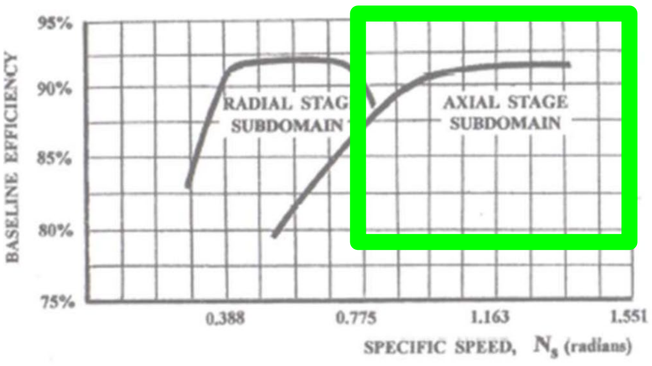
PRESSURE RATIO FEASIBILITY

Ideal	Compressor Work (required)	Turbine Work (available)
Stock	19.99 kW	48.01 kW
20% Increase	22.3 kW	46.1 kW

Compressors



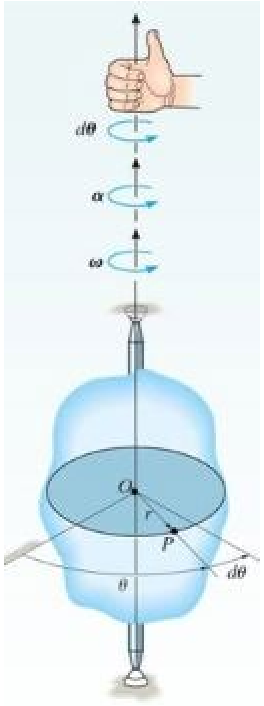
Turbines



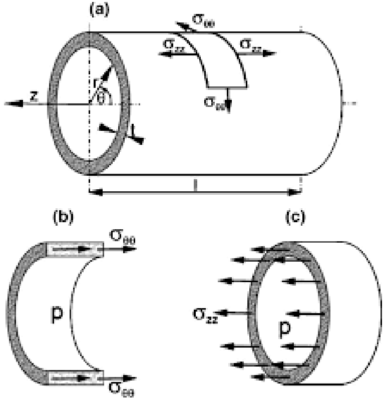
Result: Thrust increase is feasible since there is excess work available from the turbine

ENGINE COMPONENT ANALYSIS MODEL

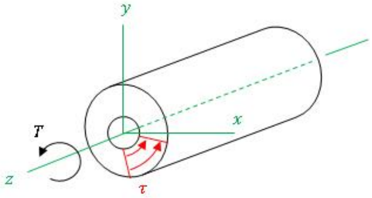
- Compressor/Turbine
  - Angular Motion
    - Low angular acceleration, high angular velocity
    - Stress at blade tip compared to material yield stress to verify integrity
- Nozzle/Engine Case
  - Thin Wall Pressure Vessel
    - Stresses calculated with total pressure at corresponding stations, compared to yield strength for estimated materials
- Shaft
  - Power-Torque Relation
    - Shear stresses from compressor and turbine calculated and compared to ultimate shear for assumed material



Angular Motion



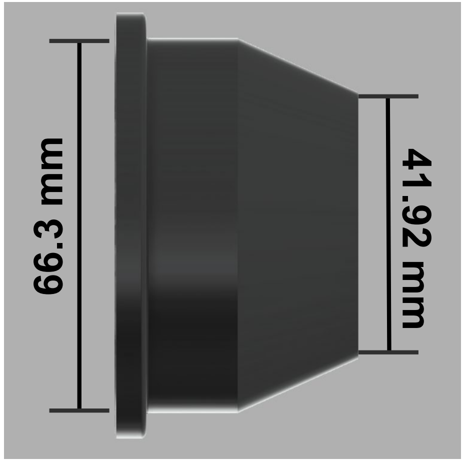
Thin Wall Pressure Vessel



Torque About Shaft

NOZZLE FEASIBILITY

- With new pressure ratio, the required exit area for perfectly expanded flow at sea level is 0.00138 m^2
- This is a 26% decrease in stock nozzle exit area
- New dimensions can be manufactured



	MATERIAL	TENSILE YIELD FAILURE	ACTUALLY EXPERIENCED	S.F.
NOZZLE DESIGN	CoCrMo	350 MPa	5.8 MPa	60.34

- Material property was found from The Japan Institute of Metals --- Mechanical Properties of Biomedical Co-33Cr-5-Mo-0.3N Alloy at Elevated Temperatures

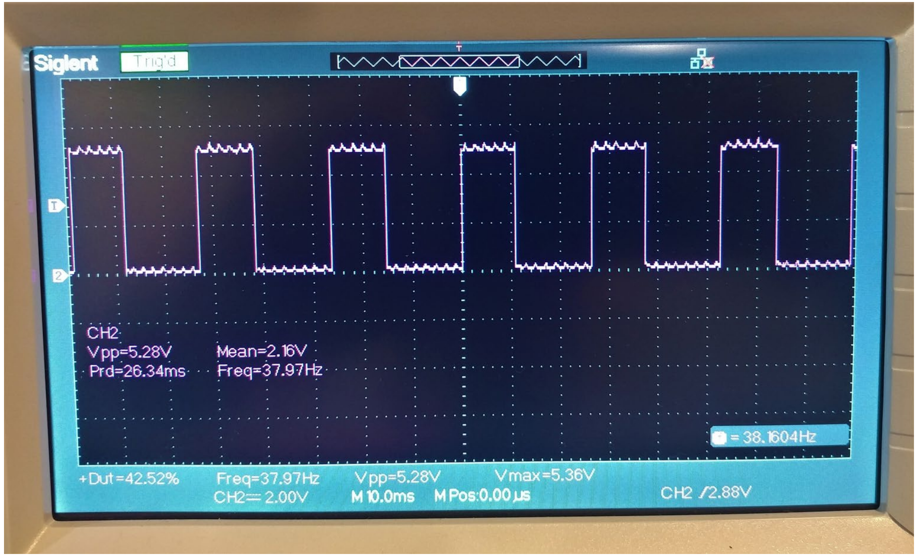
ECM HALL EFFECT SENSOR TESTING

Hall Effect Honeywell SS40A

System Settings: TEAG = 5 mm

Method: Commanded starter to run. Measured Hall effect waveform properties using oscilloscope. Duty cycle 42.52%, Freq = 37.97Hz. ECU LCD readout = 2275 RPM (37.91Hz), RPM calculation confirmed

Test Results: Verified Hall effect sensor functional, communicates and maps correct RPM

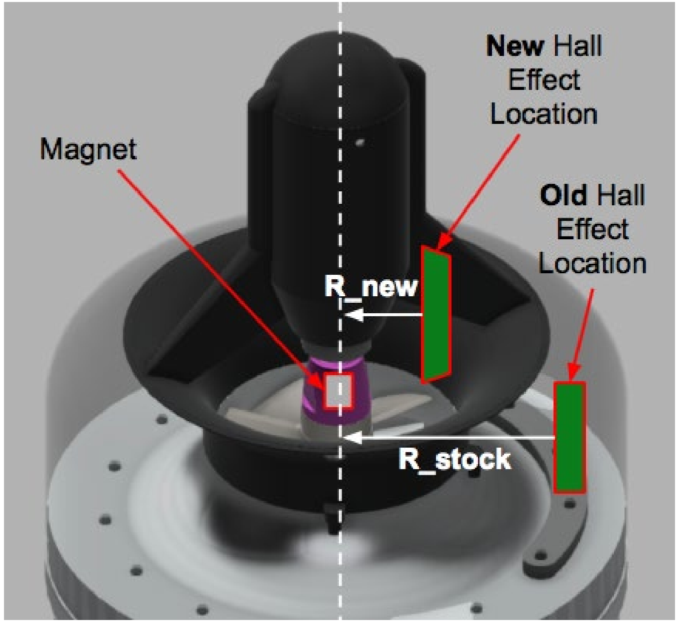


HALL EFFECT SENSOR FEASIBILITY

JetCat implementation of Hall effect sensor has been problematic. Sensor set beyond datasheet max distance for estimated magnetic field (35mm). Sensor measured <20% duty cycle (high RPM near sensor limit DC varied).

Specs Solution:

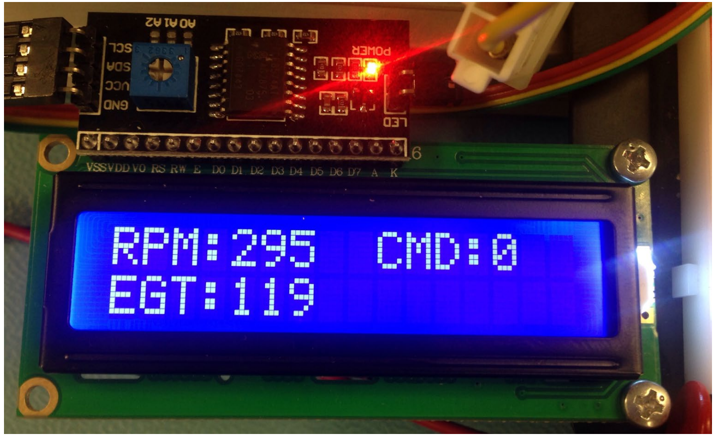
- Upgrade Hall effect sensor, relocate closer to magnet for precision
- New location provides 42% or better duty cycle with higher accuracy
- **Verified new sensor will read RPM up to 300 kRPM (5 mm away)**



ECM DATA SAMPLING RATE: RPM

Microprocessor Pulse Injection

System Settings: Square wave duty cycle = 35% benchtop waveform generator



Method: Using waveform generator, supplied frequencies from 50 Hz to 5 kHz (3 - 300 kRPM). Waveform measured on ECM, then transmitted to ECU, then converted to RPM and sent to LCD. Total communication time <20ms.

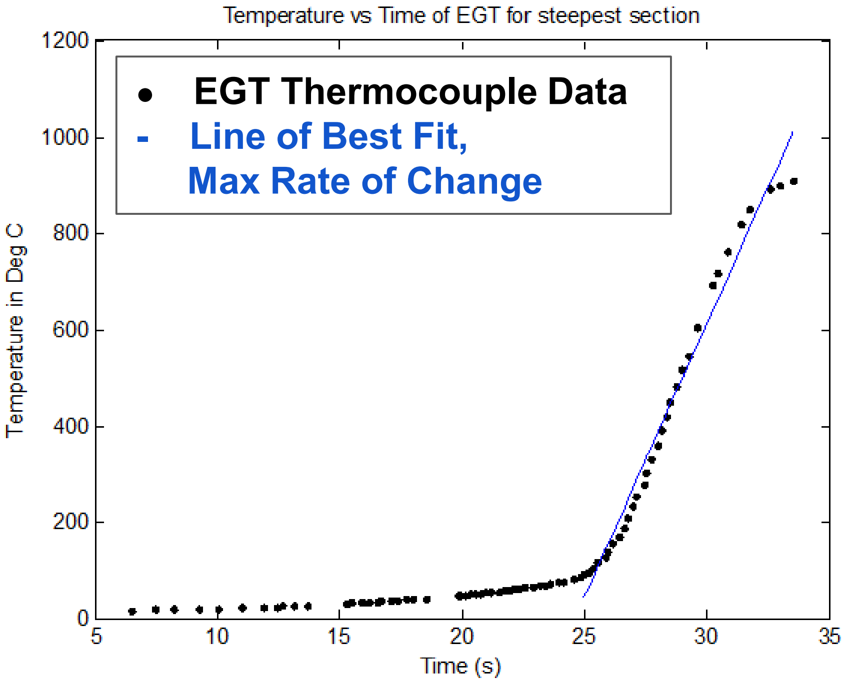
Test Results: Verified ECM can measure RPM in excess of 300 kRPM

ECM DESIGN THERMAL TRANSIENTS: EGT

Method: MEDUSA engine run EGT data showing max temp rate of change from throttle command

Needs: Design controller to limit temperature change to less than 113.7˚C/s

Future Test Requirements: Use proportional linear ramp controller to characterize fuel delivery and correlate to temperature rate of rise across RPM spectrum. Adjust fuel pump ramp rate to maintain less than 113.7˚C/s temperature increase.



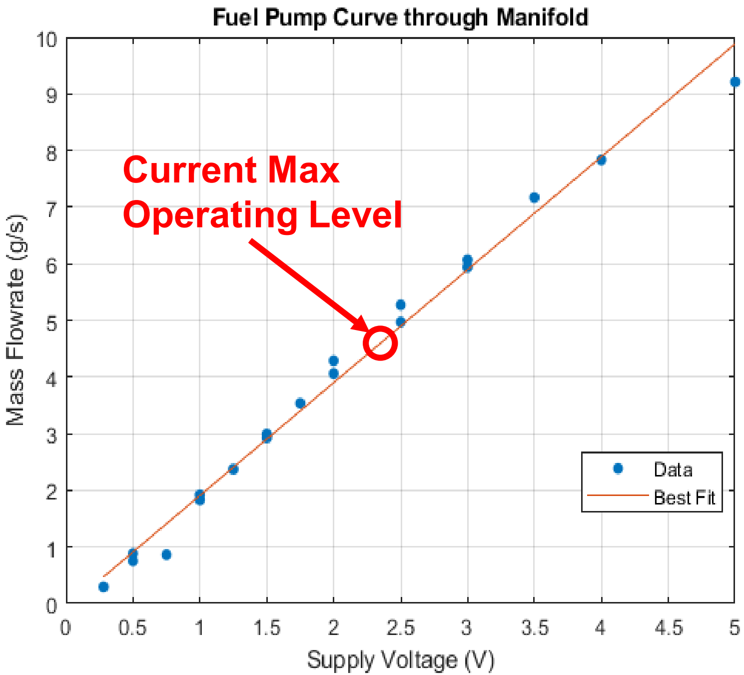
FUEL PUMP CHARACTERIZATION TESTING

DR 2.2.3: SPECS shall send PWM fuel pump command rate as a percentage of full power

Methods:

- Applied 0.28-5V to fuel pump, 0.5V increments for 10 seconds
- Video recorded weight of fuel tank and stop clock simultaneously
- Analyzed change in weight to find mass flow & voltage relationship

Test Results: Stock fuel flow at max thrust: 4.7 g/s. Pump can support higher fuel flows needed to increase T_{t4} & RPM



ECU DATA LINK FEASIBILITY

Communications testing:

1. Verify communications protocol GUI⇨ECU⇨ECM to send command and execute.
2. Calculate minimum data transfer values, test ECM to evaluate processing time.
3. Test at maximum data transfer quantity, test ECM to evaluate processing time.

Results:

1. I2C communications verified through start/shutdown sequence and LCD display.
2. Minimum data transfer found to be 5 bytes, transfer time <20ms.
3. 32 byte (I2C maximum) tested time <50 ms per request (<200ms maximum)

POWER SYSTEM FEASIBILITY

At 8.4VDC (2S LiPo full charge) or 5V (Vcc), used large benchtop power supply to measure component current consumption during design operation

- 11.2A cumulative total
- Select 2S 5200mAh battery with 50C rating
    - 260A peak current
    - ~20 min runtime at full 100% power
    - Less heating for motor control compared to 3S
    - Starter exceeded 5k RPM at 5V

<u>Test Result:</u> Supplied amperage from battery exceeds max current demand by SPECS

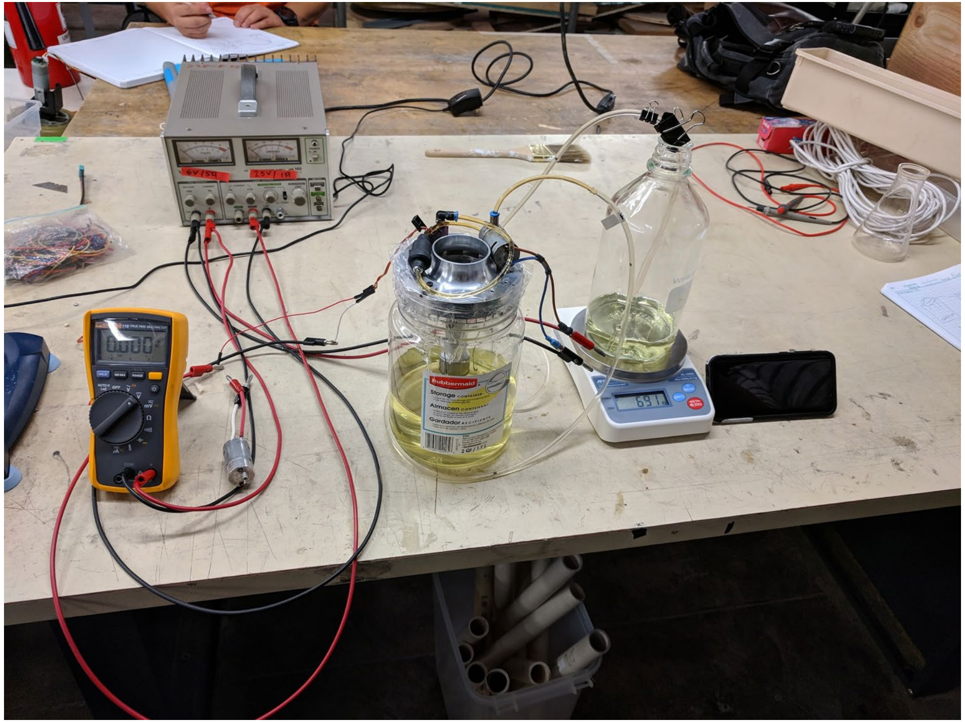
Component	Voltage (VDC)	Current (A)	Power (W)
Starter	8.4	6.2	52.08
Fuel Pump	8.4	4.8	40.32
Fuel Valve	5	0.07	0.35
ECU	5	0.02	0.1
Other	5	0.11	0.55
	Total:	11.2	93.4

FUEL PUMP CAPACITY TEST SETUP

-Linear Relationship at 2 (g/s)/V

-Mass Flow rate = -0.11V^2 + 2.57V - 0.57

-This provides < 5% error throughout the 5V range

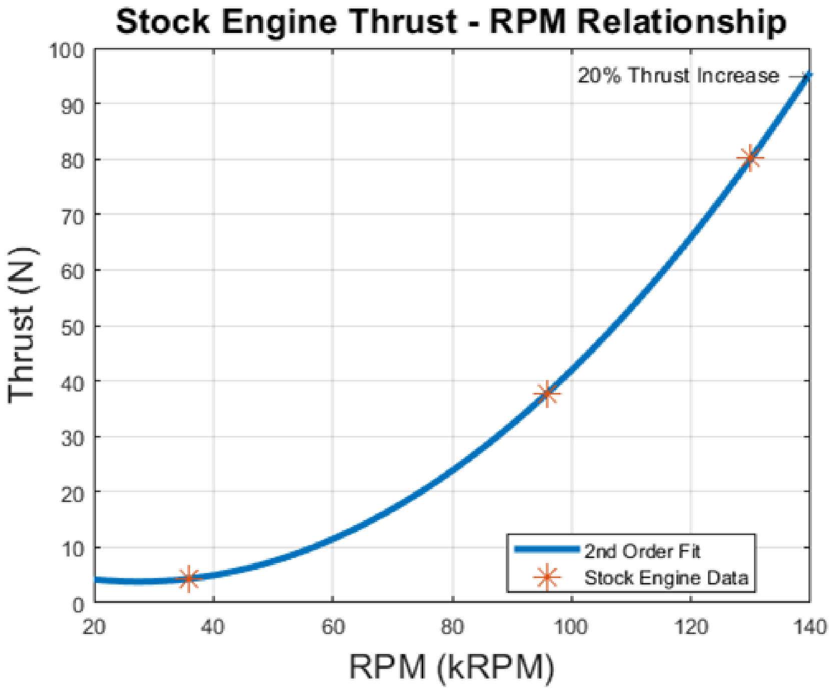


RPM -> THRUST CORRELATION

Second Order fit is:

Thrust = 0.0073(RPM)^2 - 0.4(RPM) + 9.29

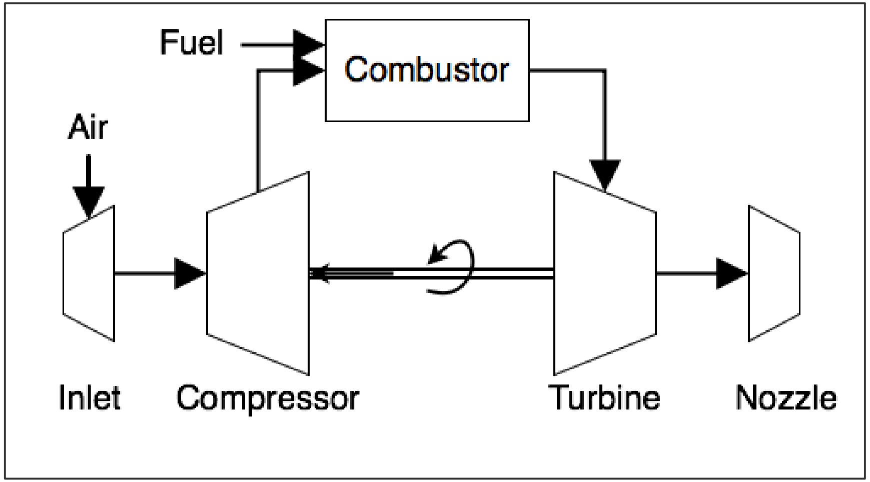
This provides ~20% thrust increase with ~10 kRPM increase

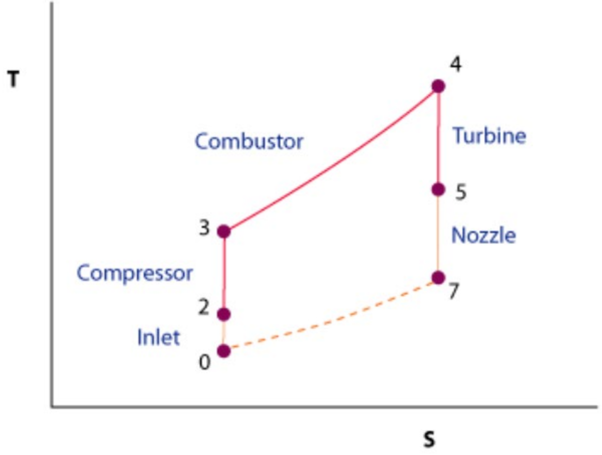


IDEAL CYCLE ASSUMPTIONS

- Ideal Brayton Cycle
    - Standard Air
        - Calorically Perfect Gas
        - Constant Specific Heat
    - Isentropic Inlet, Compression, Turbine, and Nozzle
    - Constant Pressure Heat Addition & Rejection
        - Fuel mass flow << Air mass flow
    - Perfectly Expanded Flow Exiting Nozzle
    - Closed System, no losses
- Steady 1D flow
- Axial Compressor
- Sea Level Atmospheric Conditions
- Compressor Pressure Ratio Scales Linearly with Mass Flow Rate

IDEAL BRAYTON CYCLE ANALYSIS





IDEAL BRAYTON CYCLE ANALYSIS

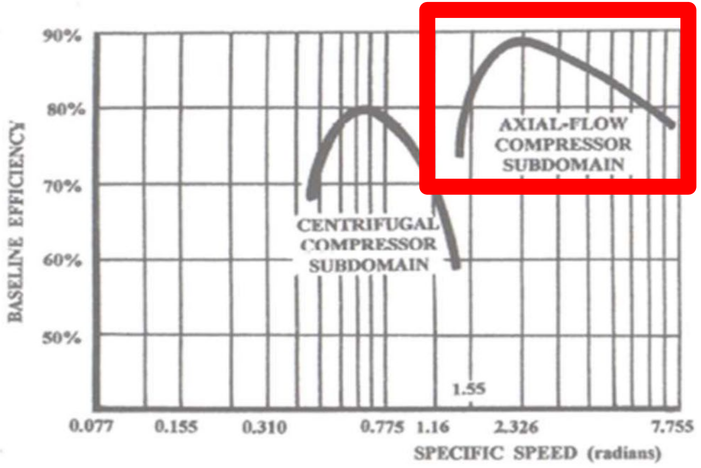
Calculation of temperature and pressure relationships	Calculation of uninstalled thrust
$\pi_c = \dfrac{P_{t_3}}{P_{t_2}} \qquad \tau_c = \pi_c^{\frac{\gamma-1}{\gamma}} \qquad \tau_r = 1 + \dfrac{\gamma-1}{2}M_0^2$	$a_0 = \sqrt{\gamma R T_0}$
$\tau_b = \dfrac{f h_{pr}}{cp T_0 \tau_r \tau_c} + 1 \qquad T_{t_3} = \tau_r \tau_c T_0 \qquad T_{t_4} = \tau_b T_{t_3}$	$\left(\dfrac{V_9}{a_0}\right) = \sqrt{\dfrac{2}{\gamma-1}\dfrac{\tau_\lambda}{\tau_r \tau_c}(\tau_r \tau_c \tau_t - 1)}$
$\tau_\lambda = \dfrac{T_{t_4}}{T_0} \qquad \tau_t = 1 - \dfrac{\tau_r}{\tau_\lambda}(\tau_c - 1)$	$F_{uninstalled} = \dot{m}_0 \left(V_9 - a_0 M_0\right)$

PRESSURE RATIO FEASIBILITY

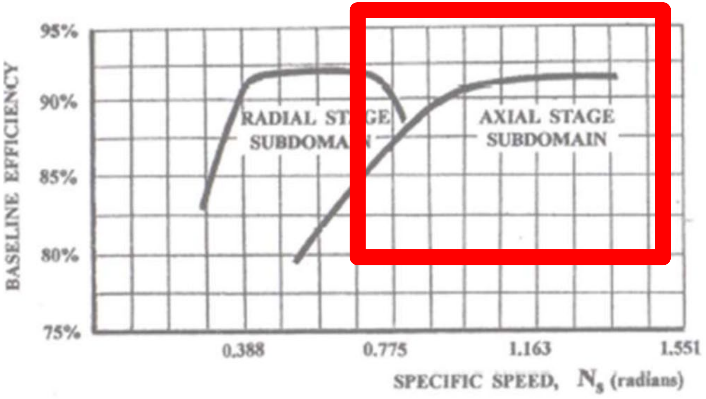
Ideal	**Compressor Work**	**Turbine Work**	η	**Thrust loss**
Stock	19.99 kW	48.01 kW	1	0%
20% Increase	22.3 kW	46.1 kW	0.98	4.5%

Baseline Compressor efficiency decrease of ~2% (with 10,000 RPM increase)

Compressors



Turbines



Component Analysis: Nozzle/ Engine Case

- Hoop (σ_h) and longitudinal (σ_l) stresses calculated at location where values are theoretically maximum, inlet:
- Total Pressure at nozzle inlet (P_{t5}), radius of nozzle inlet (R_i), thickness of nozzle inlet (t_i):

$$\sigma_l = \frac{P_T R_i}{2t_i} \qquad \sigma_h = \frac{P_T R_i}{t_i}$$

- Results compared to material properties, verify structural capability.

Component Analysis: Shaft

- Power (P) and rotation rate (ω) known for compressor and turbine.
- Calculate torque for each using:

$$T = \frac{P}{\omega}$$

- Force from both then found using radius of turbine and compressor:

$$F = \frac{T}{R}$$

- Shear stress (τ) then calculated and compared to ultimate shear of assumed material, area of shaft in contact with turbine and fan used (A):

$$\tau = \frac{F}{A}$$

Material Yield Analysis(Al 7075)

Table 3.7.4.0(b₁). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate

Specification	AMS 4045 and AMS-QQ-A-250/12																				
Form	Sheet							Plate													
Temper	T6 and T62[a]							T651													
Thickness, in.	0.008-0.011	0.012-0.039		0.040-0.125		0.126-0.249		0.250-0.499		0.500-1.000		1.001-2.000		2.001-2.500		2.501-3.000		3.001-3.500		3.501-4.000	
Basis	S	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Mechanical Properties:																					
F_{tu}, ksi:																					
L	...	76	78	78	80	78	80	77	79	77	79	76	78	75	77	71	73	70	72	66	68
LT	74	76	78	78	80	78	80	78	80	78	80	77	79	76	78	72	74	71	73	67	69
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	70[b]	71[b]	66[b]	68[b]	65[b]	67[b]	61[b]	63[b]
F_{ty}, ksi:																					
L	...	69	72	70	72	71	73	69	71	70	72	69	71	66	68	63	65	60	62	56	58
LT	63	67	70	68	70	69	71	67	69	68	70	67	69	64	66	61	63	58	60	54	56
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	59[b]	61[b]	56[b]	58[b]	54[b]	55[b]	50[b]	52[b]
F_{cy}, ksi:																					
L	...	68	71	69	71	70	72	67	69	68	70	66	68	62	64	58	60	55	57	51	52
LT	...	71	74	72	74	73	75	71	73	72	74	71	73	68	70	65	67	61	64	57	59
ST	...	...	...	...	...	...	...	...	...	...	...	...	...	67	70	64	66	61	63	57	59
F_{su}, ksi	...	46	47	47	48	47	48	43	44	44	45	44	45	44	45	42	43	42	43	39	41
F_{bru}^{c}, ksi:																					
(e/D = 1.5)	...	118	121	121	124	121	124	117	120	117	120	116	119	114	117	108	111	107	110	101	104
(e/D = 2.0)	...	152	156	156	160	156	160	145	148	145	148	143	147	141	145	134	137	132	135	124	128
F_{bry}^{c}, ksi:																					
(e/D = 1.5)	...	100	105	102	105	103	106	97	100	100	103	100	103	98	101	94	97	89	93	84	87
(e/D = 2.0)	...	117	122	119	122	121	124	114	118	117	120	117	120	113	117	109	112	104	108	98	103
e, percent (S-basis):																					
LT	5	7	...	8	...	8	...	9	...	7	...	6	...	5	...	5	...	5	...	3	...
E, 10^3 ksi	10.3							10.3													
E_c, 10^3 ksi	10.5							10.6													
G, 10^3 ksi	3.9							3.9													
μ	0.33							0.33													
Physical Properties:																					
ω, lb/in.^{3}	0.101																				
C, K, and α	See Figure 3.7.4.0																				

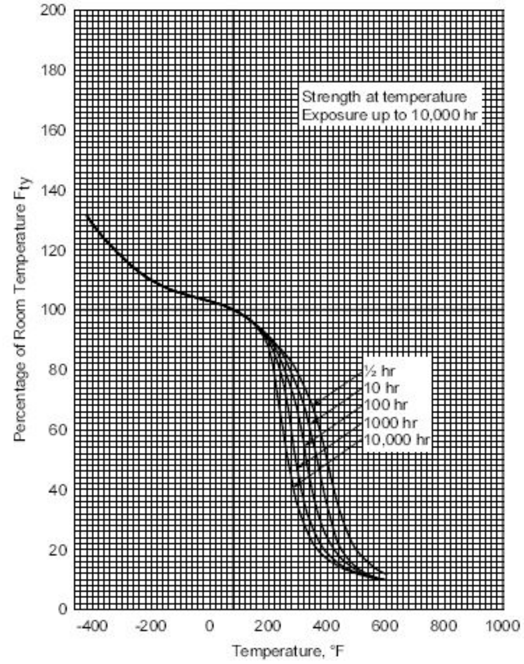


Figure 3.7.4.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).

Material Yield Analysis(AISI 301)

Table 2.7.1.0(b). Design Mechanical and Physical Properties of AISI 301 and Other[a] Annealed Stainless Steel

Specification	MIL-S-5059	AMS 5517 & MIL-S-5059		AMS 5518 & MIL-S-5059		MIL-S-5059		AMS 5519 & MIL-S-5059	
Form	Sheet and strip								
Condition	Annealed[a]	¼ Hard		½ Hard		¾ Hard		Full Hard	
Thickness, in.	≤0.187	...		...		...		...	
Basis	S	A	B	A	B	A	B	A	B
Mechanical Properties:									
F_{tu}, ksi:									
L	73	124	129	141	151	157	168	174	185
LT	75	122	127	142	152	163	173	175	186
F_{ty}, ksi:									
L	26	69	83	93	110	118	135	137	153
LT	30	67	82	92	105	113	133	125	142
F_{cy}, ksi:									
L	23	44	54	61	69	75	88	83	94
LT	29	71	88	100	116	127	152	142	164
F_{su}, ksi	50	66	69	77	82	88	93	95	100
F_{bru}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	162	262	273	292	310	327	342	346	361
F_{bry}, ksi:									
(e/D = 1.5)	...	...	...	...	...	...	...	...	...
(e/D = 2.0)	55	123	149	167	189	202	234	222	249
e, percent (S basis):									
LT	40	25	...	[b]	...	[b]	...	[b]	...
E, 10^3 ksi:									
L	29.0	27.0		26.0		26.0		26.0	
LT	29.0	28.0		28.0		28.0		28.0	
E_c, 10^3 ksi:									
L	28.0	26.0		26.0		26.0		26.0	
LT	28.0	27.0		27.0		27.0		27.0	
G, 10^3 ksi	11.2	10.6		10.5		10.5		10.5	
μ	0.27	0.27		0.27		0.27		0.27	
Physical Properties:									
ω, lb/in.^{3}	0.286								
C, K, and α	See Figure 2.7.1.0								

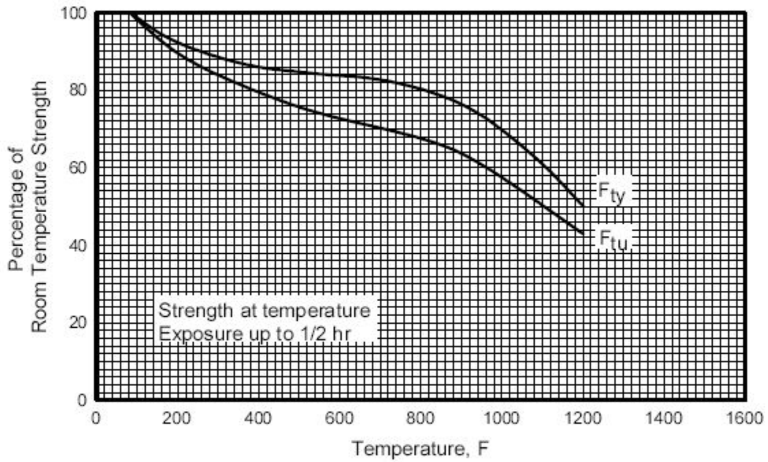


Figure 2.7.1.3.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and the tensile yield strength (F_{ty}) of AISI 301 1/2-hard stainless steel sheet.

Material Yield Analysis(Inconel 718)

Table 6.3.5.0(b). Design Mechanical and Physical Properties of Inconel 718

Specification	AMS 5596				AMS 5597	AMS 5589	AMS 5590
Form	Sheet		Plate		Sheet and plate	Tubing	
Condition	Solution treated and aged per indicated specification						
Thickness, in.	0.010-0.187		0.188-0.249	0.250-1.000	0.010-1.000	O.D. > 0.125 Wall > 0.015	
Basis	A	B	S	S	S	S	S
Mechanical Properties[a]:							
F_{tu}, ksi:							
L	180	192	180	...	...	185	170
LT	180[c]	191	180	180	180	...	...
F_{ty}, ksi:							
L	145	156	148	...	...	150	145
LT	147	158	150	150	150	...	...
F_{cy}, ksi:							
L	155	167	158	...	...	...	...
LT	158	170	161	...	...	...	...
F_{su}, ksi	124	132	124	...	...	...	...
$F_{bru}{}^{b}$, ksi:							
(e/D = 1.5)	291	309	291	...	...	...	...
(e/D = 2.0)	380	403	380	...	...	...	...
$F_{bry}{}^{b}$, ksi:							
(e/D = 1.5)	208	223	212	...	...	...	...
(e/D = 2.0)	241	259	246	...	...	...	...
e, percent (S-basis):							
L	...	...	...	...	...	12	15
LT	12	...	12	12	12	...	...
E, 10^3 ksi	29.4						
E_c, 10^3 ksi	30.9						
G, 10^3 ksi	11.4						
μ	0.29						
Physical Properties:							
ω, lb/in.^{3}	0.297						
C, K, and α	See Figure 6.3.5.0						

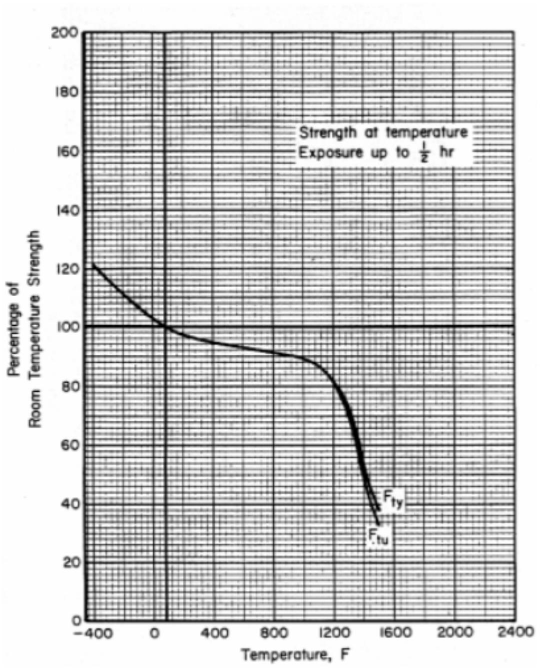


Figure 6.3.5.1.1. Effect of temperature on the tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}) of solution-treated and aged Inconel 718.

Fabrication Cost Feasibility: CNC Machine & Tool Room Lathe

Family:	Species:	Dimensions (in):	Cost:
Steel	N60	3” x 10”	$242.45
Aluminum	7075	3” x 10”	$87.20
Titanium	6AL-4V (Grade 5)	3” x 10”	$870.30
Nickel	Inconel 718	3” x 10”	$873.69

- Cost of production solely based on cost of material.
- All materials are round bar, diameter x length

Fabrication Cost Feasibility: Direct Metal Laser Sintering

Family:	Species:	Dimensions (in):	Cost:
Aluminum	ALSi10Mg	3.25’’ x 3.25’’ x 2.17’’	$1017.00
Nickel	Inconel 625	3.25’’ x 3.25’’ x 2.17’’	$822.00
Titanium	Ti64	3.25’’ x 3.25’’ x 2.17’’	$956.00
Cobalt Chrome	CoCrMo	3.25’’ x 3.25’’ x 2.17’’	$983.00

- Cost of production includes the cost of materials, manufacturing and finishing
- The dimension of the nozzle is based on SABRE’s nozzle
- It will take approximately three weeks to receive the nozzle from manufacturing facility

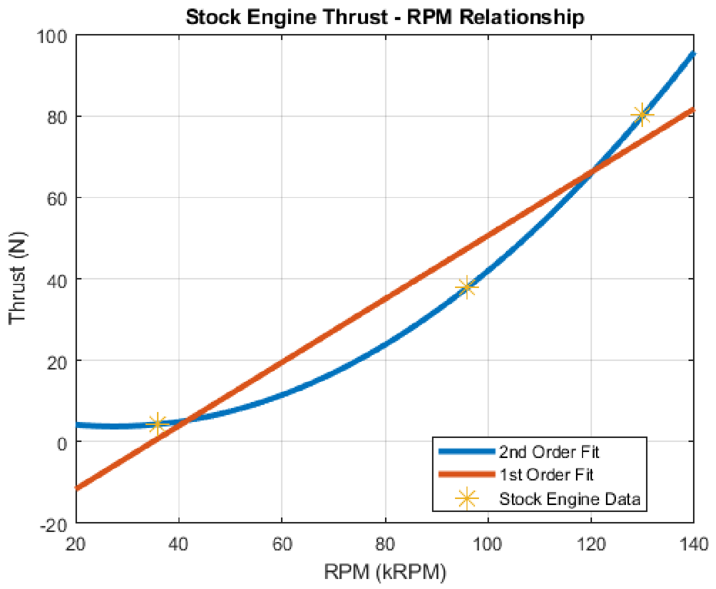
MANUFACTURING MATERIAL PROPERTIES

	N60	Al7075	Ti6AL-4V	Inconel 718	ALSi10Mg	Inconel 625	CoCrMo
Temperature Rating (k)	1422	686	1933	922	933	1563	1670
Density (g/cm^3)	8.5	2.81	4.52	8.22	2.7	8.44	8.28
Volume (cm^3)	10.16						
Mass (gram)	86.36	28.55	45.92	83.52	27.43	85.75	84.12

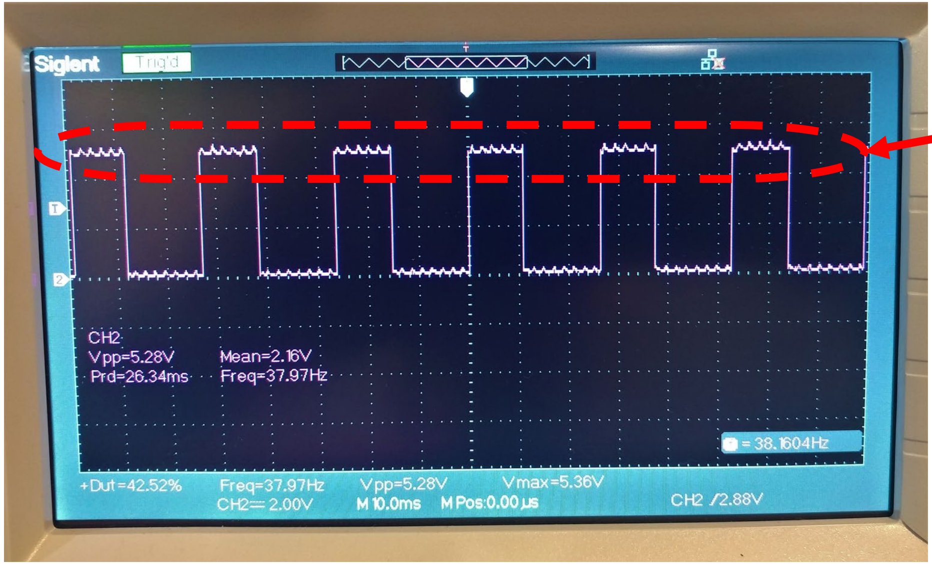
MANUFACTURING CAPABILITIES

Manufacturing Method	Tool Room Lathe	Computer Numerical Control (CNC) Machine	Direct Metal Laser Sintering (DMLS)
Tolerances	Depends on Measurement Tool	+/- 0.005''	+/- 0.005'' + 0.002 in/in

STOCK ENGINE THRUST-RPM LINEARITY



ECM HALL EFFECT SENSOR TESTING



Ripples

Notes: Ripples on waveform are from the power supply maxing out on supply current (5A). The selected battery would be able to supply much higher currents, and allow higher RPM with smaller voltage ripple. This is only present when starter is running (needed for this test but not normal operation) and does not affect functionality or reliability.

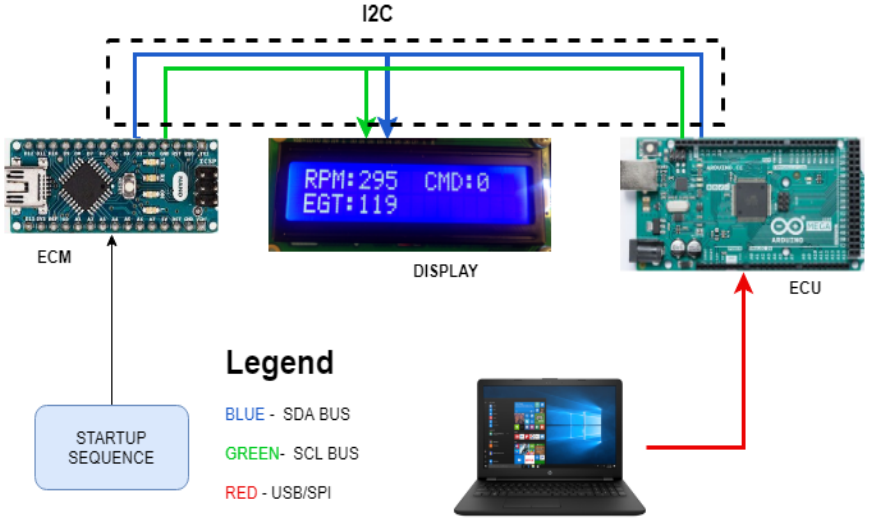
TESTING COMMUNICATION: SPECS

Method: Connected all components and verified I2C and SPI control separately. Designed startup sequence to simulate a “Start” and “Shutdown” command.

Need: Verify application of more than one communication protocol on system. Ensure that specified components can accept multiple commands from different sources and maintain normal operation without conflict or failure.

Results: Test completed successfully. Serial (SPI) command start/shutdown from PC resulted in start/shutdown sequence on ECM.

LCD displayed real time data for RPM, EGT, and command state. Further verifying I2C communication feasibility between ECU and ECM.



ECU/ECM DATA LINK FEASIBILITY

Needs:

- Allotted 3 bytes for RPM value (μs wave period measurement), 1 byte for EGT value (~3℃ resolution 255 values), 1 byte for command status (responds with RPM command input value at state). (At max transmission)

- I2C has a 32 byte maximum transmission per cycle limit, though if needed split transmissions are possible.

- SPI communications are only limited to the extent that they do not block ECU from sending or receiving data from ECM on time.

Method:

- Set up basic communications through I2C to all components.

- Established serial communications with Arduino MEGA.

- Initiated timer on command send.

- Transmitted request event, received data packets from ECM, processed data, wrote to LCD, read timer value at end of write transmission.

Results:

- Minimum Data transfer found to be 5 bytes, total transfer time <20ms.

- 32 byte (I2C maximum) tested time <50 ms per request.

- Verified communications can occur concurrently on time schedule while both microprocessors are tasked with other operations and will respond on schedule within required time constraint of <200ms.

HALL EFFECT SENSOR DATASHEET

Magnetic Position Sensors

Low-Cost, Bipolar, Hall-effect Sensors

SS40A/SS50AT Series

FEATURES

- Small size
- Low cost
- Reverse polarity protection
- Sensitive - bipolar magnetics respond to alternating north and south poles
- Thermally balanced, integrated circuit over a full temperature range
- Stable operation

TYPICAL APPLICATIONS

- Cooling fan control in computers and appliances
- RPM (revolutions per minute) sensing, speed control
- Brushless dc motor commutation
- Position sensing and motor control
- Simple magnetic encoder
- Flow-rate sensor

The SS40A/SS50AT Series sensors are low-cost, bipolar, Hall-effect sensors. These sensitive magnetic sensors offer reverse polarity protection and deliver stable output over a -40 °C to 125 °C [-40 °F to 257 °F] temperature range. Operation from any dc supply voltage from 4.5 Vdc to 24.0 Vdc is acceptable.

The SS40A/SS50AT Series sensors build upon Honeywell's popular magnetic position sensors and offer several competitive advantages. These sensors have been designed with the latest technologies to provide reliable, cost-effective solutions to commercial, computer, medical, and/or consumer applications requiring motor control and RPM sensing.

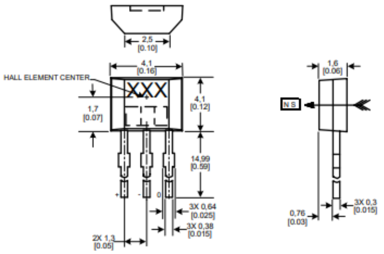
These products are available in a variety of package styles to suit a number of applications. Ammopack versions, along with tape-and-reel, are standard. The surface mount version is mounted directly on the electrical traces on a PC (printed circuit) board. It is attached by an automatic solder reflow operation which requires no hole, so it reduces the cost of the PC board.

ELECTRICAL CHARACTERISTICS

At V_S = 4.5 V to 24 V with 20 mA load with Ta = -40 °C to 125 °C [-40 °F to 257 °F] unless otherwise noted.

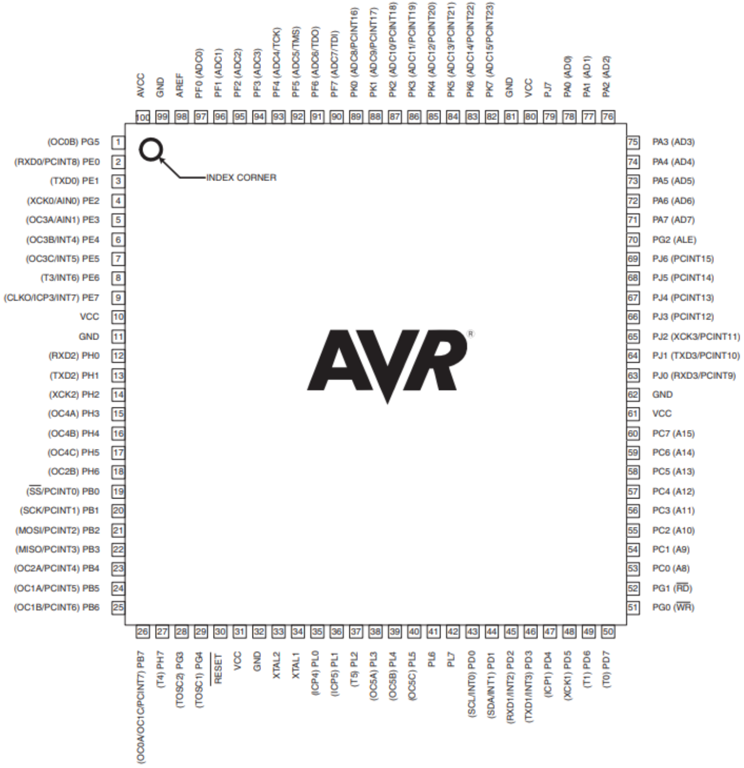
Parameter	Cond.	Min.	Typ.	Max.	Unit
Supply voltage	–	4.5	–	24.0	V
Supply current	25 °C [77 °F]	–	6.8	10.0	mA
Supply current	–	–	–	11.3	mA
Output current	–	–	–	20.0	mA
Vsat @ 15 mA	Gauss >170	–	–	0.4	V
Output leakage	Gauss <-170	–	–	10.0	µA
Rise time	25 °C [77 °F]	–	0.5	1.5	µs
Fall time	25 °C [77 °F]	–	0.2	1.5	µs
Response time	25 °C [77 °F]	–	4.0	5.0	µs
Operate	25 °C [77 °F]	–	45	110	Gauss
Operate	0 °C to 85 °C [32 °F to 185 °F]	–	50	130	Gauss
Operate	–	–	55	170	Gauss
Release	25 °C [77 °F]	-110	-45	–	Gauss
Release	-40 °C to 85 °C [-40 °F to 185 °F]	-130	-50	–	Gauss
Release	–	-170	-55	–	Gauss
Differential	–	50	–	–	Gauss
Operating temperature	-40 °C to 125 °C [-40 °F to 257 °F]				
Storage temperature	-55 °C to 165 °C [-67 °F to 329 °F]				

SS40A SERIES MOUNTING DIMENSIONS (for reference only) mm/[in]



ECU DATASHEET

Figure 1-1. TQFP-pinout ATmega640/1280/2560



8-bit Atmel Microcontroller with 16/32/64KB In-System Programmable Flash

DATASHEET

Features

- High Performance, Low Power Atmel® AVR® 8-Bit Microcontroller
- Advanced RISC Architecture
  - 135 Powerful Instructions – Most Single Clock Cycle Execution
  - 32 × 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 16 MIPS Throughput at 16MHz
  - On-Chip 2-cycle Multiplier
- High Endurance Non-volatile Memory Segments
  - 64K/128K/256KBytes of In-System Self-Programmable Flash
  - 4Kbytes EEPROM
  - 8Kbytes Internal SRAM
  - Write/Erase Cycles:10,000 Flash/100,000 EEPROM
  - Data retention: 20 years at 85°C/ 100 years at 25°C
  - Optional Boot Code Section with Independent Lock Bits
    - In-System Programming by On-chip Boot Program
    - True Read-While-Write Operation
  - Programming Lock for Software Security
    - Endurance: Up to 64Kbytes Optional External Memory Space
- Atmel® QTouch® library support
  - Capacitive touch buttons, sliders and wheels
  - QTouch and QMatrix acquisition
  - Up to 64 sense channels
- JTAG (IEEE® std. 1149.1 compliant) Interface
  - Boundary-scan Capabilities According to the JTAG Standard
  - Extensive On-chip Debug Support
  - Programming of Flash, EEPROM, Fuses, and Lock Bits through the JTAG Interface
- Peripheral Features
  - Two 8-bit Timer/Counters with Separate Prescaler and Compare Mode
  - Four 16-bit Timer/Counter with Separate Prescaler, Compare- and Capture Mode
  - Real Time Counter with Separate Oscillator
  - Four 8-bit PWM Channels
  - Six/Twelve PWM Channels with Programmable Resolution from 2 to 16 Bits (ATmega1281/2561, ATmega640/1280/2560)
  - Output Compare Modulator
  - 8/16-channel, 10-bit ADC (ATmega1281/2561, ATmega640/1280/2560)
  - Two/Four Programmable Serial USART (ATmega1281/2561, ATmega640/1280/2560)
  - Master/Slave SPI Serial Interface
  - Byte Oriented 2-wire Serial Interface
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
  - Interrupt and Wake-up on Pin Change
- Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby, and Extended Standby
- I/O and Packages
  - 54/86 Programmable I/O Lines (ATmega1281/2561, ATmega640/1280/2560)
  - 64-pad QFN/MLF, 64-lead TQFP (ATmega1281/2561)
  - 100-lead TQFP, 100-ball CBGA (ATmega640/1280/2560)
  - RoHS/Fully Green
- Temperature Range:
  - -40°C to 85°C Industrial
- Ultra-Low Power Consumption
  - Active Mode: 1MHz, 1.8V: 500µA
  - Power-down Mode: 0.1µA at 1.8V
- Speed Grade:
  - ATmega640V/ATmega1280V/ATmega1281V:
    - 0 - 4MHz @ 1.8V - 5.5V, 0 - 8MHz @ 2.7V - 5.5V
  - ATmega2560V/ATmega2561V:
    - 0 - 2MHz @ 1.8V - 5.5V, 0 - 8MHz @ 2.7V - 5.5V
  - ATmega640/ATmega1280/ATmega1281:
    - 0 - 8MHz @ 2.7V - 5.5V, 0 - 16MHz @ 4.5V - 5.5V
  - ATmega2560/ATmega2561:
    - 0 - 16MHz @ 4.5V - 5.5V

ECM DATASHEET

ATmega328/P

DATASHEET COMPLETE

Introduction

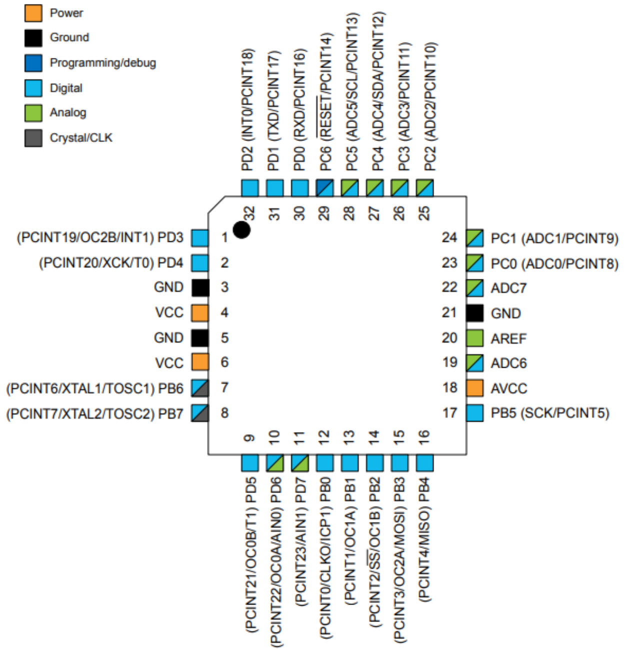
The Atmel® picoPower® ATmega328/P is a low-power CMOS 8-bit microcontroller based on the AVR® enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega328/P achieves throughputs close to 1MIPS per MHz. This empowers system designer to optimize the device for power consumption versus processing speed.

Feature

High Performance, Low Power Atmel®AVR® 8-Bit Microcontroller Family

- Advanced RISC Architecture
  - 131 Powerful Instructions
  - Most Single Clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 20 MIPS Throughput at 20MHz
  - On-chip 2-cycle Multiplier
- High Endurance Non-volatile Memory Segments
  - 32KBytes of In-System Self-Programmable Flash program Memory
  - 1KBytes EEPROM
  - 2KBytes Internal SRAM
  - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
  - Data Retention: 20 years at 85°C/100 years at 25°C[1]
  - Optional Boot Code Section with Independent Lock Bits
    - In-System Programming by On-chip Boot Program
    - True Read-While-Write Operation
  - Programming Lock for Software Security
- Atmel® QTouch® Library Support
  - Capacitive Touch Buttons, Sliders and Wheels
  - QTouch and QMatrix® Acquisition
  - Up to 64 sense channels
- Peripheral Features
  - Two 8-bit Timer/Counters with Separate Prescaler and Compare Mode
  - One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture Mode
  - Real Time Counter with Separate Oscillator
  - Six PWM Channels
  - 8-channel 10-bit ADC in TQFP and QFN/MLF package
    - Temperature Measurement
  - 6-channel 10-bit ADC in PDIP Package
    - Temperature Measurement
  - Two Master/Slave SPI Serial Interface
  - One Programmable Serial USART
  - One Byte-oriented 2-wire Serial Interface (Philips I^{2}C compatible)
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - One On-chip Analog Comparator
  - Interrupt and Wake-up on Pin Change
- Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby, and Extended Standby
- I/O and Packages
  - 23 Programmable I/O Lines
  - 28-pin PDIP, 32-lead TQFP, 28-pad QFN/MLF and 32-pad QFN/MLF
- Operating Voltage:
  - 1.8 - 5.5V
- Temperature Range:
  - -40°C to 105°C
- Speed Grade:
  - 0 - 4MHz @ 1.8 - 5.5V
  - 0 - 10MHz @ 2.7 - 5.5V
  - 0 - 20MHz @ 4.5 - 5.5V
- Power Consumption at 1MHz, 1.8V, 25°C
  - Active Mode: 0.2mA
  - Power-down Mode: 0.1µA
  - Power-save Mode: 0.75µA (Including 32kHz RTC)

Figure 5-3. 32-pin TQFP Top View



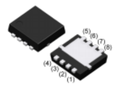
Motor Driver MOSFET n-Channel

Circuit low side driver application, will measure real drain current for application to verify thermal properties are sufficient for given Rds(on)(Max.) value for PCB mount application.

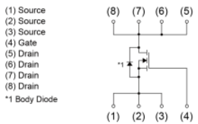
V_{DSS}	40V
$R_{DS(on)}$(Max.)	14.3mΩ
I_D	±27A
P_D	15W

●Outline

HSMT8



●Inner circuit



●Features

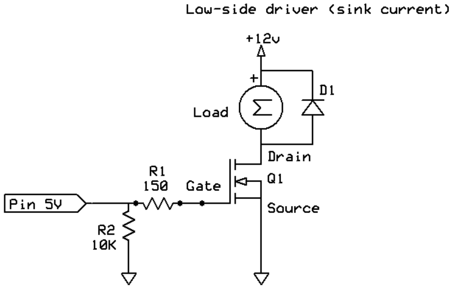
1) Low on - resistance
2) High Power Package (HSMT8)
3) Pb-free lead plating ; RoHS compliant
4) Halogen Free
5) 100% Rg and UIS tested

●Packaging specifications

Type	Packing	Embossed Tape
	Reel size (mm)	330
	Tape width (mm)	12
	Basic ordering unit (pcs)	3000
	Taping code	TB
	Marking	G100GN

●Application

Switching



R1 limits gate current
R2 is pull-down in case pin hi-impedance
D1 is flyback protection (Schottky)
Q1 is N-channel logic-level MOSFET

●Absolute maximum ratings (T_a = 25°C ,unless otherwise specified)

Parameter		Symbol	Value	Unit
Drain - Source voltage		V_{DSS}	40	V
Continuous drain current	T_c = 25°C	I_D *1	±27	A
	T_a = 25°C	I_D	±10	A
Pulsed drain current		I_{DP} *2	±40	A
Gate - Source voltage		V_{GSS}	±20	V
Avalanche current, single pulse		I_{AS} *3	10	A
Avalanche energy, single pulse		E_{AS} *3	15	mJ
Power dissipation		P_D *1	15	W
		P_D *4	2.0	W
Junction temperature		T_j	150	℃
Operating junction and storage temperature range		T_{stg}	-55 to +150	℃