Agenda

3D Printing
- Overview
- Subsystems
- Prototyping/Analysis
- Manufacturing Plan
- Testing Plan

Pressure Sensor
- Overview
- Subsystems
- Prototyping/Analysis
- Manufacturing Plan
- Testing Plan

Overall
- User Guide Compliance
- Project Management Plan
3D Printing In Microgravity

Stevens Institute of Technology

Roger Kleinmann, Matt Lagarenne, Jesse Stevenson, Nathan Tahbaz, Abe Edens, Nick Osborne, Sankee Maringanti
Mission Overview

Roger Kleinmann
The goal of this payload is to test the effects of high G’s and microgravity on 3D prints.

Collect data on layer densities vs. time printed (what point in the flight path)

We expect to observe that layer densities vary in changing G-force/microgravity

Benefit: Learn difficulties/problems of 3D printing in a high G/micro gravity environment
Theory and Concepts

• Layer lamination will be affected by varying G-forces
• Rocket vibration will cause a reduction in resolution
• 3D printers currently experience problems in resolution and layer adhesion, and require well-calibrated conditions to function well. This experiment will attempt to view print results under extreme mechanical conditions that would typically destroy prints.

• What other research has been performed in the past?
  – 2015 Virginia Tech RockSAT X 3D printed VT logo
  – M3D – newly released micro 3D printer
    • Purchased and disassembled for reverse engineering
Expected Results

• Because this is not an ideal environment, we expect varying thicknesses between the many layers along the z-axis due to changes in acceleration of the rocket.

• Vibrations of the rocket will likely cause imperfections along the x and y axes, characterized by random, jagged artifacts.
Concept of Operations

T = +130s

T = -3 min
3D Extruder heated

T = -15 sec
-Wipe extruder head and print first layer

T = +15 mins
-Returning flight
-Stop print

*Time logs pair with print layers for evaluation
Success Criteria

Minimum Success Criteria:
What is the least amount of data you can collect that will still constitute a mission success?

Comprehensive Success Criteria:
What is the ideal amount of data to have full or comprehensive mission success?
Success Criteria

• Minimum Success Criteria:
  – Completing at least 25% of a print (even a partial print will supply data on where failure occurred mid-flight)
  – Analysis will be a comparison of in-flight print and ground level print (comparison of layer height via digital analysis and number of artifacts)

• Comprehensive Success Criteria:
  – Complete print with minimal aberrations and artifacts
Functional & Design Requirements:

• Structure: The printer will be a 3-Directional Cartesian model
  – Belt, lead screw, rack & pinion driven
  – Within 4” in vertical direction (Z-axis)
  – Within 5” in each horizontal direction (xy-plane)

• Dependencies: Temperature sensor, 4 stepper motors (max 10V, 500mA), extruder heater resistor (max 12V, 4A)
## Example Functional Requirements:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>The print volume must span 1” in every direction.</td>
<td><strong>Demonstration</strong></td>
<td>Mechanical stops and linear motion will have at least 1/8” of additional space beyond the 1” requirement.</td>
</tr>
<tr>
<td>Mechanical components must remain stable in the high G’s and vibrations of the rocket.</td>
<td><strong>Test</strong></td>
<td>Main body to be machined from aluminum. Small part lengths means lower concern for stress and deformation.</td>
</tr>
<tr>
<td>Entire 3D printer must weigh under 3 lbs and fit within our size constraints.</td>
<td><strong>Inspection</strong></td>
<td>Any parts that are typically steel on classic printers will be replaced by aluminum, nylon, or 3D printed ABS.</td>
</tr>
<tr>
<td>Layer time must be less than 10 seconds per layer in order to make a 1” tall sample print.</td>
<td><strong>Analysis</strong></td>
<td>Custom G-code will allow for lowest layer time possible while also maintaining consistent print quality.</td>
</tr>
</tbody>
</table>
RockSat-C 2016 User’s Guide Compliance

- Expected to weigh 3 lbs.
  - Steppers 5 oz. each
  - Other components are plastic or aluminum
- Expected dimensions
  - 4” definite height
  - 4” max width
  - 5” max length
- Activation
  - 3 minute pre-launch for extruder preheating
  - 15 second pre-launch time to clean extruder and print first layer
System Overview
Roger Kleinmann & Company
De-Scopes & Off-Ramps

issues

- design / prototyping
- manufacturing
- pre-launch issues
- software issues
- mechanical failure
- launch issues
- post launch

- constraints
- size
- power
- weight
- cost cheaper materials
- shipping / time order extra while staying in budget
- cheaper manufacturing techniques
- cost have options
- shipping / time making sure things fit – match the actual product
- tolerances design with minimum space constraint possible
- fulfilling constraints make sure products are in technical ability
- programming program early
- breaking or mis-manufacture order multiples (beforehand)
- check wiring
- power failure built in restore-loop
- make sure batteries are charged
- extruder – jammed or clogged clean extruder
- self-cleaning routine
- write good code...
- debug
- debug
- debug
- mechanical failure
- loss of power
- write print state to EEPROM
- electrical connections
- power interruption
- write print state to EEPROM

sub assembly – mid Feb
- canister – April
- launch ready – June 6th
- launch – June 23rd

dates
System Level Block Diagram

Legend

- **Power Supply**
- **Sensor Feedback**
- **Extruder Temperature Sensor**
- **Extruder Heating Element**
- **Arduin0**
- **Motor Feedback Loop**
- **Stepper Controllers**
- **Stepper Motors**
- **Limit Switches**
System Design – Physical Model

- Linear Bearings
- Axial Bearings
- Limit Switch
- Rack/Pinion
- Pulleys
- NEMA 14 Stepper (1.5” x,y,z)
- Lead Screw (1/4” 20)
- Base Plate
Design in Canister (preliminary)
Electrical Schematic

RockSat-C 2015

CDR
Electrical Design

- Finalized decision on stepper motors and driver boards
- Raspberry Pi to send G-Code over serial link to Arduino
- Around 2-2.5 Amps at max usage (All 4 steppers running + heating element)
Software for Arduino will be based off of RepRap 3D printer G-Code interpreter

Modify to output to our driver board

Pi runs a small script to stream data from file stored on SD card to Arduino over serial

Most work will be in getting the Arduino to work consistently and accurately
Electrical Design - Software

Software will send a signal to begin heating hot end with early activation.

Print a single layer before launch for reference during acceleration.

After g-switch is triggered, start streaming data from Pi to Arduino to start the print process.
Subsystem Design
Roger Kleinmann & Company
Subsystem Design

X,Y,Z-Axis Motion

• Risks
  • Higher weight
  • Slow travel rate
  • Instability

• Restrictions
  • Cost of material
  • Weight/strength tradeoff

• Decisions
  • NEMA 14 motors (+smaller, -weaker)
  • Nylon lead screws (+lighter, +cheaper, -weaker)
  • Rack & pinion (+faster, -less precise)
Subsystem Design

Extruder

• Risks
  • Heavy top load
  • Bulky
  • Filament instability

• Restrictions
  • Dimensions
  • Weight

• Decisions
  • Bowden style extruder (+space, -less precise)
  • PLA filament (+easier calibration, -low melting point)
Subsystem Design

Additional Notes

• Extruder temp feedback to be determined
  • Undecided on what sensors to use
  • Should have no impact on constraints

• Limit switch feedback to be used
  • Motors originate at 0,0,0 limit switch position
  • Further motion is purely stepper motor operation

• Arduino
  • 4 stepper controllers
  • 3 digital ports (limit switches)
  • 1 analog port (temperature sensor)
Subsystem Design

Tradeoff Decisions

• In every decision, two requirements were necessary

1) Weight
   • Swapping steel for aluminum
   • Aluminum for plastic
   • Allowable due to small part lengths and therefore small stresses

2) Cost
   • Using guide rods instead of nylon lined rails
Subsystem Design – Risk Matrix

- RSK 1: Extruder heat conducts to and melts nearby parts
- RSK 2: Motor torque is not enough to counter rocket vibrations and print fails
- RSK 3: Filament jams and stalls print
- RSK 4: Print does not adhere to print bed
We used SolidWorks to calculate weight for all parts combined

Arduino and other electrical component weights were also clumped together

More specific weight considerations will be made for assembly

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Total Mass (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Mechanical Components</td>
<td>2.82</td>
</tr>
<tr>
<td>Electrical Components</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.87</strong></td>
</tr>
</tbody>
</table>
Test/Prototyping Plan

Roger Kleinmann
Testing & Prototyping

• The prototype will be a fully assembled model
  • Parts to be machined will be 3D printed with ABS instead
• Testing will occur in a series of stages
  • Vibration table analysis
  • Temperature testing
  • Time trials
• Each testing stage will show print results and printer stability/resilience
Manufacturing Plan

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Mechanical Elements

• Manufactured
  – Aluminum mounts
  – Nylon bushings
  – 3D printed housings

• Procured
  – Nylon threaded rod
  – Bearings
  – Electronics
Complete Manufacturing

- All aspects of completed design will be the same for both prototyping and completion.
- Coding and electrical components will be recycled from prototype to final model.
Testing Plan

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Mechanical Testing

- Testing will occur in a series of stages
  - Vibration table analysis
  - Temperature testing
  - Time trials
- Each testing stage will show print results and printer stability/resilience
- Mechanical testing will occur early 2016 upon completion of the final assembly
Electrical Testing

• Unlike mechanical, electrical testing will begin with the procurement of parts such as
  – Stepper motors
  – Hot end
  – Arduino
  – Stepper controllers
• This will better our understanding of their integration
Software Testing

• Software will be largely recycled from open source projects online
• True testing of software will occur with mechanical testing while running 3D prints
• At this point, testing will be entirely system integrated
Expected to weigh just under 3 lbs.
  – Steppers 5 oz. each
  – Other components are plastic or aluminum

Expected dimensions
  – 4” definite height
  – 4” max width
  – 5” max length

Activation
  – 3 minutes for pre-launch heating and 15 seconds to begin print
Project Management Plan

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Schedule

• Deadlines
  • Completion of design: Early January
  • Procurement of parts: Mid January
  • Build completion: End of January
  • Testing: Remainder of project

• Communication will continue through multiple online resources throughout winter break for project completion
## Budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Supplier</th>
<th>Individual Cost</th>
<th>No. Required</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMA 14</td>
<td>Pololu</td>
<td>$13</td>
<td>4</td>
<td>$52</td>
</tr>
<tr>
<td>Nylon Threaded Rod</td>
<td>McMaster</td>
<td>$4</td>
<td>1 (2 ft)</td>
<td>$4</td>
</tr>
<tr>
<td>Linear Motion Nuts</td>
<td>McMaster</td>
<td>$2</td>
<td>4</td>
<td>$8</td>
</tr>
<tr>
<td>ABS</td>
<td>Hatchbox</td>
<td>$25</td>
<td>1 (1 kg)</td>
<td>$25</td>
</tr>
<tr>
<td>PLA</td>
<td>Hatchbox</td>
<td>$25</td>
<td>1 (1 kg)</td>
<td>$25</td>
</tr>
<tr>
<td>Axial Bearings</td>
<td>McMaster</td>
<td>$6</td>
<td>4</td>
<td>$24</td>
</tr>
<tr>
<td>Linear Bearings</td>
<td>McMaster</td>
<td>$15</td>
<td>4</td>
<td>$60</td>
</tr>
<tr>
<td>Rack/Pinion</td>
<td>McMaster</td>
<td>$20</td>
<td>1 (2 ft)</td>
<td>$20</td>
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<tr>
<td>Arduino Board</td>
<td>Adafruit</td>
<td>$25</td>
<td>1</td>
<td>$25</td>
</tr>
<tr>
<td>Extruder Assembly</td>
<td>-------</td>
<td>$20</td>
<td>1</td>
<td>$20</td>
</tr>
<tr>
<td>Limit Switches</td>
<td>-------</td>
<td>$2</td>
<td>3</td>
<td>$6</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>$215</strong></td>
</tr>
</tbody>
</table>
Conclusion

- At this point we know what electronics we need and can procure them for testing
- Over winter break, mechanical design must be completed so that assembly can occur late January
- Since PDR
  - All design decisions have been made
  - Simply need to finalize the model
Under Pressure
Critical Design Review
Mission Overview
Mission Overview:

Mission Statement: The goal of this project is to measure High-Speed Boundary Layer Transitions from laminar to turbulent pressure waves using a piezoresistive and piezoelectric pressure sensor combination mounted in a custom window on the skin of the rocket.

Mission Requirements: Integrate two pressure sensors, and thermocouple in the window of the rocket. The best position would be as close as possible to the front of the rocket. Use ADC and FPGA to store accurate data about Boundary Layer Transitions at a speed of 2MHZ and a resolution of 16 bits into an SD Card.
Theory and Concepts

• High-Speed Boundary Layer Transition
  – Laminar -> Unstable Transition -> Turbulent
  – Measure transition using static pressure sensors that are perpendicular to the airflow over the boundary layer.

• Locate sensors as close as possible to the neck of rocket. The pressure will be higher here than the pressure at the center of the shock wave at the tip of the rocket.
  – Transition measurements will be easier to make at the neck of the rocket.

• Laminar to Turbulent transition in High-Speed Boundary layers helps to predict and control heat transfer, skin friction, and other boundary-layer properties.
• Static measurements will detect the state of the boundary-layer.
Expected Results

- An accurate depiction of boundary layer transitions:
  - The static pressure measured by the fast Piezoelectric sensor and slow but accurate Piezoresistive sensor will reflect the transition of the boundary layer.
  - When in the Laminar phase (subsonic), there will be little change in static measurement.
  - At Mach 1 there should be a sudden increase in static pressure. Followed by little to mild consistent fluctuations on the order of $10^1$ kPa (supersonic Laminar),
  - Once the flow turns Turbulent there will be considerable fluctuations in the static pressure. On the order of $10^{2-3}$. 
Concept of Operations

- **T = -10 min**: All subsystems activate, 3D printer warmup
  - t = 0 min

- **T = +5 sec**
  - G switch triggered
  - 3D printer begins printing sample
  - Self-healing epoxy punctured

- **T = +5 mins**
  - 3D printer stops printing

- **Bump ends**
  - Boundary layer data collection ends

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Success Criteria

• Minimum Success Criteria:
  – Successfully sample Boundary layer flow at any sample rate and resolution.
• Comprehensive Success Criteria:
  – Expect to record and measure instability waves on the boundary layer of the rocket with a combination of pressure sensors at a resolution of 16 bits and rate of 2MHz.
• Record position of rocket using accelerometer and gyroscope to get a full picture of rocket state.
• Further research can be conducted with both data collected and NASA’s own post flight data.
  – Research boundary layer transition estimation methods.
  – Correlate Transition with current angle and rotation speed of rocket using accelerometer and gyroscope.
## Functional and Design Requirements:

Ordered from greatest to least importance (format of Functional requirement then design requirement) :

<table>
<thead>
<tr>
<th>Functional Requirement</th>
<th>Design Requirement</th>
<th>Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accurate and Precise collection of data from Pressure sensors.</strong></td>
<td>A Piezoresistive and Piezoelectric Pressure sensor combination will collect data at a resolution of 16bits.</td>
<td>Pre-Flight bench testing by hooking all sensors to the ADC and FPGA along the real time clock.</td>
</tr>
<tr>
<td><strong>FPGA and ADC will process the signals in real time.</strong></td>
<td>The FPGA and ADC will convert the data at 2MHz. The ADC must support this rate.</td>
<td>Pre-Flight bench Test.</td>
</tr>
<tr>
<td><strong>FPGA SPI protocol and Storage system that can store data for entire 130s.</strong></td>
<td>The FPGA will have to be programed with the SPI protocol and designed to write at 2MHz. The complete storage size is 8.32GB (Exact). This will be extended to 32GB (multiple SDs to decrease write time).</td>
<td>Pre-Flight bench Test.</td>
</tr>
</tbody>
</table>
## Functional and Design Requirements:

Ordered from greatest to least importance:

<table>
<thead>
<tr>
<th>Functional Requirement</th>
<th>Design Requirement</th>
<th>Verification Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional watertight pressure sensor mounting design to minimize any noise in pressure readings.</td>
<td>Proper milling and design of window. Noise can extend from the pressure sensor cavity and placement. Flush placement of pressure sensor (please see payload slide.)</td>
<td>Inspection for watertightness after underwater submission during preflight testing. Mathematical analysis on the noise that may be recorded due to cavity resonance can verify best location for sensors.</td>
</tr>
<tr>
<td>Time Stamp all data in storage.</td>
<td>Integrate a Real Time Clock through Communication method.</td>
<td>Pre-Flight bench Test.</td>
</tr>
<tr>
<td>Detect and Log Boundary Layer Transitions:</td>
<td>Ensure all the previous requirements are met.</td>
<td>The final requirement can only be verified post flight through analysis of the data.</td>
</tr>
</tbody>
</table>
System Overview
Changes Since PDR

• Signal Conditioner may be required.
  – Signal from ICP pressure sensors need to be isolated from ADC and amplified.
  – Small circuit on breadboard will be designed.
  – New power requirements
• Using Honeywell sensor as alternative to Kulite Sensor.
  – Kulite sensors completely out of picture.
• Addition of 4pin SD RAW Communication Interface type.
  – Write 4 blocks of data in parallel.
  – Works similarly to SPI.
De-Scopes and Off-Ramps

- Listed in Order of Most Important (most likely):
  - Budget Restrictions: Piezoelectric sensors are expensive and require signal conditioning and supporting hardware. If this proves beyond the budget the piezoelectrics might be scrapped in favor of cheaper piezoresistive sensors.
  - Sampling rate: The 2MHz sampling rate is difficult to achieve with the space and budget restrictions. Additionally, depending on the support for the FPGA it might be very difficult to implement the SPI or other protocols. A Beaglebone with two PRUs (Programmable Real-Time Units) is also available. It should be capable of sampling in the 1MHz range or higher, making it a fallback option if the FPGA does not pan out.
  - Size: Most of this experiment should fit on a single disk in the Payload however, the combination of all the electronics might be too large. In this case we will have to balance budget and size. The smaller electronics are usually can be more expensive.
  - Thermocouple: Currently we plan to reuse the thermocouples used in a previous RockSat experiment. However if we do not have this part we can extrapolate the temperature using the previous experiment data.
  - Accelerometer and Gyroscope: We would like data from the accelerometer and gyroscope to offer a full picture of the rocket but incase we cannot get access to one our experiment can go on without it.
Block Diagram

- Power = Red
- Data = Blue

- Main Board Power
- Accelerometer Gyroscope From Main Board
- SD CARD1
- SD CARD1
- SD CARD1
- Power = Red
- Data = Blue
Mechanical and Electrical Design Elements

- **Mechanical:**
  - Window Design and Sensor Mounts

- **Electrical:**
  - FPGA
  - SD Cards
  - Piezoresistive sensor
  - Piezoelectric sensor
  - AC Coupling
  - Thermocouple
M&E Design Elements: Window Cover
Sensor Mount
Sensor Mount Engineering Drawing
Electrical Design Elements: Dimensions

- FPGA: .7” by 2.6”, ½ inches thick
- A/D Converter: 0.275591 x 0.275591, 0.019685 inches thick
- Piezoresistive, honeywell: .64” square base, .8” high
- Piezoelectric, PCB: .5” high, .125” diameter
- Signal Conditioner: ~2”x3” soldered perf-board
  ○ Op Amp, Constant Current Diode, Opto-isolator.
- Thermocouple - .05” in diameter.
- Real Time Clock: 0.122047” by 0.122047”, 0.0374016” high
Electrical Design Elements:

- 1x FPGA - Field programmable gate array used to transfer data from the sensors to the SD cards at +2MHz speeds.
  - Xilinx Spartan™-6 XC6SLX4-2CPG196 FPGA
- 2x Analog to Digital Converters - used to take analog data from the sensors and put them in a digital format for the FPGA.
  - AD7622BSTZ
- 4x SD cards - Digital storage for collected data
- 1x Piezoresistive sensor - good at low frequencies for static readings
  - Honeywell PC136
- 1x Piezoelectric sensor - good at high frequencies and dynamic readings.
  - PCB 132A31
- 1x Real Time Clock - to timestamp sensor readings
  - PCA8565TS
Software Design: Flow Diagram

FPGA

- Initialize SPI Clock for SDC 1 (Setup Master Slave Connections)
- Initialize SPI Clock for SDC 2 (Setup Master Slave Connections)

Sensor 1 Data
- Concatenate Sensor1 and Clock Data
- Split Sensor and Clock data into 8 bit chunks
- Write to SD Card 1

Sensor 2 Data
- Concatenate Sensor2 and Clock Data
- Split Sensor and Clock data into 8 bit chunks
- Write SD Card 2

Real Time Clock

SD CARD1

SD CARD2
Software Design:

- FPGA SPI Protocol
  - Inputs and outputs:
    - SCLK: Serial Clock (output from master).
    - MOSI: Master Output, Slave Input (output from master).
    - MISO: Master Input, Slave Output (output from slave).
    - SS: Slave Select
  - SD Cards will be written in RAW Format allowing for large Block Sizes up to 512 bytes. We will be writing in 3 bytes.
  - [http://opencores.org/project,spi_verilog_master_slave](http://opencores.org/project,spi_verilog_master_slave)
- Veralog will be used to program the FPGA.
  - If the backup idea utilizing a Beaglebone is implemented we will use C/C++.
Subsystem Design
Subsystems:

- This BLT or Boundary Layer Transition subsystem will include the following subsystems:
  - Electrical Subsystem:
    - Integration of all sensors with the ADC.
  - Computer Subsystem:
    - FPGA implementation consisting mainly of writing the SPI protocol (not finalized) to interface with SD cards and Real Time Clock.
  - Mechanical Structure:
    - Creation of pressure sensor mounting block that will connect to the WFF Window pocket. Along with milling holes in the window piece.
Subsystem Overview: Electrical Subsystem

- Two types of high-frequency pressure sensors:
  - Piezoresistive
    - Low frequency pressure waves and better static readings
  - Piezoelectric
    - High frequency pressure waves and better dynamic readings.

- Total Weight: Less than 8 ounces.

- Power Requirements on next Slide

- Final
## Power Requirements

<table>
<thead>
<tr>
<th>Product</th>
<th>Type</th>
<th>Voltage</th>
<th>Current (Worst-Case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cmod S6</td>
<td>FPGA</td>
<td>5-15V</td>
<td>360mA</td>
</tr>
<tr>
<td>AD7622</td>
<td>A/D C</td>
<td>4V</td>
<td>25mA</td>
</tr>
<tr>
<td>PCA8565</td>
<td>RTC</td>
<td>6.5V</td>
<td>50mA</td>
</tr>
<tr>
<td>PCB 132A31</td>
<td>ICP Sensor</td>
<td>23V</td>
<td>20mA</td>
</tr>
<tr>
<td>Honeywell 136PC</td>
<td>Sensor</td>
<td>10V</td>
<td>2.4mA</td>
</tr>
<tr>
<td>SD Cards</td>
<td>Storage</td>
<td>2.7-3.6V</td>
<td>NA</td>
</tr>
</tbody>
</table>
Subsystem: Computer Subsystem

- Pressure sensors are to be sampled at a 2 MHz sample rate with a resolution of 16 bits. While other sensors are sampled at maximum of 1 MHz.
  - This will require an A to D convertor that can translate the data at this rate without loss.
- A FPGA (Field Programmable Gate Array) will manage the data output of all the sensors. It will timestamp the data using a Real Time Clock then transfer the data into storage.
  - The FPGA can be programmed to process the data in realtime to effectively combine all sensor readings at certain moment in time.
- Multiple SDHC cards will be used for storage.
  - The FPGA will use a SPI interface for communication to SD Cards.
Subsystem Overview: Mechanical Subsystem

- The pressure sensors must be mounted flush with the skin of the rocket with an appropriate sized opening.
  - The window of the rocket must be pierced and must be airtight to conform to design requirements and prevent water from entering the modules on landing.
  - Proper mounts for the sensors are required to be designed and machined to accommodate the various pressure and thermocouple designs. (Threaded and Glued). These will integrate with the window pocket given by WFF.
  - Three possible mounting locations: flush with center, flush with edge, and halfway in between.
# Trade Studies

<table>
<thead>
<tr>
<th>ADC</th>
<th>ADS8422IBPFBT</th>
<th>ADC7622B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>8 ($51.18)</td>
<td>10 ($36.55)</td>
</tr>
<tr>
<td>Interface</td>
<td>7 (parallel)</td>
<td>10 (parallel, serial, DSP, SPI)</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>9 (4 MS/s)</td>
<td>8 (2 MS/s)</td>
</tr>
<tr>
<td>Number of channels</td>
<td>7 (1)</td>
<td>7 (1)</td>
</tr>
<tr>
<td>Average</td>
<td>7.8</td>
<td>8.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SD CARD</th>
<th>Sandisk Extreme Pro</th>
<th>PNY Elite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>5 ($49.95)</td>
<td>10 ($8.99)</td>
</tr>
<tr>
<td>Write Speed</td>
<td>10 (250 MB/s)</td>
<td>7 (80 MB/s)</td>
</tr>
<tr>
<td>Read Speed</td>
<td>8 (280 MB/s)</td>
<td>6 (90 MB/s)</td>
</tr>
<tr>
<td>Size</td>
<td>9 (16 GB)</td>
<td>9 (16 GB)</td>
</tr>
<tr>
<td>Average</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>
Other Components

• The Pressure sensors are difficult to find for this exact application so the following pressure sensors will be used:
  – Piezoelectric: PCB 132A31
  – Piezoresistive: Honeywell PC136 PC (Depending on Cost Restrictions)
  – The Mounting block for the sensors will fit in the WFF pocket and be covered by the window.
• The mounting block will have a threaded hole to accommodate PCB sensor and a small cutout for the piezoresistive sensor. The window will have small circular holes for the sensors to be flush with the skin of the rocket.
BLT: Risks

Ranked:

• Testing schedule falls behind due to difficulty in finding a piezoelectric sensor within budget.
  – Acquire sensors as early as possible.
• Measurement objectives fails due to vibrations and shock created by supersonic flight.
  – Complete a mathematical analysis using Matlab to identify a worst case scenario.
• Storage solution fails due to improper implementation of the SPI protocol.
  – Find libraries for Verilog that have already implement a communication protocol and learn from them.
• Subsystem does not fit within payload due to lack of foresight
  – Plan out physical design within Solidworks to ensure everything will fit
Test/Prototyping Plan
Prototyping Plan

- Matlab analysis of boundary layer.
  - Combination of velocity of rocket along with Reynolds number calculations.
- FPGA prototyping and research:
  - Integrate and program simulation to test FPGA to understand logic requirements for SPI protocol as well as ADC data collection
  - Utilize MATLAB Simulink to simulate maximum data collection rates of various sensors
- Analyze spatial relations in Solidworks
Analysis and Prototyping Results

• Matlab Analysis completed with the help of Prof. Parziale:
  – Utilized radar data from previous launch along with rocket measurements.
  – Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion;
  – Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic flow instabilities.

• Analyzed an ICP accelerometer and built a prototype signal conditioning system.
  – Compared a conditioned ICP Sensor signal to an unconditioned signal then designed a system to fit.
Analysis Results (MATLAB)
Signal Conditioning

Why condition signal?

• Isolate sensor from ADC; prevents the ADC and signal transmission line from altering characteristics of quartz sensor membrane
• Provide amplification of signal before ADC to achieve more precise measurements

However, ICP PCB sensors already contain internal amplifiers, and thus pre-existing external “signal conditioning” units are unnecessary.

All that is needed is a Constant Current Diode to provide power to the two-wire sensors (approx. 15 mA excitation current per sensor at about 20 volts).
• Alternatively, any constant current source circuit may be used
Support Circuitry for PCB sensor

- Due to low output impedance of internal amplifier, signal has good noise immunity from outside interference.
- Length of signal path must be minimized to reduce attenuation of signal.
Design Considerations

• As cable length increases, the maximum frequency of signal capable of being amplified decreases by the following equation, where C represents the capacitance of the coaxial cable:

\[
 f_{\text{max}} = \frac{10^9}{2\pi CV / (I_c - 1)}
\]

• Also affected by drive current of sensor \(I_c\) from constant current diode. As the current rises, \(f_{\text{max}}\) increases.

• Ultimately, keep coax cables short, and drive current high (but no more than 20 mA).
Design Considerations (Continued)

• Low frequency measurements will be affected by:
  – Discharge Time constant of PCB sensor
  – Discharge Time constant of decoupling capacitor in signal conditioner

• If decoupling capacitors are too large in capacitance, it may take excessive time for sensor initialization.
  – Sensor readings may drift upon power up as decoupling capacitors charge to equilibrium
Manufacturing Plan
Manufacturing Plan: Mechanical

- Window cover has to be drilled to specification of sensors. A sensor mount must be manufactured.
  - Wallops Ability to modify window cover.
- The mounts should be designed early on and tested using 3d models before final modifications/manufacturing.
- Schedule: (Mechanical Engineering Subteam)
  - Order sensors once selected. (January)
  - Then print first pocket, mount and cover design. (Immediately)
  - Test and if not satisfactory re-design. (Once sensors arrive - February)
Manufacturing Plan: Electrical

- A circuit board with through hole and wired connections. In addition mounts for all the integrated circuits.
- All other components will be purchased:
  - Xilinx Spartan™-6 XC6SLX4-2CPG196 (FPGA)
    - Purchased
  - AD7622BSTZ (ADC)
  - 4x SD cards- Digital storage for collected data
  - Honeywell PC136 (Piezoresistive Sensor)
  - PCB 132A31 (Piezoelectric Sensor)
  - PCA8565TS (RTC)
  - Wires, Blank PCBs other supplies.
Manufacturing Plan: Software

• SPI Implementation:
  – Started basic Implementation. This will require the most effort and time.
  – SD card will be written to in the RAW format allowing for a block size of up to 512 Bytes.

• ADC Interface:
  – Design interface between ADC and ICP sensors.
  – This will require some elements of electrical and software design when programming the ADC.

• FPGA:
  – In addition to SPI, the FPGA will have to be programmed to concatenate the sensor and RTC data.

• Schedule: Start the SPI implementation now!
  – Once SPI Implementation is complete, complete ADC and FPGA software.
Testing Plan
Mechanical Testing

• 3D Model Testing of sensor mount and window modifications.
  – 3D print WFF Pocket and test fit with actual sensors.
    • Test fit will be verified using observation.
• Vibration test of final sensor assembly. Smallest vibrations in mount can throw off sensor readings.
  Test using 3D printed sensors.
  – Vibration test for 168 seconds on final assembly. (Time to apogee) Passed if no crevices come up.
• Testing of placement of sensors:
  – Best placement: flush with center vs. sides.
  – Test in wind lab to identify the best placement.
- Test SPI Interface:
  - Write multiple 16bit data blocks. Measure time to completion and data loss.

- Test ADC Interface with sensors:
  - Measure known values and rate required in wind tunnels. Post analysis on data to detect data loss.

- Power Requirements
  - Test power requirements through multimeter testing.

- FPGA Program testing.
  - Testing ability of FPGA to concatenate inputs. Use controlled inputs and test for data loss.

- Wiring Check:
  - Test wiring through all IC’s using simple multimeter continuity checks.
Budget

The total cost of the project is estimated to be $971.

<table>
<thead>
<tr>
<th>Device</th>
<th>Cost/Device</th>
<th>Quantity</th>
<th>Lead Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPGA: ZYBO Zync - 7000</td>
<td>$69</td>
<td>1</td>
<td>2 weeks</td>
</tr>
<tr>
<td>ADC: 16B 1.5 LSB INL 2MSPS</td>
<td>$36.55</td>
<td>2</td>
<td>1 week</td>
</tr>
<tr>
<td>PNY Elite</td>
<td>$8.99</td>
<td>2</td>
<td>1 week</td>
</tr>
<tr>
<td>PCB Micro Pressure Sensor</td>
<td>$625.50</td>
<td>1</td>
<td>3 weeks</td>
</tr>
<tr>
<td>Honeywell 136 PC</td>
<td>≈$186</td>
<td>1</td>
<td>2 weeks</td>
</tr>
</tbody>
</table>
Members/ Advisors

• Arun Aruljothi (Team Lead)
• John Anticev
• Robert Fea
• Chris Blackwood
• Akshay Sampath
• Doug Sholander
• Vincent Persky

• Prof. Miles
• Prof. Parziale
• Ethan Hayon
• Miklos Nyary
• Andrew Isherwood
Schedule

- Initial SPI Interface Creation (Dec-March)
- Component Purchases (around Jan. 1)
- Start Coding all other software elements (Jan-March)
- Mechanical Design and Testing of Sensor mounts and board mounts (Feb-March)
- Integrate with main payload (May)
- Launch
Project Overview
Current Limiting for Battery Charging

Current Limiting 1A (Off Payload)
## Power Budget

<table>
<thead>
<tr>
<th>Overall System</th>
<th>Voltage (v)</th>
<th>Max Current (A)</th>
<th>Power Consumption (W)</th>
<th>Time in Operation (hour)</th>
<th>Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beaglebone Black</td>
<td>5</td>
<td>0.46</td>
<td>2.3</td>
<td>2</td>
<td>0.92</td>
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<tr>
<td>Beaglebone Black</td>
<td>5</td>
<td>0.46</td>
<td>2.3</td>
<td>2</td>
<td>0.92</td>
</tr>
</tbody>
</table>

**Main computer**

### 3D Printer Power Requirements

- **Stepper Motor X**: 10 V, 0.5 A, 5 W, 5 hour, 0.75 Ah, 375 Ah consumption
- **Stepper Motor Y**: 10 V, 0.5 A, 5 W, 5 hour, 0.75 Ah, 375 Ah consumption
- **Stepper Motor Z**: 10 V, 0.5 A, 5 W, 5 hour, 0.75 Ah, 375 Ah consumption
- **Stepper Motor filament**: 10 V, 0.5 A, 5 W, 5 hour, 0.75 Ah, 375 Ah consumption
- **Arduino Pro Mini**: 3.3 V, 0.02 A, 0.066 W, 2 hour, 0.04 Ah
- **Heating Element (initial heating)**: 12 V, 3.3 A, 39.6 W, 1 hour, 0.1 Ah, 0.33 Ah consumption
- **Heating Element (sustained heating)**: 12 V, 1.5 A, 18 W, 7.5 hour, 0.75 Ah, 1.125 Ah consumption
- **Stepper controller X**: 3.3 V, 0.008 A, 0.0264 W, 0.75 hour, 0.006 Ah
- **Stepper controller Y**: 3.3 V, 0.008 A, 0.0264 W, 0.75 hour, 0.006 Ah
- **Stepper controller Z**: 3.3 V, 0.008 A, 0.0264 W, 0.75 hour, 0.006 Ah
- **Stepper controller filament**: 3.3 V, 0.008 A, 0.0264 W, 0.75 hour, 0.006 Ah

**2MSPS ADC**

### Under Pressure

- **AD7622**: 4 V, 0.025 A, 0.1 W, 2 hour, 0.2 Ah
- **AD7622**: 4 V, 0.025 A, 0.1 W, 2 hour, 0.2 Ah
- **PCA8565**: 6.5 V, 0.05 A, 0.325 W, 2 hour, 0.65 Ah
- **Honeywell 136PC**: 10 V, 0.0024 A, 0.0000576 W, 2 hour, 0.00001152 Ah
- **PCB 132A31**: 23 V, 0.02 A, 0.46 W, 2 hour, 0.92 Ah
- **Cmod S6**: 5 V, 0.36 A, 1.8 W, 2 hour, 3.6 Ah

**FPGA**

Entire payload power consumption, assuming 2 hour run time: 45 Minutes of continuous printer operation, worst case

<table>
<thead>
<tr>
<th>Overall System</th>
<th>Voltage (v)</th>
<th>Max Current (A)</th>
<th>Power Consumption (W)</th>
<th>Time in Operation (hour)</th>
<th>Ah</th>
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<tbody>
<tr>
<td>Overall System</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Total Ah consumption</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25.00</td>
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<tr>
<td><strong>Total Power Capacity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14.57</td>
</tr>
<tr>
<td><strong>Over (+)/Under (-)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>52.15</td>
</tr>
</tbody>
</table>

We will consume approximately 64% of our energy storage, assuming 80% efficiency of LiPO and energy conversion circuitry.
User Guide Compliance

Predicted Mass: With only 3D printer and Pressure Sensor teams, payload mass is approximately 3.46 lbf.

Predicted Volume: Half canister

Activation: T-3 mins

Access to external window for pressure sensor project
Will share can
Partner unknown. No preference
Schedule

Procurement begins once project is officially approved

3D printer prototype completed by end of January

Pressure sensors obtained and tested in wind tunnel by end of January
# Team Contact Matrix

<table>
<thead>
<tr>
<th>Name</th>
<th>Email Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethan Hayon</td>
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