Rapid Aerial Photographic Target Recognition

**Team Members**: Austin Abraham, Nick Carvo, Greg Clements, Zach Donovan, Tyler Faye, Thad Gleason, Everett Hale, Jeremiah Lane, Aubrey Mckelvy, Logan Thompson, Anna Tiberi

**Customer**: Lockheed Martin - Ben Mihevc, Tim Moon, Eileen Liu, Theresa Brown

**Advisor**: Dr. Dennis Akos
Project Purpose and Objectives
Project Motivation

The purpose of this project is to design, manufacture, and test a portable, user-deployable system that can image and identify ground targets of interest and provide real time threat location and classification of said targets to a ground station within three minutes of initial system deployment.
RAPTR CONOPs

Objective: Image and locate target within area of interest

1. Launch Stand Setup, Angle Calibration, and Vehicle Mount

2. Launch Command and Manual Control Initiation

3. Manually Controlled Ascent with Rocket Motor

4. Ascent End, Automatic Control, and Motor Detach

5. Controlled Image Capture and Telemetry Transmission

6. Glide Phase and Vehicle Mission End

Presence of target and general target direction identified near ground station

Manual Controller Ready to Command Vehicle

θ ≤ 20º

Known 5’x5’x5’ Target at Unknown Distance

Camera FOV

Camera FOV

2000 ft Downrange

4000 ft Downrange

1000 ft Altitude

500 ft Altitude

600 ft Altitude
Major Changes From PDR

- Modify a COTS Hyperflight AndREaS glider instead of building vehicle
- Rocket motor changed from 5 F-class to single I-class
- Approval to fly conforming to NAR regulations
- Detachable motor with parachute
- Manually controlled ascent
ASEN/ECEN Responsibility Division

<table>
<thead>
<tr>
<th>ASEN</th>
<th>ECEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle (6”x2.5”x1.5” payload volume)</td>
<td>Image Capturing Payload (1.5 lb max)</td>
</tr>
<tr>
<td>Transmission and Reception of Commands and Flight Data</td>
<td>Transmission and Reception of Image Data</td>
</tr>
<tr>
<td>Target Recognition/Geo-location Software</td>
<td>Target Classification Software</td>
</tr>
</tbody>
</table>

**Mission Profile**

- Customer Requirements
- Mission Profile
- Mass and Volume limits for EE Payload
### Functional Requirements

<table>
<thead>
<tr>
<th>FR 1</th>
<th>The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 2</td>
<td>The system shall be man portable.</td>
</tr>
<tr>
<td>FR 3</td>
<td>The system shall transmit images to a ground station.</td>
</tr>
<tr>
<td>FR 4</td>
<td>The system shall identify a distinctly colored target and relay the target's latitude and longitude.</td>
</tr>
<tr>
<td>FR 5</td>
<td>The system shall complete its mission (launch to images processed) within 3 minutes.</td>
</tr>
<tr>
<td>FR 6</td>
<td>The system shall comply with all federal and state laws regarding testing and functionality.</td>
</tr>
</tbody>
</table>
Hyperflight AndREaS

<table>
<thead>
<tr>
<th>Item(s)</th>
<th>Mass [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe</td>
<td>1.14</td>
</tr>
<tr>
<td>Motor and Mount</td>
<td>1.50</td>
</tr>
<tr>
<td>Electronics</td>
<td>0.48</td>
</tr>
<tr>
<td>Payload</td>
<td>1.10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.22</strong></td>
</tr>
</tbody>
</table>
Propulsion Overview

Cesaroni I-55 Rocket Engine
COTS Reloadable Engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Thrust</td>
<td>21.25 lbf</td>
</tr>
<tr>
<td>Average Thrust</td>
<td>12.41 lbf</td>
</tr>
<tr>
<td>Burn Time</td>
<td>7.25 sec</td>
</tr>
<tr>
<td>Black Powder Ejection Charge</td>
<td>9 sec</td>
</tr>
</tbody>
</table>
Motor Mounting and Separation

- Motor to be mounted below the airframe
- Low Profile Linear Bearing
- Small torsion spring to hold during launch
Electronics

- HK Pilot Transceiver
- GPS/Compass Unit
- Pixhawk Controller
- Servos
- Battery
- Power Management Board
- Payload
- FrSky X8R
- TELEM1 Port
- GPS Port
- Servo Rail Signal and Power
  - 6V Servo Rail Power
  - 5V Pixhawk Power
- SBUS (Pixhawk RC Port)
- I2C

Airspeed/Temperature Sensor
Ground Processing: Region of Interest Detection and Location During Glide

- **Objectives**
- **Design**
- **Solution**
- **CPEs**
- **Requirements**
- **Risks**
- **Validation**
- **Planning**

Images/Data Transmission

User begins program to search for image data

RGB image data

Image filtering/noise removal

ROI Detection

Load Ancillary data attached to each image

GPS data

Attitude/Speed Data

Move to next image

Highlight Region of Interest (ROI)

Are there any detections?

YES

NO

Perform geo-referencing

Output:
1. Region of Interest pixels
2. Bounding Box over Image
3. Relative/world Target Location

Latitude:

Longitude:

Distance:

Index 3
Critical Project Elements
## CPE Selection

<table>
<thead>
<tr>
<th>CPE</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial Vehicle Design</td>
<td>Intense Performance Requirements (FR1)</td>
</tr>
<tr>
<td>Vehicle and Payload Integration</td>
<td></td>
</tr>
<tr>
<td>Vehicle Electronics</td>
<td></td>
</tr>
<tr>
<td>Transmission and Reception</td>
<td>Complex Theory (FR5)</td>
</tr>
<tr>
<td>FAA compliance</td>
<td></td>
</tr>
<tr>
<td>Target Recognition/GeoLocation Software</td>
<td>High Risk Propulsion System (FR4)</td>
</tr>
<tr>
<td>Propulsion System</td>
<td>High Speeds (FR1 &amp; FR4)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
</tr>
</tbody>
</table>
Design Requirements and Satisfaction
## Structural Requirements

<table>
<thead>
<tr>
<th>Derived Requirements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 1</td>
<td>The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.</td>
</tr>
<tr>
<td>DR 1.4</td>
<td>The vehicle shall withstand the forces of the launch and glide phases.</td>
</tr>
</tbody>
</table>

**Structural Integrity**

(DR 1.4)
Structural Requirements

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<tr>
<th>Derived Requirements</th>
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<tbody>
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<td>DR 1.4</td>
<td>The vehicle shall withstand the forces of the launch and glide phases.</td>
</tr>
</tbody>
</table>

A Matlab model of shear force and bending moment along the wing.

Flexure Formula for 0.25” diameter rod → slight climb $\sigma_{\text{max}} = 12,457$ psi

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_y$ [psi]</th>
<th>FOS (slight climb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balsa</td>
<td>2,828</td>
<td>0.227</td>
</tr>
<tr>
<td>Al-6061</td>
<td>40,000</td>
<td>3.211</td>
</tr>
<tr>
<td>Steel</td>
<td>53,700</td>
<td>4.310</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>82,762</td>
<td>6.643</td>
</tr>
</tbody>
</table>
Structural Requirements

- Model of Load Distribution Along Wing
- Model of Bending Moment Along Wing
- Model of Shear Force Along Wing

Structural Integrity (DR 1.4) ✓
# Vehicle Performance Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 1</td>
<td>The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.</td>
</tr>
<tr>
<td>DR 1.1.5</td>
<td>The vehicle shall be exhibit natural stability in all phases of flight.</td>
</tr>
<tr>
<td>DR 1.1.1</td>
<td>The vehicle shall be capable of a turn radius of 350 feet.</td>
</tr>
<tr>
<td>DR 1.2</td>
<td>The vehicle shall achieve a glide slope less than or equal to 5.7 degrees.</td>
</tr>
</tbody>
</table>

**Stability Requirements** (DR 1.1.5)  
**Range Requirements** (DR 1.2)  
**Maneuver Requirements** (DR 1.1.1)
## Aerodynamics - Stability Analysis

<table>
<thead>
<tr>
<th>CFD Analysis</th>
<th>Datcom Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidworks model imported to ANSYS Fluent</td>
<td>Input file containing geometry information</td>
</tr>
<tr>
<td>Vary angle of attack, sideslip angle, and velocity</td>
<td>Calculates most stability derivatives</td>
</tr>
<tr>
<td>Calculate ([X,Y,Z]) forces and ([l,m,n]) moments for each case</td>
<td>Used in conjunction with CFD to confirm and improve results</td>
</tr>
</tbody>
</table>
Stability Results

\[ C_{m\alpha} = -0.4143 \]

\[ C_{n\beta} = 0.0248 \]
Thrust and Glide Phase Stability

<table>
<thead>
<tr>
<th></th>
<th>Static Margin</th>
<th>$C_{n\beta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glide Phase</td>
<td>0.90</td>
<td>0.0248</td>
</tr>
<tr>
<td>Thrust Phase</td>
<td>1.45</td>
<td>0.0283</td>
</tr>
</tbody>
</table>

- Calculated values of static margin
- Margin decreases after dropping motor but remains stable in both phases

- Calculated values of yaw stiffness
- Margin decreases after dropping motor but remains stable in both phases
Range Requirements

<table>
<thead>
<tr>
<th>Derived Requirements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.2</td>
<td>The vehicle shall achieve a glide slope less than or equal to 5.7 degrees.</td>
</tr>
</tbody>
</table>

- Mission range: 3,000 foot glide with less than 300 foot drop
Satisfaction of DR 1.2

\[ \frac{L}{D_{\text{max}}} = 13 \]

\[ \gamma = \tan^{-1} \left( \frac{1}{L/D} \right) \]

\[ \gamma = 4.4^\circ \]
Maneuver Requirements

<table>
<thead>
<tr>
<th>Derived Requirements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.1.1</td>
<td>The vehicle shall be capable of a turn radius of 350 feet.</td>
</tr>
</tbody>
</table>

- Course correction - After engine cut-off
- Roughly 1000 feet of downrange to correct

\[ r_{\text{turn}} = X_{\text{min}} \left[ 2 \sin \left( \arctan \left( \frac{1000 \tan \sigma_{\text{launch}}}{X_{\text{min}}} \right) \right) \right]^{-1} \]
Satisfaction of DR 1.1.1

Requirement: Capable of executing 350 foot radius turn
## Propulsion Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 5</td>
<td>The system shall complete its mission (launch to images processed) within 3 minutes.</td>
</tr>
<tr>
<td>DR 5.2</td>
<td>The vehicle shall take 35 seconds to travel 2000 ft laterally and 700 ft vertically.</td>
</tr>
<tr>
<td>DR 5.2.1</td>
<td>The vehicle shall utilize a rocket engine propulsion system.</td>
</tr>
<tr>
<td>DR 5.2.2</td>
<td>The vehicle shall attain a speed of at least 100 feet per second.</td>
</tr>
</tbody>
</table>

### Diagram

- **Vehicle Altitude (DR 5.2)**
- **Vehicle Velocity (DR 5.2.2)**
Propulsion Model

- Three Models
  - RockSim: 3D CAD model
  - OpenRocket: 3D CAD model
  - MATLAB: Point-mass model

- Structural Differences
  - Cylindrical Frame
  - No Rocket Nose Cone
  - No Polyhedral Wings

Initialization → Atmospheric Conditions → Flight Parameters → Aerodynamic Forces and Moments → Thrust and Gravitational Forces → Mass and Moment of Inertia → Runge-Kutta 4th Order Numerical Integration
Nominal Propulsion Model

Vehicle Altitude (DR 5.2)  
Vehicle Velocity (DR 5.2.2)
Propulsion: Monte-Carlo

Vehicle Altitude (DR 5.2) ✔

Vehicle Velocity (DR 5.2.2)
Propulsion: Monte-Carlo

Vehicle Altitude (DR 5.2)

Vehicle Velocity (DR 5.2.2)
## Target Recognition/Geolocation Software

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 4</td>
<td>The system shall identify a distinctly colored target and relay the target's latitude and longitude.</td>
</tr>
<tr>
<td>DR 4.1</td>
<td>The ground station shall output a bounding box over potential targets.</td>
</tr>
<tr>
<td>DR 4.2</td>
<td>The ground station shall compute local relative coordinates of the target as well as global latitude and longitude of the target within 150 feet of its true location.</td>
</tr>
</tbody>
</table>
Software: Target Detection

Compare statistics between windows using T-test:

Window slides across image looking for potential targets

Highlight regions of interest for classification and geolocation

\[ T = \frac{|\bar{X}_1 - \bar{X}_2|}{\sqrt{s_1^2 + s_2^2}} \]

\( \bar{X} = \text{mean}, s = \text{variance} \)
Detection

**Identify Potential Target Pixels**

**Output Bounding Box over ROI**

Output Bounding Box (DR 4.1) ✓

Determine Location of ROI (DR 4.2)
Pixel to World Transformation

**Knowns: Pixels and altitude**

\[
\begin{bmatrix}
u \\
v \\
R \text{ (range)}
\end{bmatrix}
\]

**Unknown: World Coordinates**

\[
\begin{bmatrix}
N \text{ (north)} \\
E \text{ (east)} \\
D \text{ (down)}
\end{bmatrix}
\]
Pixel to World Transformation

Problem to solve:

\[ \tilde{P} \tilde{\rho}_w = x_s \]

\[ x_s = \begin{bmatrix} u \\ v \\ 1 \\ R(\text{range}) \end{bmatrix} \]

\[ \tilde{\rho}_w = \begin{bmatrix} N(\text{north}) \\ E(\text{east}) \\ D(\text{down}) \\ 1 \end{bmatrix} \]

\[ P = K(R|t) \]

\[ \tilde{P} = \begin{pmatrix} K & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix} \]

\[ K \equiv \text{Camera Matrix} \]

\[ R \equiv \text{world to camera rotation} \]

\[ t \equiv \text{world to camera translation} \]
Geo-Location Preliminary Testing

Example Target:

Output Bounding Box (DR 4.1)

Determine Location of ROI (DR 4.2)
### Vehicle Control Requirements

<table>
<thead>
<tr>
<th>Derived Requirements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 1</td>
<td>The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.</td>
</tr>
<tr>
<td>FR 4</td>
<td>The system shall identify a distinctly colored target and relay the target’s latitude and longitude.</td>
</tr>
<tr>
<td>DR 1.1.2</td>
<td>The vehicle shall be capable of being controlled by the user.</td>
</tr>
<tr>
<td>DR 4.2.1</td>
<td>The vehicle shall use a sensor suite to quantify its location.</td>
</tr>
</tbody>
</table>
Sensor Attitude Determination

Measurement | Accuracy of Measurement
---|---
GPS Position | Within 2.5 meters
GPS Velocity | +/- 0.164 ft/s
Airspeed | +/- 0.82 ft/s
Magnetic Heading | +/- 0.3 degrees

Sensor Attitude Determination (DR 4.2.1)✓

Capable Vehicle Control (DR 1.1.2)
Vehicle Control

<table>
<thead>
<tr>
<th>Control Surface</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rudder</td>
<td>Enable both yaw and roll control due to RAPTR’s dual dihedral. Enables lateral stability</td>
</tr>
<tr>
<td>Elevator</td>
<td>Enables pitch control and longitudinal stability</td>
</tr>
</tbody>
</table>

RAPTR does not have ailerons so servo roll gains are irrelevant.
Vehicle Control

Pixhawk Control Architecture

- Sensor Attitude Determination (DR 4.2.1)
- Capable Vehicle Control (DR 1.1.2)
Vehicle Control

Fundamental Equations
\[
\dot{x} = Ax + Bu \\
y = Cx + Du
\]

\[
X(s) = C(sI - A)^{-1}Bu
\]

\[
G(s) = K_P + K_Ds + K_I \frac{1}{s}
\]

PID Gain Approximation Architecture

**Objectives**

**Design**

**Solution**

**CPEs**

**Requirements**

**Risks**

**Validation**

**Planning**
Vehicle Control

Dynamic Modes

<table>
<thead>
<tr>
<th>Dynamic Modes</th>
<th>PID Servo Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>$K_P = 0.0154$</td>
</tr>
<tr>
<td></td>
<td>$K_D = 0.0069$</td>
</tr>
<tr>
<td></td>
<td>$K_I = 0$, assumption</td>
</tr>
<tr>
<td>Yaw</td>
<td>$K_P = 0.178$</td>
</tr>
<tr>
<td></td>
<td>$K_D = 0.075$</td>
</tr>
<tr>
<td></td>
<td>$K_I = 0$, assumption</td>
</tr>
</tbody>
</table>

Sensor Attitude Determination (DR 4.2.1)

Capable Vehicle Control (DR 1.1.2)
Project Risks
## Risk Matrix

<table>
<thead>
<tr>
<th></th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
</tr>
<tr>
<td>Probability</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>6</td>
</tr>
<tr>
<td>M</td>
<td>11</td>
</tr>
<tr>
<td>L</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

### Risks
1. Uneven Rocket Engine Moments
2. Wing Integrity on Launch
3. Ascent Pitch Control Authority
4. Autopilot Adaptation
5. NAR Certification/FAA Testing Permission
6. Communication System Interference
7. Payload Weight
8. Payload Volume
9. Physical Payload/Vehicle Integration
10. Rocket Thermal Effects
11. Data Transmission Rate
12. Data Synchronization
13. Image Processing Time
## Risk Mitigation

<table>
<thead>
<tr>
<th>Probability</th>
<th>Impact</th>
<th>L</th>
<th>M</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td></td>
<td>6</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td></td>
<td>7</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>12</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

### Risk Mitigation Off-Ramp

<table>
<thead>
<tr>
<th>Risk</th>
<th>Mitigation</th>
<th>Off-Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Ascent Pitch Control Authority</td>
<td>Short Motor Mount</td>
<td>Utilize Smaller Rocket Motor or Electric Propeller System</td>
</tr>
<tr>
<td>10. Rocket Thermal Effects</td>
<td>Coat Vehicle Belly with Thermal Tape</td>
<td>Electric Propeller System</td>
</tr>
</tbody>
</table>

**Index**
Verification and Validation
## Test Overview

<table>
<thead>
<tr>
<th>Objective</th>
<th>FR/DR</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Software</strong></td>
<td>FR 4</td>
<td>The system shall identify a distinctly colored target and determine the unique target shape and relay the target's latitude and longitude.</td>
</tr>
<tr>
<td><strong>Structures</strong></td>
<td>DR 1.4</td>
<td>The vehicle shall withstand the forces of the launch and glide phases.</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>DR 5.2.1</td>
<td>The vehicle shall utilize a rocket engine propulsion system.</td>
</tr>
<tr>
<td><strong>Aerodynamics</strong></td>
<td>DR 1.2</td>
<td>The vehicle shall achieve a glide slope less than or equal to 5.7 degrees.</td>
</tr>
<tr>
<td><strong>Controls</strong></td>
<td>DR 1.1.2</td>
<td>The vehicle shall be capable of being controlled by the user.</td>
</tr>
<tr>
<td><strong>Full Systems</strong></td>
<td>FR’s 1-6</td>
<td></td>
</tr>
</tbody>
</table>

Footnote: FR = Functional Requirement, DR = Design Requirement
## Thermal Testing

<table>
<thead>
<tr>
<th>FR 1</th>
<th>The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.</th>
</tr>
</thead>
</table>

| **Purpose** | Verify no damage to vehicle during engine burn |
| **Methods** | Static burn of motor positioned near fuselage |
| **Location** | Boulder East Campus |
| **Key Equipment** | Aluminum tape, Lava Heat Shield, 155 Motor, IR camera |
| **Measurements** | Temperature of exhaust, Dimensions of exhaust |
## Controls/Pixhawk

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Verify accurate control and authority over vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Methods</strong></td>
<td>Slope soar glider in AUTOTUNE mode of ArduPilot</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>South NCAR</td>
</tr>
<tr>
<td><strong>Key Equipment</strong></td>
<td>Fully built AndREaS glider with transmitter controller</td>
</tr>
<tr>
<td><strong>Measurements</strong></td>
<td>Roll, Pitch, Yaw, Airspeed of glider</td>
</tr>
</tbody>
</table>

| FR 1                     | The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading. |

- **Purpose**: Verify accurate control and authority over vehicle
- **Methods**: Slope soar glider in AUTOTUNE mode of ArduPilot
- **Location**: South NCAR
- **Key Equipment**: Fully built AndREaS glider with transmitter controller
- **Measurements**: Roll, Pitch, Yaw, Airspeed of glider
# Full systems testing

<table>
<thead>
<tr>
<th><strong>Purpose</strong></th>
<th>Validate success criteria of project are met</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Methods</strong></td>
<td>Full systems launch through NCR with and without payload</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Atlas Site, North Site (West of Pawnee Grasslands)</td>
</tr>
<tr>
<td><strong>Key Equipment</strong></td>
<td>Fully built AndREaS vehicle, launch rails, test target</td>
</tr>
<tr>
<td><strong>Measurements</strong></td>
<td>Vehicle position, velocity, attitude, time for setup/detection, images of target</td>
</tr>
</tbody>
</table>
Project Planning
# Test Plan

**Thermal Testing:** Access to IR camera and static launch site

**Vehicle/Full Systems Testing:** Access to high powered rocket launch site

<table>
<thead>
<tr>
<th>Test</th>
<th>Date Range</th>
<th>Description</th>
<th>Location</th>
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<tbody>
<tr>
<td><strong>Thermal Test</strong></td>
<td>01/14/19 - 02/01/19 (Exact Date TBD)</td>
<td>Verify thermal protection</td>
<td>East Campus</td>
</tr>
<tr>
<td><strong>Structural Test</strong></td>
<td>12/01/18</td>
<td>Verify structural integrity</td>
<td>ITLL</td>
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<tr>
<td><strong>Wind Tunnel Testing</strong></td>
<td>01/28/19 - 02/01/19 (Exact Date TBD)</td>
<td>Verify CFD Analysis</td>
<td>ITLL</td>
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<tr>
<td><strong>Communications Integration Test</strong></td>
<td>02/04/19 - 02/08/19 (Exact Date TBD)</td>
<td>Verify comm. systems</td>
<td>ITLL</td>
</tr>
<tr>
<td><strong>Controls Testing/Tuning</strong></td>
<td>02/04/19 - 02/15/19 (Exact Date TBD)</td>
<td>Tune PixHawk and verify controllability</td>
<td>South NCAR</td>
</tr>
<tr>
<td><strong>Vehicle Systems Testing</strong></td>
<td>03/02/19, 03/09/19, 03/30/19</td>
<td>Test launch vehicle without payload</td>
<td>Northern Colorado</td>
</tr>
<tr>
<td><strong>Full Systems Testing</strong></td>
<td>04/06/19, 04/13/19, 05/03/19</td>
<td>Test launch vehicle with payload</td>
<td>Northern Colorado</td>
</tr>
</tbody>
</table>
Organizational Chart

Customer
Lockheed Martin – Ben Mihevc

Director
Jelliffe Jackson

Advisor
Dennis Akos

Project Manager
Aubrey McKelvy

Systems Lead
Logan Thompson

CFO
Everett Hale

Manufacturing Lead
Austin Abraham

Testing/Safety Lead
Greg Clements

Software Lead
Jeremiah Lane

Mechanical Lead
Nick Carvo

Aerodynamics Lead
Thad Gleason

Propulsion Lead
Anna Tiberi

Controls Lead
Zach Donovan

Electronics Lead
Tyler Faye
Work Breakdown

Legend

- Complete
- Planned

Vehicle CAD Model
- Geolocation Algorithm
- Wiring Diagram
- Launch Dates and Sites
- Fall Deliverables
- PDD

Structural Analysis
- ROI ID Algorithm
- Approximate Gains
- Motor Selection
- CFD Modeling
- CDD

Vehicle Assembly
- Uncertainty Propagation
- Controller Simulation
- Propulsive Simulation
- Stability Derivatives
- PDR

Structural Testing
- Preliminary Test Validation
- Finalize Gains
- Motor Acquisition
- Control Derivatives
- CDR

Finalize Vehicle
- Optimization
- Validate Controls
- Thermal Testing
- Wind Tunnel Testing
- FFR

Integration and Test
- Integration and Test
- Integration and Test
- Integration and Test
- Integration and Test
- Index 57
Cost Plan

<table>
<thead>
<tr>
<th>Expenditure</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Vehicles</td>
<td>$785</td>
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<tr>
<td>Pixhawk 4</td>
<td>$211</td>
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<tr>
<td>I-55 Engines</td>
<td>$450</td>
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<tr>
<td>Auxiliary Structures</td>
<td>$247</td>
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<tr>
<td>Auxiliary Propulsion</td>
<td>$245</td>
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<tr>
<td>Auxiliary Electronics</td>
<td>$266</td>
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<tr>
<td><strong>Expected Cost</strong></td>
<td><strong>$2204</strong></td>
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<tr>
<td>Budget Uncertainties</td>
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<tr>
<td><strong>Maximum Cost</strong></td>
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<tr>
<td><strong>Budget Margin</strong></td>
<td><strong>$1721</strong></td>
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</table>
Acknowledgements

- Ben Mihevc
- Theresa Brown
- Tim Moon
- Eileen Liu
- Dr. Akos
- Professor Gerren
- Professor Holzinger
- Professor Rhode
- Professor Lopez
- Christine Reilly & Ian Cooke

- Professor Nabity
- Professor Ahmed
- Professor Lawrence
- Arielle Blum
- CU Boulder Quadcopter Club
- IRIS
- James Mack
- Dan Hesselius
- Joe Hinton
Questions?
References

  - https://www.activaripg.com/torsion-springs.html
- Markforged Material Properties Data Sheet
  - https://www.rocketarium.com/Build/Ejection-Baffles
  - http://www.aerospaceweb.org/question/propulsion/q0220.shtml
  - http://knight-mfg.com/folding_launch_pads
References

- CU Boulder Quadcopter Club
- [https://journals.sagepub.com/doi/pdf/10.5772/52500](https://journals.sagepub.com/doi/pdf/10.5772/52500)
- [https://cdn.automationdirect.com/static/manuals/d4user/ch8.pdf](https://cdn.automationdirect.com/static/manuals/d4user/ch8.pdf)
- [https://core.ac.uk/download/pdf/52106533.pdf](https://core.ac.uk/download/pdf/52106533.pdf)
- Attitude Estimation of Quadcopter through EXK by Wenjing Liang
- Design of Robust Controller of Fixed-Wing UAV for Transition Flight by Satoshi Kohno and Kenji Uchiyama
- Attitude Estimation for UAV Using Extended Kalman Filter by ofei Jing1, Jiarui Cui1, Hongtai He2, Bo Zhang3, Dawei Ding1, Yue Yang1
- Experimental validation of Unmanned Aerial Vehicles to tune PID controllers in open source autopilots by Pedro L. Jimenez*, Jorge A. Silva** and Juan S. Hernandez***
- Modeling of Closed Loop PID Controller for an Auto-Pilot Aircraft Roll Control by E.Gouthami and M. Asha Rani
- Quadrotor Tuning for Attitude Control based on PID Controller using Fictitious Reference Iterative Tuning (FRIT) by Arthit Julkananusart*, Itthisek Nilkhamhang‡, Rangsarit Vanijjirattikhan† and Atsushi Takahashi‡
- PIXHAWK: A System for Autonomous Flight using Onboard Computer Vision by Lorenz Meier, Petri Tanskanen, Friedrich Fraundorfer and Marc Pollefeys
- Dynamics of Flight Stability and Control by Bernard Etkin and Lloyd Duff Reid
- Feedback COntrol of Dynamic Systems by Gene Franklin
## Backup Slides

<table>
<thead>
<tr>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objectives</strong></td>
</tr>
<tr>
<td><strong>Design Solution</strong></td>
</tr>
<tr>
<td><strong>CPEs</strong></td>
</tr>
<tr>
<td><strong>Requirements</strong></td>
</tr>
<tr>
<td><strong>Risks</strong></td>
</tr>
<tr>
<td><strong>Validation</strong></td>
</tr>
<tr>
<td><strong>Planning</strong></td>
</tr>
<tr>
<td><strong>Backups</strong></td>
</tr>
</tbody>
</table>
## Backup Slides

### Backup Slides Index

<table>
<thead>
<tr>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Planning</td>
</tr>
<tr>
<td>Aerodynamics</td>
</tr>
<tr>
<td>Electronics</td>
</tr>
<tr>
<td>Controls</td>
</tr>
<tr>
<td>Propulsion</td>
</tr>
<tr>
<td>Software</td>
</tr>
<tr>
<td>Structures</td>
</tr>
<tr>
<td>Testing</td>
</tr>
</tbody>
</table>
RAPTR CONOPs – Launch Phase

1. Launch Stand Setup, Angle Calibration, and Vehicle Mount
2. Launch Command and Manual Control Initiation
3. Manually Controlled Ascent with Rocket Motor

$\theta \leq 20^\circ$
RAPTR CONOPs – Glide Phase

1. Ascent End and Automatic Controlled Guide Correction

2. Steady Controlled Glide for Image Capture

3. 600 ft Altitude

4. 1000 ft Altitude

5. 500 ft Altitude

6. 4000 ft Downrange

7. 2000 ft Downrange

8. 900 ft Downrange

Camera FOV

Camera FOV

Manual Controller Ready to Command Vehicle

Vehicle Mission End

RAPTR CONOPs – Mission Profile Top View

1. Launch and Thrust Phase

2. Glide with Course Correction Phase

3. Glide and Target Recognition Phase

4. Image Analysis for Regions of Interest

Launch Site

900 ft Downrange

2000 ft Downrange

4000 ft Downrange

Observation Window Shrinking with Glide Distance
# Detailed Cost Breakdown - Subteams

<table>
<thead>
<tr>
<th>Subteam</th>
<th>Minimum Budget</th>
<th>Budget Uncertainty</th>
<th>Maximum Budget</th>
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<tr>
<td>Electronics and Controls</td>
<td>$477</td>
<td>$405</td>
<td>$882</td>
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<tr>
<td>Structures</td>
<td>$1032</td>
<td>$340</td>
<td>$1372</td>
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<tr>
<td>Propulsion</td>
<td>$695</td>
<td>$330</td>
<td>$1025</td>
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<tr>
<td>Totals</td>
<td>$2204</td>
<td>$1075</td>
<td>$3279</td>
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</table>
### Detailed Cost Breakdown - Electronics

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>Pixhawk 4 and GPS Module</td>
<td>$211</td>
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<tr>
<td>Digital Airspeed Sensor</td>
<td>$64.59</td>
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<tr>
<td>FrSky X8R Receiver</td>
<td>$34.99</td>
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<tr>
<td>Radio Telemetry Set</td>
<td>$45.00</td>
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<tr>
<td>Sevos (x2)</td>
<td>$71.98</td>
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<tr>
<td>950mAh Battery</td>
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<tr>
<td>Voltage Regulator (x6)</td>
<td>$3.24</td>
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<tr>
<td>Diode (x6)</td>
<td>$9.42</td>
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<td>Printed Circuit Board (x10)</td>
<td>$15.00</td>
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</table>
### Detailed Cost Breakdown - Structures

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
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<tbody>
<tr>
<td>AndREaS Glider (x4)</td>
<td>$560.32</td>
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<tr>
<td>Oracover Monokote (x4)</td>
<td>$77.92</td>
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<tr>
<td>Carbon Rod (x4)</td>
<td>$21.92</td>
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<tr>
<td>Bearing Carriage</td>
<td>$6.26</td>
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<tr>
<td>Guide Rails</td>
<td>$15.00</td>
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<tr>
<td>Manufacturing Supplies</td>
<td>$36.86</td>
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<tr>
<td>Pre-CDR Purchases</td>
<td>$314.05</td>
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</table>
## Detailed Breakdown - Propulsion

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Cone (x3)</td>
<td>$24.94</td>
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<tr>
<td>Parachute (x3)</td>
<td>$3.63</td>
</tr>
<tr>
<td>I-55 Engine (x10)</td>
<td>$450.00</td>
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<td>Grain Casing (x3)</td>
<td>$39.75</td>
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<tr>
<td>Launch Controller</td>
<td>$39.99</td>
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</tbody>
</table>
Aero Backup Slides
Lift and Drag - CFD

$L$ vs Angle of Attack

$C_D$ vs Angle of Attack

Launch Error Correction (DR 1.1)
Range Requirements (DR 1.2)
Maneuver Requirements (DR 1.1.1)
Pitching and yawing moment - CFD

- $C_M$ vs Angle of Attack
- $C_N$ vs Sideslip Angle

Launch Error Correction (DR 1.1)  Range Requirements (DR 1.2)  Maneuver Requirements (DR 1.1.1)
Digital Datcom Input

CASEID ----- RAPTR-PROJECT -----

$FLTDAT MMACH=1.0,MACH(1)=0.12$
$FLTDAT NALPHA=16.0,ALSCHD(1)=-6.0,-4.0,-2.0,$
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20.0,22.0,24.0$
$FLTDAT NALT=1.0,ALT(1)=6000.0,$
$WT=4.2,LOOP=1.0$
$OPTINS SREF=3.64,CBARR=0.5598,BLREF=6.5$
$SYNTHS XCG=1.18,ZCG=0.0,XW=0.96,ZW=0.03,ALIW=0.0,XH=2.98,$
ZH=0.02,ALIH=0.0,XV=3.32,ZV=-0.4,VERTUP=.TRUE.$
$BODY NX=10.0,$
X(1)=0.0,0.04,0.23,0.96,1.38,2.37,2.97,3.2,3.28,3.53,$
S(1)=0.0,0.0036,0.0144,0.0169,0.0121,0.0036,0.0007,0.007,0.0025,0.0025$
NACA-W-4-2412
$WGPLNF CHRDTP=0.37,SSPNOP=1.6,SSPNE=3.16,SSPN=3.25,CHRDR=0.63,SAVSI=0.0,$
CHSTAT=0.25,CHRDBP=0.63,TWISTA=0.0,DHDADI=0.0,DHDADO=10.2,TYPE=1.0$
NACA-H-4-0012
$HTPLNF CHRDTP=0.25,SSPNE=1.39,SSPN=1.39,CHRDR=0.35,SAVSI=0.0,$
CHSTAT=0.25,TYPE=1.0$
NACA-V-4-0012
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CHSTAT=0.25,TYPE=1.0$
DIM FT
DAMP
NEXT CASE
Lift and Drag - Datcom

\[ C_L \text{ vs Angle of Attack} \]

\[ C_D \text{ vs Angle of Attack} \]

Launch Error Correction (DR 1.1)
Range Requirements (DR 1.2)
Maneuver Requirements (DR 1.1.1)
Stability Plots

- $C_L$ vs Angle of Attack
- $C_Y$ vs Sideslip Angle
- $C_Z$ vs Velocity
- $C_L$ vs Angle of Attack
- $C_Y$ vs Sideslip Angle
- $C_Z$ vs Velocity
- $C_M$ vs Angle of Attack
- $C_Y$ vs Sideslip Angle
- $C_Z$ vs Velocity

Graphs show the relationship between various forces and angles in a stability analysis.
## Control Derivatives

### Results from CFD analysis

<table>
<thead>
<tr>
<th>$u$</th>
<th>$C_x$</th>
<th>$C_y$</th>
<th>$C_z$</th>
<th>$C_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$-4.58 \cdot 10^{-4}$</td>
<td>-0.0062</td>
<td>-0.0124</td>
<td>-1.9344</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.1559</td>
<td>-4.0189</td>
<td>-1.4944</td>
<td>-4.9263</td>
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<tr>
<td>$\dot{\alpha}$</td>
<td>0</td>
<td>-1.4944</td>
<td>-5.1164</td>
<td>-16.866</td>
</tr>
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</table>

### Results from Datcom analysis

<table>
<thead>
<tr>
<th>$u$</th>
<th>$C_x$</th>
<th>$C_y$</th>
<th>$C_z$</th>
<th>$C_m$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$-4.58 \cdot 10^{-4}$</td>
<td>-0.0062</td>
<td>-0.0124</td>
<td>-1.9344</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.1559</td>
<td>-5.8041</td>
<td>-2.3715</td>
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<td>$\dot{\alpha}$</td>
<td>0</td>
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<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$C_y$</th>
<th>$C_l$</th>
<th>$C_n$</th>
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<tr>
<td>$\beta$</td>
<td>-0.1112</td>
<td>-0.0019</td>
<td>0.0347</td>
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<tr>
<td>$p$</td>
<td>-0.0139</td>
<td>-0.5091</td>
<td>-0.018</td>
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<tr>
<td>$r$</td>
<td>1.9344</td>
<td>0.0386</td>
<td>-0.0296</td>
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</tbody>
</table>
Stall:

\[ \frac{W_{cr}}{S} = \frac{1}{2} \rho V_s^2 C_{L_{max}} \]

Thrust Man.:

\[ \frac{T}{W_{cr}} = \frac{q C_{D_0}}{W_{cr}} + \frac{n^2}{q \pi A R_e} \frac{W_{cr}}{S} \]

Cruise Man.:

\[ \frac{W_{cr}}{S} = V \left( \frac{2n}{\rho C_L} \right)^{-\frac{1}{2}} \]

\[ n_{cruise} = \sqrt{\left( \frac{V^2 \cos^2 \gamma}{R_{turn} g} \right)^2 + \cos^2 \gamma} \]

\[ n_{thrust} = \frac{V_{max}^2}{h_{end}} \]
Electronics Backup Slides

Electronics Slides Appendix
  1. Electronics Hardware
  2. Servo Design Envelope
Sensor Attitude Determination  (Electronics Assembly Procedure)

PCB

- Solder surface mount components to solder pads
- Solder battery leads to input power solder pads
- Solder 5V and 6V output power leads to applicable solder pads

Pixhawk and Sensors

- Connect GPS and compass module via GPS pins (pre-installed plug)
- Connect telemetry radio via TELEM 1 pins (pre-installed plug)
- Connect buzzer and safety switch via SWITCH and BUZZER pins (pre-installed plugs)
- Connect airspeed sensor via I2C pins (pre-installed plug)
- Connect XR8 sensor to XR8 SBUS pins and Pixhawk RC pins on servo rail (pre-installed plug)
- Connect servo rail power wires (solder or JST SM 2 pin connector)

Servos

- Plug into appropriate servo rail pins (3-pin PWM JST SM connectors)
  - Rudder connects to pin 4
  - Elevator connects to pin 2
Sensor Attitude Determination (Power Consumption and Physical Specifications)

Battery (Turnigy Graphene Panther 950mAh)
- 950mAh, 7.4V 2 cell lithium polymer battery
- Capable of continuous discharge of up to 71.25 Amps (1.9 hour life with 750mA current draw)
- Weight of 50g

Servos (Futaba S3152, 2 used)
- 87 oz-in of torque at 6V and .18 seconds per 60 degrees of rotation
- Idle current of approximately 10mA, operating current of 100-250mA, stall current of approximately 1 amp (all at 6V)
- Weight of 41g each

Pixhawk
- Operating current draw of approximately 300mA at 5V when battery powered (includes safety switch and LED power consumption)
- Weight of 15.8 grams

Airspeed/Temperature Sensor
- Measures from 0 to 100 m/s (0 to 223 mph) with temperature correction
- Operating current draw of approximately 25mA at 5V
- Weight of 12g

GPS/Compass Module
- Operating current draw of approximately 60mA at 5V
- Weight of 32g with case

FrSky X8R
- Operating current draw of approximately 100mA at 5V
- Weight of 16.6g

HK Pilot Transceiver
- Operating current draw of 25mA and 100mA at 5V (receiving and transmitting)
- Weight of approximately 20g with antenna

Totals
- Max current draw of approximately 2,585mA with typical operating current draw of approximately 725mA, idle current draw of approximately 560mA
- Approximate operating (flying) battery life of approximately 1.3 hours, idle battery life of approximately 1.7 hours
- Weight of 219.9g without transceiver antenna, approximately 230g with antenna

Sensor Attitude Determination (DR 4.2.1)
Capable Vehicle Control (DR 1.1.2)
Servo Design Envelope

Elevator Design Envelope
Elevator Size: 16.5x1.5 [in]

- Elevator Design Area
- Elevator Torque
- Servo Torque @ 4.8V
- Max Airspeed

Rudder Design Envelope
Rudder Size: 9.5x1.6 [in]

- Rudder Design Area
- Rudder Torque
- Servo Torque @ 4.8V
- Max Airspeed
Controls Backup Slides

Controls Slides Appendix
- EKF FBD
- Longitudinal and Lateral dynamics
- Gains
Vehicle Control

Extended Kalman Filter Architecture

IMU State Prediction

Acceleration Transformation: X,Y,Z to N,E,D

Acceleration: N,E,D

Velocity: N,E,D

Position: N,E,D

"Innovation": Difference ∆

State Correlation

GPS Position

GPS Error

Sensor Attitude Determination (DR 4.2.1)

Capable Vehicle Control (DR 1.1.2)
Longitudinal Open-Loop Dynamics
Lateral Open-Loop Dynamics
Longitudinal Gains
Longitudinal Gains

Lateral Proportional-Derivative Control
Short Period Mode

Target Zone
P-Control
PD-Control

PD Control: Design Point
Dutch Roll Mode

Target Zone
P-Control
PD-Control
Gain Design Point
Lateral Gains
Lateral Gains

Lateral Proportional-Derivative Control
Dutch Roll Mode

Lateral PD Control: Design Point
Dutch Roll Mode
Control Surface Deflection

Elevator Response: $\Delta \theta = 10^\circ$

Longitudinal Dynamics

Rudder Response: $\Delta \psi = 10^\circ$

Lateral Dynamics
Propulsion Backup Slides

1. MATLAB model - Trajectory/Velocity
2. MATLAB model - Thrust uncertainty
3. MATLAB model - Thrust uncertainty
4. OpenRocket Governing Equations
5. Parachute Choice
6. Motor Recovery
7. Launch Controller
8. Igniter
9. Plume Characteristics
10. Plume Characteristics
11. Engine Assembly
12. Thermal Risk Mitigation
13. Baffle
14. Launch Pad
15. Reducing Velocity
MATLAB Model - Trajectory/Velocity

Max Altitude: 1163 ft
Burnout Altitude: 801 ft
Max Speed: 177 ft/s
Time to Apogee: 11.9s
MATLAB Model - Thrust Uncertainty

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Burnout Altitude [ft]</th>
<th>Max Speed [ft/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>801</td>
<td>177</td>
</tr>
<tr>
<td>-5%</td>
<td>738</td>
<td>159</td>
</tr>
<tr>
<td>+5%</td>
<td>873</td>
<td>194</td>
</tr>
</tbody>
</table>
MATLAB Model - Thrust Uncertainty

Velocity over time

Altitude
OpenRocket Equations - Aerodynamics

\[ C_D = \frac{D}{\frac{1}{2} \rho v_0^2 A_{\text{ref}}} \]

\[ C_l = \frac{l}{\frac{1}{2} \rho v_0^2 A_{\text{ref}} d} \]

\[ C_m = \frac{m}{\frac{1}{2} \rho v_0^2 A_{\text{ref}} d} \]

\[ X = \frac{C_m}{C_N} \]

\[ C_{f_c} = \frac{C_f}{(1 + 0.15 M^2)^{0.58}} \]

\[ \bar{c} = \frac{1}{A_{\text{fin}}} \int_0^s c^2(y) \, dy \]

\[ y_{\text{MAC}} = \frac{1}{A_{\text{fin}}} \int_0^s yc(y) \, dy \]

\[ x_{\text{MAC,LE}} = \frac{1}{A_{\text{fin}}} \int_0^s x_{\text{LE}}(y)c(y) \, dy \]

Wind Turbulence Equation:

\[ \frac{S_u(f)}{\sigma_u^2} = \frac{4L_{1u}/U}{(1 + 6fL_{1u}/U)^{5/3}} \]

\[ \frac{S_u(f)}{\sigma_u^2} = \frac{4L_{2u}/U}{(1 + 70.8(fL_{2u}/U)^2)^{5/6}} \]
Parachute Choice

\[ D = \sqrt{\frac{8mg}{\pi \rho C_D V_g^2}} = \sqrt{\frac{8 \cdot 0.2521[kg] \cdot 9.81[m/s^2]}{\pi \cdot 0.975[kg/m^3] \cdot 1.5 \cdot (5[m/s])^2}} = 0.415[m] = 41.5[cm] = 16.34[in] \]
Motor Recovery
Launch Controllers

2240 PS II Launch Controller

![Diagram of Launch Controller and circuit diagram](image-url)
Igniter

**Igniter specifications**:

**Bridgewire resistance:**

1.2 – 1.8Ω

**Rated all-fire current:**

1.2 Amps for 10 milliseconds

**Typical response:**

2.3ms @ 1.2 Amps

(*) These are manufacturer’s specs. CTI assumes no responsibility for their use or misinterpretation
Exhaust Plume Regions

Fig. 3.1.2 Description of a Typical Supersonic Plume
Rocket Engine Integration

Grain Integration  Motor Integration  Fully Integrated Motor and Casing
Nozzle Flow - Ideal vs. Realistic
Exhaust Plume Expansion

- Underexpanded nozzle at altitude leads to expanded exhaust plume

(a) Bell Nozzle at Sea Level: the exhaust plume is "pinched" by high ambient air pressure, reducing its efficiency.

(b) Bell Nozzle at Optimum Altitude: the exhaust plume is column-shaped producing maximum efficiency.

(c) Bell Nozzle at High Altitude: the exhaust plume continues to expand past the nozzle exit reducing efficiency.
Thermal Risk Mitigation

- **Worst Case: Lava Heat Shield**
  - Made from crushed volcanic rock
  - Shields 80% radiant heat
  - Direct temperatures up to ~1400K
  - ~$130 for 36”x48” sheet

- **Best Case: Aluminum Tape**
  - Aluminum foil with glass cloth
  - Performs consistently up to ~600K
  - $23.74 for 1/2"x 5 yd
What is a Baffle?

The ejection baffle eliminates the requirement for recovery wadding. It is used to protect the parachute from the ejection charge.
Launchpad and Launch Lug

**Launchpad** - Knight Manufacturing, FLP-48
**Launch Rail** - Standard 1010 Aluminum
**Launch Lug** - Linear, compatible with 1010 rail
Reducing Velocity

- **Maximum Altitude (ft):**
  - Current Mass: 67.65 oz
  - Velocity Maximum: 162 feet/sec
  - Ideal Mass: 105 oz

- **Total Vehicle Mass (oz):**
  - Altitude Minimum: 700 feet

![Graph showing the relationship between maximum altitude and total vehicle mass.](image)
Software Backup
Preliminary Testing Targets
Example Image from Drone:

Same target pixel size compared to mission profile
Pixel to World Transformation

**Problem to solve:**
\[ \tilde{P} \tilde{p}_w = x_s \]

\[ P = K(R|t) \]
\[ \tilde{P} = \begin{pmatrix} K & 0 \\ 0^T & 1 \end{pmatrix} \begin{pmatrix} R & t \\ 0^T & 1 \end{pmatrix} \]

\[ K \equiv Camera\ Matrix \]
\[ R \equiv world\ to\ camera\ rotation \]
\[ t \equiv world\ to\ camera\ translation \]

\[ x_s = \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \]

\[ \tilde{p}_w = \begin{bmatrix} N(north) \\ E(east) \\ D(down) \end{bmatrix} \]

\[ K = \begin{bmatrix} f & s & C_x \\ 0 & af & C_y \\ 0 & 0 & 1 \end{bmatrix} \]

\[ R = R_1(\phi)R_2(\theta)R_3(\psi) \]

Vehicle Roll, pitch, yaw
Geolocation Compared to Truth:

Scene GeoLocation

- Origin
- RAPTR
- Target Estimate
- Target Truth

Error = 44 ft
Dist = 311 ft
Attitude Uncertainty for Geo-Location:

\[ \Delta = h[L\tan(\phi + \alpha + F/2) + (1 - L)\tan(\phi - \alpha - F/2) + (1 - 2L)\tan(F/2 + \alpha)] \]

- \( \Delta \equiv \text{Ground Distance [ft]} \)
- \( \phi \equiv \text{Bank Uncertainty [deg]} \)
- \( \alpha \equiv \text{True Bank Angle [deg]} \)
- \( L \equiv \text{Target Location in image (left = 0, right = 1)} \)
Pixel Mapping Diagram
Attitude Error with Payload & Algorithm Simulation

- Max pitch, roll uncertainty of 8-10 degrees
- Attitude uncertainty much less than max allowable value
- EE Payload specs compatible with requirements
Structures Backup
Structural Requirements

<table>
<thead>
<tr>
<th>Derived Requirements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.4</td>
<td>The vehicle shall withstand the forces of the launch and glide phases.</td>
</tr>
</tbody>
</table>

A Matlab model of shear force and bending moment along the wing.

Flexure Formula for 0.25” diameter rod → slight climb $\sigma_{\text{max}} = 12,457$ psi → worst case $\sigma_{\text{max}} = 376,232$ psi

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_y$ [psi]</th>
<th>FOS (slight climb)</th>
<th>FOS (worst case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balsa</td>
<td>2,828</td>
<td>0.276</td>
<td>0.007</td>
</tr>
<tr>
<td>Al-6061</td>
<td>40,000</td>
<td>3.916</td>
<td>0.106</td>
</tr>
<tr>
<td>Steel</td>
<td>53,700</td>
<td>5.257</td>
<td>0.142</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>82,762</td>
<td>8.102</td>
<td>0.219</td>
</tr>
</tbody>
</table>
Structural Requirements

Worst Case

Model of Load Distribution Along Wing

Model of Bending Moment Along Wing

Model of Shear Force Along Wing

Structural Integrity (DR 1.4) ✓
Fuselage Modification

- Need to widen fuselage from 1.5” to approximately 2.5”.
- Bulkheads will be re-made or modified to accommodate the additional width
Fuselage Modification

- Top covering will also be modified to fit the new fuselage
Wing Loading Test

- Whiffletree loading test to verify Matlab model.
- Will hang 8.245 pounds to simulate straight and level flight with FOS of 2
Motor Mount Ansys Analysis

- Maximum stress: 1036.7 psi
- Epoxy rating: 3400 psi

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Strength [psi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLA</td>
<td>6066.23</td>
</tr>
<tr>
<td>ABS</td>
<td>5656.47</td>
</tr>
<tr>
<td>Onyx with Carbon Fiber</td>
<td>101526</td>
</tr>
</tbody>
</table>
Structural Requirements

- 3D print engine mount and epoxy base to stationary balsa wood
- Epoxy hook to engine side of engine mount
- Hang weight from hook to emulate thrust
- Add weight until mount breaks
- Note how it broke (shear, bending, glue failure, etc.)
Structural Requirements

<table>
<thead>
<tr>
<th>Item(s)</th>
<th>Mass [g]</th>
<th>Mass [lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe</td>
<td>518</td>
<td>1.1419</td>
</tr>
<tr>
<td>Motor and Mount</td>
<td>680.29</td>
<td>1.4998</td>
</tr>
<tr>
<td>Electronics</td>
<td>218.09</td>
<td>0.4808</td>
</tr>
<tr>
<td>Payload</td>
<td>498.95</td>
<td>1.1000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,915.33</strong></td>
<td><strong>4.2225</strong></td>
</tr>
</tbody>
</table>
Test Backup

1. Software Testing
2. Structures Testing
3. Aerodynamics Testing
4. Controls/PixHawk
5. Test Regulations
6. Test Regulations
Software

- **Purpose:** Verify functionality of target detection and geolocation software *(FR 4)*
- **Location/Facilities:** North Boulder Park
- **Equipment:**
  - DGI Phantom Standard (Drone)
  - Cardboard
  - Bright Tape
- **Measurements:**
  - GPS and altitude data of drone
  - Images of target
  - Actual GPS location of target
- **Methods:** Capture images of scaled down target with drone from up to 350ft altitude.
Structures

- **Purpose:** Verify structural integrity of wing/motor mount *(FR 1)*
- **Location:** Outside of ITLL
- **Equipment:**
  - AndREaS Glider
  - Eye Hook
  - 5 Gallon Bucket
  - Epoxy
  - 3D Printed Motor Mount
  - Vice Grips
- **Measurements:**
  - Failure of Wings/Motor Mount
- **Methods:**
  - Insert eye hook into nose of glider
  - Hold glider by wingtips
  - Hang weight from eye hook
  - Progressively increase weights
  - Repeat for motor mount

Picture coming soon
Aerodynamics

- **Purpose**: Verify CFD analysis
- **Location/Facilities**: ITLL
- **Equipment**:
  - 3D Printer
  - ASEN Dept. Wind Tunnel
- **Measurements**:
  - Axial force
  - Normal force
  - Pitching moment
- **Methods**:
  - 3D print a scale model of glider
  - Mount model in wind tunnel
  - Vary angle of attack
  - Compute $C_L$, $C_d$, and $C_m$
Controls/PixHawk
## Test Regulations

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Derived From</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A member at launch shall have a level 1 certification for high powered rockets</td>
<td>NFPA Code 1127</td>
</tr>
<tr>
<td>2. Rocket shall be launched no greater than 20 degrees from vertical</td>
<td>NFPA Code 1127</td>
</tr>
<tr>
<td>3. Shall be launched through a local rocketry club at an appropriate launch site</td>
<td>NFPA Code 1127</td>
</tr>
<tr>
<td>7. Unmanned and does not create a hazard to any persons, property, or other aircraft</td>
<td>14 CFR Part 101.23</td>
</tr>
<tr>
<td>5. Operating requirements in Part 101.25</td>
<td>14 CFR Part 101.25</td>
</tr>
<tr>
<td>6. Proper notification is given to FAA as defined in Part 101.27</td>
<td>14 CFR Part 101.27</td>
</tr>
<tr>
<td>7. Aircraft shall be capable of manual controls override</td>
<td>AMA Doc #560</td>
</tr>
<tr>
<td>8. Vehicle shall weigh less than 55 lbs (Fig. 101.41)</td>
<td>14 CFR Part 101.41</td>
</tr>
</tbody>
</table>
§ 101.25 Operating limitations for Class 2-High Power Rockets and Class 3-Advanced High Power Rockets.

When operating Class 2-High Power Rockets or Class 3-Advanced High Power Rockets, you must comply with the General Operating Limitations of § 101.23. In addition, you must not operate Class 2-High Power Rockets or Class 3-Advanced High Power Rockets -

(a) At any altitude where clouds or obscur[ing phenomena of more than five-tenths coverage prevails;]

(b) At any altitude where the horizontal visibility is less than five miles;

(c) Into any cloud;

(d) Between sunset and sunrise without prior authorization from the FAA;

(e) Within 9.26 kilometers (5 nautical miles) of any airport boundary without prior authorization from the FAA;

(f) In controlled airspace without prior authorization from the FAA;

(g) Unless you observe the greater of the following separation distances from any person or property that is not associated with the operations:

   (1) Not less than one-quarter the maximum expected altitude;

   (2) 457 meters (1,500 ft.);

(h) Unless a person at least eighteen years old is present, is charged with ensuring the safety of the operation, and has final approval authority for initiating high-power rocket flight; and

(i) Unless reasonable precautions are provided to report and control a fire caused by rocket activities.

[74 FR 38092, July 31, 2009, as amended by Amdt. 101-8, 74 FR 47435, Sept. 16, 2009]