A.C.E.S.
Air-breathing Cold Engine Start

Manufacturing Status Review

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Outline

- Overview
- Schedule
- Manufacturing
- Budget
Overview

Overview Schedule Manufacturing Budget
Project Description

- Design, build, and test a system to facilitate starting a JetCat P90-SXi jet engine at a temperature of -50°F by:
  - Controlling the temperature and mass flow rate of the fuel into the engine
  - Ensuring that the engine electronics are within their operating temperature range
  - Ensuring that the heating system has sufficient power to heat the fuel delivery system and engine electronics

- Motivation
  - Air Force Research Lab (AFRL) conference
  - Proof of concept for high-altitude (cold-temperature) restart for jet-powered UAS
## Course Project Objectives

<table>
<thead>
<tr>
<th>Level</th>
<th>Fuel Delivery System (FDS)</th>
<th>Electronics Heating</th>
<th>Startup Time</th>
<th>AFRL Conference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>System will control mass flow rate &amp; temperature of fuel when placed in an environment cold-soaked to -30°F.</td>
<td>The electronics will be heated to 60°F after being placed in an environment cold-soaked to -30°F.</td>
<td>The fuel delivery and electronics heating systems objectives will be completed in less than 3 hours.</td>
<td></td>
</tr>
<tr>
<td>Level 2</td>
<td>System will control mass flow rate &amp; temperature of fuel when placed in an environment cold-soaked to -40°F.</td>
<td>The electronics will be heated to 60°F after being placed in an environment cold-soaked to -40°F.</td>
<td>The fuel delivery and electronics heating systems objectives will be completed in less than 1.5 hours.</td>
<td></td>
</tr>
<tr>
<td>Level 3</td>
<td>System will control mass flow rate &amp; temperature of fuel when placed in an environment cold-soaked to -50°F.</td>
<td>The electronics will be heated to 60°F after being placed in an environment cold-soaked to -50°F.</td>
<td>The fuel delivery and electronics heating systems objectives will be completed in less than 8 m 42 s</td>
<td></td>
</tr>
<tr>
<td>Level 4</td>
<td></td>
<td></td>
<td></td>
<td>Entire system will be integrated with engine and successfully start within 3 hours.</td>
</tr>
</tbody>
</table>
Mission CONOPS

1) Carrier plane flies at 30,000 ft.
2) Carrier releases UAS with redesigned JetCat engine.
3) Engine startup sequence is initiated (see project conOps).
4) Engine starts and produces thrust (see project conOps).
5) Engine provides enough thrust to avoid the ground.
6) Aircraft is capable of providing ground surveillance.
Project Conops

1. Cold Soak in -50°F Environment

2. Initiate Start-up Heaters

3. Initiate Fuel Flow

-50°F Boundary

Q
Baseline Design

- **Initial Energy:** Cryogel insulated battery

- **Fuel Delivery System:** Resistive heating wire wrapped around fuel delivery components insulated in Cryogel

- **Electronics Heating:** Resistive heating within manufactured plastic box, ESB heated by power resistors in engine cowling

- **Heating Control Unit (HCU):** Microcontroller powered by cold temperature batteries, controls temperatures and fuel flow rate
Baseline Design

![Diagram of the Baseline Design with dimensions: 31.75 cm height and 27.30 cm width.]

- Battery Compartment
- Cold Temp Batteries
- Heating Control Unit
- ECU
- Flow Meter
- Fuel Pump
- Fuel Hopper
Cold temperature batteries provide power to the HCU

HCU commands main heater battery to provide power to heating elements

Electronics and FDS are heated

ECU & ESB reach operational temperature as dictated by HCU

Fuel in hopper and in fuel lines reaches desired temperature as dictated by HCU

HCU commands fuel pump to provide fuel to engine at desired rate

Fuel enters engine at desired flow rate & temperature
Critical Project Elements

CPE 1: Temperature of main heater battery must be > 30°F and < 122°F

CPE 2: ECU, ESB, and engine battery must be 60°F while not exceeding 122°F for the battery and 150°F for the ECU and ESB

CPE 3: Temperature of fuel in fuel delivery system must be > 60°F and < 115°F

CPE 4: A Heating Control Unit (HCU) must control the mass flow rate of fuel and heating systems
Executive Summary

- **Design Changes Since CDR**
  - Multiple HCU PCB changes
    - Removed slave microcontroller
  - Refined electronics housing design
  - Changed resistive wire wrapping pattern
  - Added flow meter to CAD model
  - Refined fuel delivery system design

- **Schedule**
  - HCU PCB schedule has slipped
  - With margin, still on schedule

- **Budget**
  - $2037.71 spent to date
  - On budget
Schedule
Status Summary

Ahead of Schedule:
- HCU Software

Behind Schedule:
- HCU PCB Design
Manufacturing

Electronics Box
HCU Hardware
HCU Software
Testing Apparatus
Electronics Box

Dimensions:
- Width: 31.75 cm
- Height: 27.30 cm
- Depth: 9.52 cm
Electronics Box ProGrEss

Status:
- Electronics box fully designed, including joints and mounting brackets
- Component layout has been finalized

Tasks Still to be done:
- Updating of thermal simulations (for test comparisons)
- Layout design for wiring connections
- 3D Printing L-brackets, corner brackets, and mounting brackets
- Confirm resistor wire length after updated thermal simulations
- Construction of shell prototype and iterate as necessary

Expected Lead Times:
- 3D Printing Brackets: 1 week,
- Prototype: 2 weeks,
- Final Construction: 4 weeks
Components

- Insulation
- Resistive heating elements
- Internal Component Mounts
- Electronics Box Corner Brackets & Clip
Insulation Manufacturing

Status:
- Cryogel purchased and received
- Cryogel pieces will be sewn together; see diagrams

Concerns:
- Cannot be bent easily at small scale
- Produces more dust than anticipated
- Airborne dust is an irritant but not hazardous

Mitigation Strategies:
- Wear gloves, eye protection, long sleeve clothing, and respirator during manufacturing
- Wrap insulation in cellophane
Status:
- Resistive wire ordered, ETA 2-3 wks
- Power resistors to be ordered, 1-2 wks lead time
- Wire will be wrapped around electronic components & batteries as shown on right
- Power resistor configuration within hopper shown on right

Concerns:
- Induced magnetism from wire coils could affect electronics and batteries
- Little room inside fuel hopper to place resistors

Mitigation Strategies:
- V shaped wrap pattern eliminates wire coils around electronic components
- Bulky fuel filter within hopper removed, replaced with inlet at bottom of hopper
Electronics Box Hardware - brackets

- 3D printed with ABS plus-P430 thermoplastic using uPrint SE Plus printer
  - Alternative option: PolyLite ABS plastic with Lulzbot Taz5 printer
- All dimensions in millimeters
- Tolerances for all dimensions are +/- 1 mm
ELectronics Box Hardware - Clip

- 3D printed with ABS plus-P430 thermoplastic using uPrint SE Plus printer
  - Alternative option: PolyLite ABS plastic with Lulzbot Taz5 printer
- All dimensions in millimeters
- Tolerances for all dimensions are +/- 1 mm
TEMPERATURE SENSORs

Status:
- TMP-36 temperature sensors purchased and received
- Sensors will be placed as shown in diagrams
- Sensors will be mounted using low temperature adhesives

Concerns:
- Noise between sensors and HCU

Mitigation Strategies:
- Digital sensor with onboard ADC an option to eliminate noise concerns
Manufacturing

Electronics Box
HCU Hardware
HCU Software
Testing Apparatus
HCU PCB Fabrication

Status:
- Board completely designed in Altium
- **Submitted to Advanced Electronics this week** (lead time 1 week)

Concerns:
- Population of the board will produce errors.
- Noise will produce inaccuracies with the ADC.

Mitigation Strategies:
- Population of the board will occur in the ITLL or Bobby’s lab (w/ supervision)
- **0 Ω** resistors have been placed within the design to allow for debugging capabilities.
Heating Control Unit: FBD

PCB

- LEDs
- ATmega32L
- MOSFET (5V, 4A)
- Buck Converter
- Voltage Regulator

FDS/ECU/ESB Heating

- MOSFET
- Heater
- Temp Sensor

FDS Flow

- Fuel Pump
- Flow Meter

Batteries

- Low-Temp Batteries
- High Power Battery

Key:
- Power
- Command
- Data
- High Power
- Not Unit Tested
- Unit Tested
- Partially Unit Tested
- Alternate Solution
HCU: Biggest Concerns

- Noise in the analog temperature sensors.
  - Long lead wires from sensor location to board (ESB->HCU) will act like antennas.

- Solution
  - Use temperature sensors which on board ADC which will then communicate with the HCU over I²C lines.

- Magnetic field caused by resistor wire coils
  - Faraday’s Law states that a magnetic field will be induced by a coil of wire with a current flow through it.

- Solution
  - Surround component in Faraday Cage and electrically insulate from resistor wire.
Manufacturing

Electronics Box
HCU Hardware
HCU Software
Testing Apparatus
HCU Software Development

Status:
- Code has been completely written
- Only Alive_LED has been unit tested

Concerns:
- Relying on one person for code writing and debugging could result in unresolved bugs

Mitigation Strategies:
- Documentation for the code is being autogenerated by Doxygen
  - Will greatly decrease the amount of time debugging as other group member will be able to understand the code much faster
- Debugging wire harness is due to arrive by Mon Feb. 5 (JTAG)
1. Performs TempConversion() on loop until all components reach desired temperature.
2. Performs TempConversion() and flowMeter() during the pumping phase.
3. TempConversion() only once fuel is exhausted.
HCU: Software

- **TempConversion()**
  - Measures temperature of all sensors
  - Compares temperature to desired and toggles MOSFETs for heating circuits
- **flowMeter()**
  - Counts pulse train from flow meter
  - Compares flow rate to desired and alters PWM duty cycle
Software timing is not an issue
  ○ There are no exact timing constraints for code execution
  ○ The only ISR’s are very short and will be completed within ~10 clock cycles
    ■ ISR for Alive_LED
    ■ Flow meter pulse train ISR
  ○ All 6 temperature conversions should occur within 3 ms
    ■ This was tested in the Atmel Simulator, built in feature of the IDE
  ○ Flow meter code should take 0.262 sec
    ■ This is because the sampling period is this amount of time.
Manufacturing

Electronics Box
HCU Hardware
HCU Software
Testing Apparatus

Overview  Schedule  Manufacturing  Budget
Test Apparatus

Summary:

- Dry ice chamber with active temperature control
- Capable of sustaining $-50 \pm 5^\circ F$ for 1 hour
- Ability to house full electronics box and engine
- Computer fans for temperature control
- Thermocouples for temperature validation and model verification
- Fully constructed
Foam cooler consisting of:

1. Dry ice blocks
2. 2 temperature control fans
3. 1 circulation fan
4. Chicken wire cage to support additional ice and thermocouples
5. National Instruments DAQ
6. 4 type K thermocouples
7. Wiring for fan power
8. Arduino MEGA

ALL COMPONENTS ACQUIRED
Test Apparatus Progress

Status:
- Conducted initial trials with test chamber (see plot for results)
- Test chamber feasibility demonstrated
- Test chamber fully constructed

Concerns:
- Test chamber warms too quickly to control when fans are operated
- Fans become very cold, could cease to function

Mitigation Strategies:
- Arduino fan control to be implemented
- Fans can be replaced between tests
Cost Plan

Current Total Expenditures = $2037.71
Remaining Budget = $2962.29
## Critical Parts Received

<table>
<thead>
<tr>
<th>Part</th>
<th>Cost (Including Shipping)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Pump with Cable</td>
<td>$383.90</td>
</tr>
<tr>
<td>ATMEGA32L, In circuit Debugger, Adapter Cable</td>
<td>$290.58</td>
</tr>
<tr>
<td>Cryogel Insulation</td>
<td>$319.84</td>
</tr>
<tr>
<td>Resistive Heaters</td>
<td>$249.91</td>
</tr>
<tr>
<td>Altium License</td>
<td>$124.01</td>
</tr>
<tr>
<td>Turnigy Heavy Duty Lip (Heater Battery)</td>
<td>$81.36</td>
</tr>
<tr>
<td>HCU Batteries</td>
<td>$92.91</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$1,542.51</strong></td>
</tr>
</tbody>
</table>
Pending/Planned orders

<table>
<thead>
<tr>
<th>Item</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB Printing</td>
<td>$300</td>
</tr>
<tr>
<td>3D Printing L-Brackets</td>
<td>$150 (U-print)</td>
</tr>
<tr>
<td>4 Thermocouple Breakout Boards</td>
<td>$60</td>
</tr>
<tr>
<td>Miscellaneous Electronic Components</td>
<td>$100</td>
</tr>
<tr>
<td>Custom Electronics</td>
<td>$800</td>
</tr>
<tr>
<td>Travel Expenses</td>
<td>$800</td>
</tr>
<tr>
<td>Printing</td>
<td>$300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2,510</strong></td>
</tr>
</tbody>
</table>
## Lead Time for Ordered Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Lead Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive Wire</td>
<td>2-3 Weeks (Already Ordered)</td>
</tr>
<tr>
<td>PCB Printing</td>
<td>1 Week per iteration</td>
</tr>
<tr>
<td>3D Printing L-Brackets</td>
<td>1 Day per iteration</td>
</tr>
<tr>
<td>Thermocouple Breakout Board</td>
<td>1-2 Weeks</td>
</tr>
</tbody>
</table>
Questions?
BACKUP SLIDES
First Run 1/19:
- Initial test conducted to establish feasibility of dry ice test chamber
- No active temperature control
- Two thermocouples placed with 5 inch vertical displacement
  - Placed at 1 inch and 6 inches above dry ice
  - Easy to maintain one, but proved test-bed was unhomogenized

Takeaways and lessons learned:
- Issues with temperature control and uniform temperature distribution
- Surprisingly good temperature consistency
- Sublimation a non issue
- Active temperature control necessary
Functional Requirements

- **FR 1) ENERGY:** An initial energy source shall provide adequate power for the fuel delivery system heating and electronics heating.

- **FR 2.1) FDS:** The Fuel Delivery System shall provide a specified fuel flow rate from 0 to 4.8 g/s ± 0.13 g/s to the engine.

- **FR 2.2) FDS:** The Fuel Delivery System shall provide fuel at a specified temperature from 60 to 110°F ± 3.6°F to the engine.

- **FR 3) Electronics Heating:** The electronics (ECU, ESB, batteries) shall be heated to their operating temperature of 60°F.

- **FR 4.1) HCU:** The Heating Control Unit (HCU) shall monitor and regulate the temperature of the electronic components and fuel delivery heating systems.

- **FR 4.2) HCU:** The Heating Control Unit (HCU) shall monitor and regulate the mass flow rate of the fuel delivery heating system.
HCU: SoftwARE

Initial()

- Data direction registers for Digital I/O Ports
- Flow meter pulses, pump duty cycle, and allowable error for pulses
- Enable global interrupts
- Configure ADC: 62.5 kHz (50-200 kHz), left justified, set enable bit
- Set up Timer (16 bit) for overflow interrupts and 500ms
- Turn on heaters and set appropriate PWM heater channels
- Return

Program Main

- Initial()
- TempConversion()
- Check if opMode equal to 1
- Yes
- flowMeter()
HCU: Software
flowMeter()

pulse_count = 0

Enable External Interrupts INT2

Setup Timer to run for 0.262 seconds, and begin

Wait for timer overflow flag to be set

Were any pulses recorded?

Yes

Pulses received

Decrease Duty Cycle

Pulse_error < pulse_error_allowed

No

Toggle Fuel_LED

Yes

Make Fuel_LED solid on

Turn off the pump and turn all 3 LEDs on

No

Increase Duty cycle

Pulse_error < pulse_error_allowed

No

Toggle Alive_LED

Yes

Return

Program Main

Initailize

TempConversion()

Is the opMode equal to 1?

Yes

flowMeter()
Bead inductor: 50-100 ohms @ 100MHz
Expected Temperature Change vs Time

- Heater On
- Heater Off
- Heater On

Temperature

Time

Δtemp << 1°F

0.25 Sec Delay

Desired Temp
HCU: Software Mass flow

Mass Flow Rate of Fuel Pump vs Voltage

- Fuel Pump Recorded Data
- Voltage at Full Throttle = 2.0322
- Mass Flow at Full Throttle = 4.8 g/s
- Best Fit Line
- Maximum Voltage = 4.5 V
- Maximum Mass Flow Rate = 11.2503 g/s

\[
\frac{g/s}{V} = 2.61379
\]

<table>
<thead>
<tr>
<th>4.8 g</th>
<th>1 mL</th>
<th>1 L</th>
<th>110,000 pulses</th>
<th>0.262144 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 s</td>
<td>0.81 g</td>
<td>1000 mL</td>
<td>1 L</td>
<td>1 period</td>
</tr>
</tbody>
</table>

= 171 pulses per period

\[
\text{4.8 g} \quad \frac{1 \text{ period}}{1 \text{ s}} \quad \frac{0.02807 \text{ g/s}}{171 \text{ pulses}} = 0.02807 \text{ g/s error per pulse}
\]

<table>
<thead>
<tr>
<th>1 pulse</th>
<th>0.02807 g/s</th>
<th>0.382587 V</th>
<th>20,000 counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 pulse</td>
<td>1 g/s</td>
<td>6 V</td>
<td></td>
</tr>
</tbody>
</table>

= 35.797 DACR1B per pulse error
Wire Wrapping

- Need to prevent wire wrapping from being an electromagnet.
  - Could/probably will disrupt the Lipo battery equalizing circuits and ECU
    - This configuration will produce destructive B fields.
  - Fuel lines do not have this concern so they will be wrapped in the more traditional sense.
Test Chamber Software

- Software is currently not written or tested
  - However, this is not a concern.

- Same conditional control law as for the heater circuits (controlled by the HCU)
  - Makes implementation very simple.

- Need to interface with the SparkFun Thermocouple Breakout Board - MAX31855K
  - This is done over the SPI lines for the Arduino.
  - Arduino has built in libraries which makes this incredibly easy.
Power Resistors for ESB

- **Vishay/Dale 12 Ohm 15W** power resistors to heat ESB (x2)
- These will be mounted to the underside of the ESB using a Cyanoacrylate
  - An example of this is super glue
  - These have temperature ranges of -67 to 482 F.
Lengths of Resistor Wire

- 14 ft (0.88Ω/ft) for both Lipo batteries
- 3.86 ft (3.17 Ω/ft) for the ECU
- 11.92 ft (3.17 Ω/ft) for outside the hopper
- 0.54 ft (3.17 Ω/ft) for Fuel line section 1
- 0.83 ft (3.17 Ω/ft) for Fuel line section 2
- 2.69 ft (3.17 Ω/ft) for Fuel line section 3