Critical Design Review

**Team**
- Ian Barrett
- Grant Dunbar
- George Duong
- Jesse Holton
- Sam Kelly
- Lauren McIntire
- Benjamin Mellinkoff
- Justin Norman
- Severyn Polakiewicz
- Michael Shannon
- Brandon Sundahl

**Customers**
- Jean Koster
- James Nestor
- David Gruber

**Advisor**
- Donna Gerren

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**Purpose/Objectives**

**Design Solution**

**Critical Project Elements**

**Requirements Satisfaction**

**Project Risks**

**Verification and Validation**

**Project Planning**
Search and Help Aquatic Mammals UAS

will design an **unmanned aerial system** to carry a **future** instrument payload capable of **locating sperm whales in the ocean.** The future unmanned aerial vehicle will be **launched and recovered from a research vessel’s helipad.**
Multi-Year User CONOPS

**Purpose/Objectives**

- Multi-Year User CONOPS

**Design Solution**

- Transport/Arrival
- Assembly/Setup
- Pre-flight Check
- Launch
- Cruise/Search
- Whale Located
- Landing
- Turnaround
- Disassemble

**Project Risks**

**Requirements Satisfaction**

**Project Planning**

**Verification and Validation**

**Critical Project Elements**

**Legend**

- Flight Path
- Loiter Path
## Functional Requirements

1. Operate in **manually piloted** mode throughout **all phases of flight** with autonomous mode capability at cruise altitude.

2. **Takeoff and land** from/to a **stationary 9.1 m x 9.1 m platform** obstructed fore (represents ship superstructure) and aft (represents ship crane).

3. **12 km communication range** for telemetry, images, and RC control **from ground control station**.
<p>| | |</p>
<table>
<thead>
<tr>
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<td>4.</td>
<td>Aircraft shall support <strong>downward-facing 2.0 kg simulated instrument payload</strong> with 15 cm x 15 cm x 23 cm dimensions.</td>
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<td>5.</td>
<td>Aircraft shall be <strong>operable and recoverable</strong> onto stationary platform in <strong>winds up to 10 m/s.</strong></td>
</tr>
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<td>6.</td>
<td>Aircraft shall have <strong>100 km ground track range endurance.</strong></td>
</tr>
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Design Solutions
## Design Solutions

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<thead>
<tr>
<th>Aircraft</th>
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</table>
Aircraft Design: Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span</td>
<td>3.0 m (10 ft)</td>
</tr>
<tr>
<td>Length</td>
<td>1.4 m (4.5 ft)</td>
</tr>
<tr>
<td>Height</td>
<td>0.53 m (1.8 ft)</td>
</tr>
<tr>
<td>Wing Area</td>
<td>0.93 m² (10 ft²)</td>
</tr>
<tr>
<td>Wing Aspect Ratio</td>
<td>10</td>
</tr>
<tr>
<td>Empty Weight</td>
<td>4.5 kg (10 lbs)</td>
</tr>
<tr>
<td>Payload Weight</td>
<td>2.0 kg (4.4 lbs)</td>
</tr>
<tr>
<td>Gross Weight</td>
<td>8.45 kg (19 lbs)</td>
</tr>
<tr>
<td>Motor Power</td>
<td>1300 W (1.74 hp)</td>
</tr>
</tbody>
</table>

Three Views of the SHAMU UAV
### Aircraft Design: Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>Cruise Speed</td>
<td>20 m/s (38 kts)</td>
</tr>
<tr>
<td>Stall Speed</td>
<td>11 m/s (20 kts)</td>
</tr>
<tr>
<td>Range</td>
<td>100 km (62 mi)</td>
</tr>
<tr>
<td>Climb Rate</td>
<td>&gt;5.1 m/s (&gt;1000 ft/min)</td>
</tr>
<tr>
<td>Cruise L/D</td>
<td>12 - 16.2</td>
</tr>
<tr>
<td>Wing Loading</td>
<td>9.8 kg/m² (2.0 lbs/ft²)</td>
</tr>
</tbody>
</table>

Three Views of the SHAMU UAV
Material Selection

- Expanded polypropylene wing/fuselage core
- G10 fiberglass bulkheads
- S-fiberglass/epoxy fuselage covering
- 5 mm CP film wing covering
- Carbon fiber spar in each wing half, aluminum 7075 carry-through spar
- Winglets attached with N52 neodymium magnets, reinforced with carbon strip
- Folding pusher prop to accommodate dolly configuration
# Design Solution

## Design and Validate Airframe

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**Design Solution Components:**
- PX4 Pro
- Raspberry Pi 3 Model B
- RFD900+
- OpenLRS RC
- PX4 Pro
- Raspberry Pi 3 Model B
- RFD900+
- OpenLRS RC

**Component List:**
- PX4 Pro
- Raspberry Pi 3 Model B
- RFD900+
- OpenLRS RC
## Takeoff Design Overview

<table>
<thead>
<tr>
<th>Bungees</th>
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<tbody>
<tr>
<td>Initial length of Bungee</td>
<td>1.99 m</td>
</tr>
<tr>
<td>Spring Constant</td>
<td>86 N/m</td>
</tr>
<tr>
<td>Tension Force</td>
<td>343.33 N</td>
</tr>
<tr>
<td>Final Velocity</td>
<td>13.2 m/s</td>
</tr>
<tr>
<td>Rail Length</td>
<td>5.25 m</td>
</tr>
<tr>
<td>PVC Diameter</td>
<td>2”</td>
</tr>
<tr>
<td>Takeoff Angle</td>
<td>5 degrees</td>
</tr>
<tr>
<td>Max Deflection of Rails</td>
<td>3.86 mm</td>
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<tr>
<td>Time</td>
<td>0.69 s</td>
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**Takeoff Design Overview**

- **Bungees**: 5
- **Initial length of Bungee**: 1.99 m
- **Spring Constant**: 86 N/m
- **Tension Force**: 343.33 N
- **Final Velocity**: 13.2 m/s
- **Rail Length**: 5.25 m
- **PVC Diameter**: 2”
- **Takeoff Angle**: 5 degrees
- **Max Deflection of Rails**: 3.86 mm
- **Time**: 0.69 s

**SHAMU UAV, Dolley, and Launch Ramp**

**Dolley Model (Side)**

**Dolley (Front)**
## Design Solution

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**Component List:**
- PX4 Pro
- Pixhawk 2.1
- Raspberry Pi 3 Model B
- RFD900+
- OpenLRS
- RC

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Recovery System

- **Net** suspended between two poles
- **Pulley connections to extend upon impact**
- **Extension** of net **reduces forces** upon landing and **closes the net to capture aircraft**
- **Impact forces** are **damped** by a **bungee** attached to the pulley line
- **Sailing Cleat** prevents line from rebounding
- **Hook on nose** of aircraft will **catch** the net to prevent impact with ground

[Diagram showing net front and back views with measurements]
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The table above outlines the design solution for the aircraft. The design involves developing an aircraft capable of takeoff using a bungee launch with a rail system and recovery via a net with extending lines. The autopilot system is based on Pixhawk 2.1 with PX4-Pro, and the flight computer is a Raspberry Pi 3 Model B. The radio frequency communication (RF) system uses RFD900+ Datalink, and the RC component list includes OpenLRS RC. The design solution also involves validating the airframe using a bungee launch with a rail system.
Navigation Hardware/Software Design
## Design Solution

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- PX4 Pro
- Raspberry Pi 3 Model B
- RFD900+ Datalink
- OpenLRS RC
- Component List

**Design and Validate**

- **Airframe**
  - Bungee Launch with Rail
  - Net with Extending Lines
  - PX4 Pro with Pixhawk 2.1
  - Raspberry Pi 3 Model B
  - RFD900+ Datalink
  - OpenLRS RC

**Component List**
## Electronic Components

<table>
<thead>
<tr>
<th>Battery*</th>
<th>Tattu 22000mah 6S Li-po Battery</th>
<th>Camera*</th>
<th>Raspberry Pi Camera Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor*</td>
<td>Propdrive 5060 v2 380kV Brushless Motor</td>
<td>Flight Controller</td>
<td>Pixhawk 2.1 Autopilot</td>
</tr>
<tr>
<td>Speed Controller</td>
<td>Turnigy Plush 100A Speed Controller w/ 5V UBEC</td>
<td>Plane Radio Receiver</td>
<td>OrangeRx Open LRS 433MHz 9Ch Receiver</td>
</tr>
<tr>
<td>Servos</td>
<td>HK15298B High Voltage Coreless Digital MG/BB Servo</td>
<td>Ground Station Transmitter</td>
<td>OrangeRx Open LRS 433MHz Transmitter 1W</td>
</tr>
<tr>
<td>GPS</td>
<td>Here+ GNSS GPS for Pixhawk 2.1</td>
<td>Telemetry Radio</td>
<td>RFD 900+</td>
</tr>
<tr>
<td>Airspeed Sensor</td>
<td>PX4 Airspeed Sensor w/ Pitot Tube</td>
<td>R/C Controller</td>
<td>Turnigy 9XR PRO Radio Transmitter Mode 2 w/o Module</td>
</tr>
<tr>
<td>Sensor Board and BEC</td>
<td>MAUCH PL-100A Sensor Board and PL 2-6S BEC w/ 2 5V Outputs</td>
<td></td>
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Critical Project Elements
## Critical Project Elements

<table>
<thead>
<tr>
<th>CPE</th>
<th>Requirement Considerations</th>
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<tr>
<td>Aerial Vehicle Design</td>
<td>• Stability and control&lt;br&gt;• Future sensor payload&lt;br&gt;• Tradeoff between maximizing lift-to-drag ratio and structural/manufacturing complexity</td>
</tr>
<tr>
<td>Takeoff and Recovery</td>
<td>• Accelerate/decelerate aircraft under maximum structural load&lt;br&gt;• Capability to transport and setup on 9.1m x 9.1m helipad</td>
</tr>
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# Critical Project Elements

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<tr>
<th>Communication with Ground Station</th>
<th>Requirement Considerations</th>
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<tbody>
<tr>
<td>● Communication range of 12 km from ground station</td>
<td>● Collects sensor data for virtual cockpit</td>
</tr>
<tr>
<td>● Transmit images at one per minute</td>
<td>● Autopilot keeps aircraft in steady, level flight</td>
</tr>
<tr>
<td>● Piloted manual control</td>
<td>● Accepts flight waypoints and executes</td>
</tr>
<tr>
<td>● Transmit updated flight waypoints</td>
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</tr>
<tr>
<td>● Transmit telemetry to ground station</td>
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<tr>
<th>Flight Computer / Autopilot</th>
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<td>● Collects sensor data for virtual cockpit</td>
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Design Requirements Satisfaction
Airframe & Powerplant
## CPE: Aerial Vehicle Design Key Requirements

<table>
<thead>
<tr>
<th>FR 1</th>
<th>The aircraft shall operate in remotely piloted and fully autonomous modes throughout all phases of flight.</th>
</tr>
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<tbody>
<tr>
<td>DR 1.1</td>
<td>The aircraft shall have static longitudinal stability.</td>
</tr>
<tr>
<td>DR 1.2</td>
<td>The control system shall provide required control surface deflections for aircraft longitudinal and lateral stability throughout all phases of flight.</td>
</tr>
<tr>
<td>FR 2</td>
<td>Takeoff and land from/to a stationary 9.1 m x 9.1 m platform obstructed fore (represents ship superstructure) and aft (represents ship crane).</td>
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<tr>
<td>DR 2.1</td>
<td>The aircraft shall have a nose hook that sustains 5 g net recovery forces.</td>
</tr>
<tr>
<td>DR 2.2</td>
<td>The aircraft wings shall sustain 5 g forces for maneuvers and net recovery.</td>
</tr>
<tr>
<td>FR 4</td>
<td>Aircraft supports downward-facing 2.0 kg simulated instrument payload with 15 cm x 15 cm x 23 cm dimensions.</td>
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### CPE: Aerial Vehicle Design Key Requirements

<table>
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<th>FR 6</th>
<th>The aircraft shall have a 100 km ground track range.</th>
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<td>DR 6.1</td>
<td>The aircraft shall have a lift-to-drag ratio of 12.</td>
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<td>DR 6.2</td>
<td>Battery shall have 1.4 hr endurance</td>
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CPE: Aerial Vehicle Design Key Requirements

**FR 4** Aircraft supports downward-facing 2.0 kg simulated instrument payload with 15 cm x 15 cm x 23 cm dimensions.

- **FR 4 Satisfied**

*Downward facing RPi Cam mount*
CPE: Aerial Vehicle Design Key Requirements

**DR 1.1** The aircraft shall have static longitudinal stability.

- Aerodynamic center: 71.75 cm behind the nose
  - Including wing and fuselage effects
- Center of gravity w/ 2 kg payload: 64.93 cm behind the nose
- Static Margin: 22.4% (6.82 cm)

\[ \therefore \text{DR 1.1 Satisfied} \]

C.G. A.C.
CPE: Aerial Vehicle Design Requirements

**DR 6.1** The aircraft shall have a lift-to-drag ratio of 12.

**Design choices to maximize L/D**

- Wing covering to create smooth surface
- Fuselage covering to create smooth surface
- AVL, XFLR5, OpenVSP, X-Plane models all predict an L/D > 12*

MATLAB L/D prediction

\[ \therefore DR\ 6.1 \text{ Satisfied} \]

* To be verified by L/D tests in half-scale
## CPE: Aerial Vehicle Design Requirements

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Needed</th>
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<tr>
<td>Motor (Steady Flight)</td>
<td>277 Wh</td>
</tr>
<tr>
<td>Motor (Climb)</td>
<td>39.6 Wh</td>
</tr>
<tr>
<td>Pixhawk</td>
<td>1.75 Wh</td>
</tr>
<tr>
<td>RFD 900+</td>
<td>5.6 Wh</td>
</tr>
<tr>
<td>OrangeRX Open LRS</td>
<td>0.28 Wh</td>
</tr>
<tr>
<td>Raspberry π w/ Camera</td>
<td>2.45 Wh</td>
</tr>
<tr>
<td>Servo</td>
<td>14 Wh</td>
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</table>

**Total Required Energy:** 375 Wh

### Selected Battery Pack

**Tattu 22000mAh 6S 25C 22.2V Lipo Battery Pack**
- **Capacity:** 22000 mAh
- **Voltage:** 22.2V
- **Watt-hours:** 488 Wh
- **Available Energy:** 390 Wh
- **Weight:** 2.65 kg

390 Wh > 375 Wh
∴ DR 6.2 is satisfied

---

**DR 6.2**

Battery shall have 1.4 hr endurance

---
**CPE: Aerial Vehicle Design Key Requirements**

**DR 2.1** The aircraft shall have a nose hook that sustains 5 g landing forces.

---

Initial proof-of-concept tests show 88% success rate (29 of 33) with potential for improvement

**One hook prong under 5 g must sustain**
Bending Moment : 37 Nm

**For a (32mm x 96mm rectangular prong)**
Internal Stress : 766 MPa

**Solution**
Titanium Grade S Tensile Strength : 880 MPa > 766 MPa

1.2 Safety Factor :: DR 2.1 Satisfied ✓
CPE: Aerial Vehicle Design Requirements

**DR 2.2** The aircraft wings shall sustain 5 g forces for maneuvers and net recovery.

These rods connect the wings to the fuselage and must sustain

Shear Force: 103.5 N

For a 3/16” diameter rod

Shear Stress: 5.65 MPa

**Solution**

Aluminum (6061) rod:

Shear Strength is 204 MPa

204 MPa > 5.65 MPa
CPE: Aerial Vehicle Design Key Requirements

DR 2.2  The aircraft wings shall sustain 5 g forces for maneuvers and net recovery.

Wing spar must sustain
Bending Moment : 116 Nm
Shear Force : 169 N

For a (20mm x 18mm Tube)
Internal Stress : 430 MPa
Shear Stress : 2.8 MPa

Solution
Carbon Fiber: Tensile Strength is 650 MPa > 430 MPa
Shear Strength is 450 MPa > 2.8 MPa
Aluminum (7075-T6) Carry Through (solid rod):
Tensile Strength is 500 MPa > 280 MPa

1.5 Safety Factor ∴ DR 2.2 Satisfied
Controllability:

- A & B state space matrices calculated
- Longitudinal & Lateral Controllability matrix
  - Full rank

Controllability Matrices

\[
C_{\text{long}} = \begin{bmatrix}
B_{\text{long}} & A_{\text{long}}B_{\text{long}} & A^2_{\text{long}}B_{\text{long}} & A^3_{\text{long}}B_{\text{long}}
\end{bmatrix}
\]

\[
C_{\text{lat}} = \begin{bmatrix}
B_{\text{lat}} & A_{\text{lat}}B_{\text{lat}} & A^2_{\text{lat}}B_{\text{lat}} & A^3_{\text{lat}}B_{\text{lat}}
\end{bmatrix}
\]

System is controllable:
Elevons (deflection) allows for modification of poles (eigenvalues) for desired stability

DR 1.2 Satisfied
## CPE: Aerial Vehicle Design Key Requirements Recap

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Launch System
### CPE: Launch Design Key Requirements

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<tr>
<td>DR 2.1</td>
<td>The launch system shall accelerate the UAV to 13.2 m/s by the end of ramp.</td>
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<tr>
<td>DR 2.2</td>
<td>The launch system shall launch the UAV under 5 g.</td>
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</table>
CPE: Launch Design Key Requirements

FR 2: Takeoff and land from/to a stationary 9.1 m x 9.1 m platform obstructed fore (represents ship superstructure) and aft (represents ship crane).

- Rail system length: 5.8 m
- Rail system width: 2.4 m
- Bungee anchor position forward of rail system: 1.0 m

Total length < 9.1 m

FR 2 Satisfied ✓
CPE: Launch Design Key Requirements

| DR 2.1 | The launch system shall accelerate the UAV to 13.2 m/s by the end of ramp. |
| DR 2.2 | The launch system shall launch the UAV under 5 g. |

Concerns:
G-force on launch needs to be < 5 g
UAV/Cradle speed $\geq 13.2 \text{ m/s by end of ramp}$ (5.25 m)

Solution:
Acceleration spread out across a long ramp

Assumptions:
Newton’s 1st law
Mass of UAV/Cradle is 14.0 kg

Results:
UAV/Cradle speed of 13.2 m/s at 4 m < 5.25 m
UAV/Cradle experiences 1.90 g

∴ DR2.1, DR 2.2 Satisfied
## CPE: Launch Design Key Requirements Recap

<table>
<thead>
<tr>
<th>FR 2</th>
<th>Takeoff and land from/to a stationary 9.1 m x 9.1 m platform obstructed fore (represents ship superstructure) and aft (represents ship crane).</th>
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</thead>
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</tr>
</tbody>
</table>
Recovery System
### CPE: Recovery System Requirements

<table>
<thead>
<tr>
<th>FR 2</th>
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<tbody>
<tr>
<td>DR 2.1</td>
<td>The recovery system shall exert forces on the aircraft under 5 g.</td>
</tr>
<tr>
<td>DR 2.2</td>
<td>Capture system shall sustain 5 g aircraft recovery forces.</td>
</tr>
</tbody>
</table>

![Front View](image1.png)

![Side View](image2.png)

![Top View](image3.png)
CPE: Recovery System Requirements

Details:

- Initial recovery KE 572 J (9.1 kg, 12 m/s)
- 2 bungees hold ½ of PE each
- Spring constant 118 N/m at 2.2 m stretch
- Selected bungee has 260 N force at 100% extension

2.2 m extension results in
4.8m recovery distance < 9.1m helipad

∴ FR 2 Satisfied  ✓
CPE: Recovery System Requirements

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</table>

- Recovery System Dimensions:
  \[7.6 \text{ m} \times 3.0 \text{ m} < 9.1 \text{ m} \times 9.1 \text{ m}\]
  \[\therefore \text{ FR 2 Satisfied}\]

- Maximum Line Tension 130 N
- Maximum force on aircraft
  \[395 \text{ N} = 4.4 \text{ g} < 5 \text{ g}\]
  \[\therefore \text{ DR 2.1 Satisfied}\]
CPE: Recovery System Requirements

**DR 2.2** Capture system shall sustain 5 g aircraft recovery forces.

- **Primary Failure Mode:** Bending at uppermost support
- 130 N in each net line, results in 555 N*m moment
- 9 cm outer, 7.6 cm inner diameter pipe
- Gives 17.5 MPa bending stress

17.5 MPa < 34 MPa PVC Tensile Strength

∴ DR 2.2 Satisfied
## CPE: Recovery System Requirements Recap

<table>
<thead>
<tr>
<th>FR 2</th>
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</table>
## CPE: Nav/Comm Design Key Requirements

<table>
<thead>
<tr>
<th>FR 1</th>
<th>Developing requirement: Operate in manually piloted mode throughout all phases of flight with autonomous mode capability at cruise altitude.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 1.1</td>
<td>Aircraft shall transmit telemetry to ground station.</td>
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<tr>
<td>DR 1.2</td>
<td>Ground control station shall provide virtual cockpit.</td>
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<tr>
<td>DR 1.3</td>
<td>Aircraft shall fly autonomous missions based on waypoints and loiter points.</td>
</tr>
<tr>
<td>DR 1.4</td>
<td>Mission shall be reprogrammable during flight.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FR 3</th>
<th>Developing requirement: 12 km communication range for telemetry, images, and RC control from ground control station.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 3.1</td>
<td>Telemetry radio shall have a range of 12 km at 90+ kbps.</td>
</tr>
<tr>
<td>DR 3.2</td>
<td>Aircraft shall capture and transmit images to ground station at 1/60 Hz.</td>
</tr>
</tbody>
</table>
CPE: Nav/Comm Requirements

| DR 1.1 | Aircraft shall transmit telemetry to ground station. | ✔ ✔ |
| DR 1.2 | Ground control station shall provide virtual cockpit. | ✔ ✔ |
| DR 3.2 | Aircraft shall capture and transmit images to ground station at 1/60 Hz. | ✔ ✔ |

- Telemetry captured by:
  - Attitude @ 20 Hz - Pixhawk 2.1 running PX 4 Pro
  - Position @ 5 Hz - Here+ GPS
  - System Status (including battery) @ 1 Hz
- Telemetry sent over MAVLink connection to the ground station.
  - Requires 17.5 kbps (112.5 kbps of download available)
- Virtual cockpit provided by QGroundControl.
  - Digital six pack
  - Moving map display
  - Battery monitoring
- Image transmission accomplished with mavimage

![QGroundControl digital six pack](image.png)
## CPE: Nav/Comm Requirements

| DR 1.3 | Aircraft shall fly autonomous missions based on waypoints and loiter points. |
| DR 1.4 | Mission shall be reprogrammable during flight. |

- Pixhawk 2.1 autopilot running PX4 Pro
  - Flies autonomous missions based on a flight plan consisting of waypoints.
  - Reprogrammable during flight while in loiter mode.
- QGroundControl (GCS)
  - Flight plan creation and upload.
  - 330 waypoint uploads per second.
    - Given 12.5 kbps upload rate (the amount remaining assuming full rate download)

![QGroundControl flight plan editor](image-url)
CPE: Nav/Comm Requirements

<table>
<thead>
<tr>
<th>Datalink Link Budget Contributors</th>
<th>Gain/Loss</th>
<th>Associated Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX Power</td>
<td>30 dBm</td>
<td>RFD900+ specification</td>
</tr>
<tr>
<td>TX Antenna Gain</td>
<td>2.1 dBi</td>
<td>UAV ¼ wave monopole</td>
</tr>
<tr>
<td>Free Space Path Loss</td>
<td>-113.1 dB</td>
<td>900 Mhz @ 12 km</td>
</tr>
<tr>
<td>RX Antenna Gain</td>
<td>25 dBi</td>
<td>Yagi Ground Station Antenna</td>
</tr>
<tr>
<td>SNR</td>
<td>-30 dB</td>
<td>Rayleigh Fading Model for 99.9% time availability</td>
</tr>
<tr>
<td>RX Sensitivity (for 125 kbps)</td>
<td>90 dB</td>
<td>RFD900+ Specification</td>
</tr>
<tr>
<td><strong>Link Budget</strong></td>
<td><strong>3.59 dB</strong></td>
<td>DR 3.1 satisfied.</td>
</tr>
</tbody>
</table>
## CPE: Nav/Comm Design Key Requirements Recap

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</table>
Project Risks
<table>
<thead>
<tr>
<th>Risk</th>
<th>Pre mitigation likelihood/impact</th>
<th>Mitigation Plan</th>
<th>Post mitigation likelihood/impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Software delay</td>
<td>3 / 3</td>
<td>Extra manpower</td>
<td>2 / 3</td>
</tr>
<tr>
<td>2) Comm system failure during test flight</td>
<td>5 / 5</td>
<td>Extensive testing, autopilot failsafe mode</td>
<td>2 / 2</td>
</tr>
<tr>
<td>3) Manufacturing time delay</td>
<td>3 / 4</td>
<td>Detailed plan, add manpower</td>
<td>2 / 4</td>
</tr>
<tr>
<td>4) Crash during testing</td>
<td>4 / 4</td>
<td>Pilot preparation, shock absorbent airplane, half-scale</td>
<td>3 / 3</td>
</tr>
<tr>
<td>5) Shipping delays</td>
<td>2 / 4</td>
<td>Order parts with long lead times before break</td>
<td>1 / 4</td>
</tr>
<tr>
<td>Risk</td>
<td>Pre mitigation likelihood/impact</td>
<td>Mitigation</td>
<td>Post mitigation likelihood/impact</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>6) Wing failure during sandbag test</td>
<td>2 / 3</td>
<td>Buy 2 sets of wings, Produce extra</td>
<td>2 / 2</td>
</tr>
<tr>
<td>7) Battery overheating</td>
<td>3 / 5</td>
<td>Test components and circuit</td>
<td>1 / 5</td>
</tr>
<tr>
<td>8) Injury during testing</td>
<td>2 / 5</td>
<td>Safety plan</td>
<td>1 / 5</td>
</tr>
<tr>
<td>9) Over-budget</td>
<td>4 / 4</td>
<td>Budget plan, half-scale testing</td>
<td>2 / 4</td>
</tr>
<tr>
<td>10) Insufficient battery duration during flight</td>
<td>3 / 4</td>
<td>Battery testing, autopilot safeguard</td>
<td>2 / 3</td>
</tr>
<tr>
<td>11) Bad weather</td>
<td>3 / 2</td>
<td>Plan ahead, have multiple options</td>
<td>3 / 1</td>
</tr>
</tbody>
</table>

**Legend**

- **Red** = High Risk
- **Yellow** = Mitigated Risk

1 = lowest likelihood/impact (desired)

5 = highest likelihood/impact (undesired)
Verification and Validation
DR 1.1- Half Scale Stability Test

**Anticipated Date:** On or before the week of January 15th

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Expected Result According to Models</th>
<th>Off-Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validate stability model</td>
<td>Use accelerometers to confirm predicted behavior</td>
<td>Iteration of model</td>
</tr>
</tbody>
</table>

**Test set-up:**
Half scale UAV
Accelerometer

**DR 1.1**
The control system shall provide required control surface deflections for aircraft longitudinal and lateral stability throughout all phases of flight.
### DR 1.1- Half Scale Stability Test

**Expected Location:** South Campus

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Availability</th>
<th>Capabilities</th>
<th>Requirements</th>
<th>Satisfied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half scale model</td>
<td>Acquired through funds</td>
<td>Provide reliable test data for validation</td>
<td>Validate stability model</td>
<td>Stability model verified</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>COTS</td>
<td>Range: 0-14.2g Resolution: 16 bit</td>
<td>Continuously track the UAV’s roll pitch and yaw</td>
<td>COTS accelerometer capable with resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

**Key Measurements Issues:** Accelerometer resolution
DR 2.1 - Launch Speed Test

**Anticipated Date:** After TRR

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Expected Result According to Models</th>
<th>Off-Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validate Speed Model</td>
<td>Dolly speed is 13.2 m/s</td>
<td>Add or remove bungees, vary pull back distance on ramp.</td>
</tr>
</tbody>
</table>

**Test set-up:**
Camera captures dolly as it moves up the ramp.

**DR 2.1**
The launch system shall accelerate the UAV to 13.2 m/s by the end of ramp.
### DR 2.1 - Launch Speed Test

**Expected Location:** Open Field

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Availability</th>
<th>Capabilities</th>
<th>Requirements</th>
<th>Satisfied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>ITLL</td>
<td>60 fps camera&lt;br&gt;Launch time: 0.766 s</td>
<td>&gt; 20 frames for track time</td>
<td>45 frames in launch time ✓</td>
</tr>
<tr>
<td>Tripod/Stand</td>
<td>ITLL</td>
<td>Any height is achievable</td>
<td>0.25 m height</td>
<td>Any Height ✓</td>
</tr>
<tr>
<td>Logger Pro Software</td>
<td>ITLL</td>
<td>Frame by frame tracking of dolly to find position and speed</td>
<td>Calculate the speed of the dolly</td>
<td>Access to software ✓</td>
</tr>
</tbody>
</table>

**Key Measurements Issues:** Error in height of camera leading to issues in software
DR 2.1 - Recovery System Force Test

**Anticipated Date:** After TRR

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Expected Result According to Models</th>
<th>Off-Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validate Recovery Force Model</td>
<td>Accelerometer on dummy mass will experience &lt; 5g</td>
<td>Redesign of bungees</td>
</tr>
</tbody>
</table>

**Test set-up:**
Camera captures dummy weight as it is thrown into the net, accelerometers collect data

**DR 2.1**
The recovery system shall exert forces on the aircraft under 5 g.
DR 2.1 - Recovery System Force Test

Expected Location: Open Field

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Availability</th>
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<th>Requirements</th>
<th>Satisfied?</th>
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</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>COTS</td>
<td>Range: 0-14.2 g Resolution: 16 bit</td>
<td>5 g</td>
<td>Available</td>
</tr>
<tr>
<td>High Speed Camera</td>
<td>ITLL</td>
<td>120 fps</td>
<td>Record dummy mass to find net extension</td>
<td>Available</td>
</tr>
<tr>
<td>Dummy Mass</td>
<td>ITLL</td>
<td>N/A</td>
<td>8.45 kg</td>
<td>Available</td>
</tr>
</tbody>
</table>

Key Measurements Issues: Consistent throw speeds, error in measurements from accelerometer.
DR 3.1 - Datalink Range Test
Anticipated Date: February 1, 2018

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Expected Result According to Models</th>
<th>Off-Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verify 12 km communication range</td>
<td>Successful image transfer Uplink rate of 8 kbps Datalink rate of 88 kbps.</td>
<td>Implementation of ground station tracking system</td>
</tr>
</tbody>
</table>

Test set-up:
Ground station setup will be 12 km away from transmitter

DR 3.1
Telemetry radio shall have a range of 12 km at 90+ kbps.
**DR 3.1 - Datalink Range Test**

**Expected Location:** Flatiron summit to Boulder/Lafayette City limit at Baseline Rd

<table>
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<th>Availability</th>
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<th>Satisfied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 FTDI Cables</td>
<td>Acquired through funds</td>
<td>Communicate between radio and laptop</td>
<td>5V capacity</td>
<td>Can be purchased with budget</td>
</tr>
<tr>
<td>2 Battery Powered USB Hubs</td>
<td>Acquired through funds</td>
<td>Provide extra power to radio</td>
<td>At least 88 kbps transfer rate</td>
<td>Can be purchased with budget</td>
</tr>
</tbody>
</table>

**Key Measurements Issues:** Ground station pointing angle of antenna.
DR 6.2 - Battery Endurance Test
Verify the battery can reach the mission time requirement

**Anticipated Date:** Before TRR

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Expected Result According to Models</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Validate Power Budget</td>
<td>Battery holds charge for: 3 min at 65.6A, 81 min at 15.6A</td>
<td>Reduce required range of mission.</td>
</tr>
</tbody>
</table>

**Test set-up:**
Ground test of battery connected to load and voltmeter

**DR 6.2** Battery shall have 1.4 hr endurance.
## DR 6.2 - Battery Endurance Test

**Expected Location:** ITLL

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Availability</th>
<th>Capabilities</th>
<th>Requirements</th>
<th>Satisfied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor, Autopilot, Flight Computer</td>
<td>Acquired through funds</td>
<td>Simulate mission load on battery</td>
<td>Components chosen for project</td>
<td>Components to be ordered ✓</td>
</tr>
<tr>
<td>Compact DAQ</td>
<td>ITLL</td>
<td>Verify the battery voltage over time and measure the cutoff voltage</td>
<td>84 min measurement time</td>
<td>Can measure values over time ✓</td>
</tr>
</tbody>
</table>

**Key Measurements Issues:** Error in DAQ measurements.
## Verification & Validation Summary

<table>
<thead>
<tr>
<th>Models Validated</th>
<th>Requirements verified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability model</td>
<td>Aircraft stability during flight</td>
</tr>
<tr>
<td>Launch system speed model</td>
<td>Capability of launch system to deliver necessary energy to UAV</td>
</tr>
<tr>
<td>Recovery system force model</td>
<td>Capability of landing system to capture UAV with forces in under 5g</td>
</tr>
<tr>
<td>Battery depletion model</td>
<td>Battery shall have 1.4 hour endurance between climb and cruise</td>
</tr>
<tr>
<td>Link Budget</td>
<td>Capability of ground system to communicate with UAV at range</td>
</tr>
</tbody>
</table>
Organizational Chart
Test Plan

Test Plan Diagram:

- Tests
  - Wing Loading
  - Magnet Pull Test
  - Control Surface Test
  - Bungee/Rope Test
  - Dolly Rope Catch Test
  - Beam Deflection Test
  - PVC Tensile Test
  - Hook Test
  - Component Testing
  - Motor Test
  - MAV Table/Frame Unit Testing

- Subsystem Tests
  - Half Scale Flight Test
  - Stability Autopilot HIL Test
  - Speed Test
  - Recovery System Force Test
  - Datalink Range Test
  - Battery Endurance Test

- Integration Tests
  - Autopilot Integration Test
  - Launch/Recovery Force Test
  - Full Software Integration Test

- Full Integration Testing
  - Full Integration Flight Test

Legend:
- Tests Independent of other subsystems
- Tests Dependent of other subsystems
- TRR

Test and Readiness Review: March 5th, 2018
Work Plan (Gantt Chart)

Winter Break/
Parts Procurement /
Software Development

Critical Path

Manufacturing /
Software Development
Work Plan (Gantt Chart Continued)

Critical Path:
Component Testing / Integration and Assembly
Integration Testing

Planned Margin

Activities:
- MSR (Manufacturing Status Review)
- PVC Tensile Test
- Bungee Testing
- Battery Endurance
- Wing Loading Test
- Electronics Circuit Testing
- Hardware-in-the-Loop Xplane Model
- Half-scale Autopilot/Stability Tests
- Ramp Dolley Test
- Modular Assembly Testing
- Hook-Capture Test
- TRR Compilation
- TRR (Test Readiness Review)
- Imaging HIL
- Full Flight Mission Testing
- Integration Testing Complete
## Budget Estimations

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe w/ motor</td>
<td>$1230</td>
</tr>
<tr>
<td>Communications</td>
<td>$530</td>
</tr>
<tr>
<td>Electronics</td>
<td>$800</td>
</tr>
<tr>
<td>Launch system</td>
<td>$295</td>
</tr>
<tr>
<td>Recovery system</td>
<td>$510</td>
</tr>
<tr>
<td>Software</td>
<td>$320</td>
</tr>
</tbody>
</table>

**Total:** $3,685 < $5,000

Leaves the SHAMU team with a 26% margin
Acknowledgements

Thank you to Dr. Gerren, Dr. Koster, Dr. Lawrence, Trudy Schwartz, Bobby Hodgkinson, Matt Rhode, PAB, Tim Kiley, Lee Huynh, James Nestor, and David Gruber.
References

- QGroundControl: http://qgroundcontrol.com/ (retrieved 12/3/17)
- UIAA climbing rope: http://www.theuiaa.org/safety-standards/
- Solidworks: http://www.solidworks.com/
- PVC porperties: https://www.engineeringtoolbox.com/physical-properties-thermoplastics-d_808.html
- PVC pressure ratings: https://www.engineeringtoolbox.com/pvc-cpvc-pipes-pressures-d_796.html
Questions?

Thank you.
## Backup Slides Directory

### Airframe & Powerplant:
- **Propeller**
- **Winglet Magnets**
- **Modularity**
- **Half Scale Model**
- **X-Plane Model**
- **Climb Rate**
- **Cooper-Harper**
- **Servo Selection**

### C.G. Range Longitudinal Stability
### C.G. Range Lateral Stability
### Uncontrolled Eigenvalues

### Launch System:
- **Launch Flow Chart**
- **Forces and Displacements (Dolly)**
- **Restraining Rope**
- ** Anchors (Bungee and Rope)**
- ** PVC Cement**
- ** Dolly pictures**
- ** Modularity and dimensions**
- **Beam Bending**

### Capture System:
- **Modularity and Dimensions**
- **Pulley/Cleat System CAD**
- **Connection Details**
- **Tipping and Sliding**

### Electronics:
- **Electronics Layout**
- **Climb Power**
- **Cruise Power**
- **Component Current Draw**
- **Electronics Diagram**
- **From Electronics Diagram**
- **Motor Requirement**

### Nav/Comm:
- **Software Overview**
- **mavimage Overview**
- **mavimage UML Class Diagram**
- **(overview)**
- **mavimage UML Class Diagram**
- **mavtables Overview**
- **mavtables UML Class Diagram**
- **(overview)**
- **mavtables UML Class Diagram**
- **mavlogger overview**
- **mavlogger UML Class Diagram**
- **Image Resolution**
- **Image Transfer Rate**
- **Datalink Budget**

### Slide 132: CPE: Nav/Comm Requirements

### Testing:
- **Testing Backup**
Propeller backup slide

Propeller configuration

- 16 x 10 inch 2-blade propeller
- Carbon fiber
- Folding design
- Up to 6.4 kg thrust
- Pitch speed: 31 m/s (cruise speed: 20 m/s)
Magnet backup slide

- Neodymium N52 magnets with 25.1 N pull force
- Two magnet sets per wing to prevent rotation: 2*25.1 = 50.2 N pull force per winglet
- Simulation at 30.5 m/s (never exceed speed) and beta angle of 10 degrees produced side force of 17.4 N lbs per winglet
- Winglets will not depart during worst case scenario flight loads (50.2 N > 17.4 N) safety factor = 2.9
- Winglet will depart under non-nominal landing load (> 50.2 N)
Aerial Vehicle Design Key Requirements

50% Scale Model:
- Useful for static stability and handling characteristics
  - Statically stable ($C_{Ma} < 0$) except at stall
  - Poor stall behavior
- 3° wing twist requirement developed for design as a result

Launching the half-scale model.
Aerial Vehicle Design Key Requirements

**X-Plane 10 Model:**

- Useful for modeling stability and handling characteristics from a pilot’s perspective
  - Max roll rate: 70°/s
  - Max pitch rate: 45°/s
  - Statically stable ($C_{Ma} < 0$) in all flight conditions with 3° wing twist
  - Dynamically stable

- Will be used for hardware in the loop simulations with autopilot.
Aerial Vehicle Design Key Requirements

DR 7.1 Aircraft and associated systems shall break down to fit in a 168 x 122 x 46 cm container for transportation.

**Design Decisions for modularity**

- Winglet magnets detach
- Remove 2 nuts to detach wings
- 4 bolts removed to detach payload bay

Packs into a 152 cm x 97 cm x 31 cm volume.
Aerial Vehicle Design Key Requirements

Servo selection:
- AVL used to calculate worst-case control surface hinge moment
  - $V_{ne} = 1.5 * V_{cruise}$
  - Max elevon deflection
- Hinge moment = 14 kg*cm
- HK15298B servo
  - Stall torque: 18.0 kg*cm @ 6.0V
  - **Stall torque: 20.0 kg*cm @ 7.4V**
  - Dimension: 18.0 x 121.0 x 80.0 mm
  - Mass: 0.09 kg

Aerial Vehicle Design Key Requirements

Cooper-Harper Scale 3: “Satisfactory without improvement. Fair; some mildly unpleasant deficiencies - minimum pilot compensation required for desired performance.”

Quantitatively:
- Maximum pitch and roll rates: 30 - 360°/s at minimum controllable airspeed.
- $C_{Ma} < 0$ through flight regime (angles of attack from zero to stall) $\rightarrow$ \textit{statically stable}.
- Real component of phugoid/short period/dutch roll/rolling modes must be less than zero $\rightarrow$ \textit{dynamically stable}.
CPE: Aerial Vehicle Design Key Requirements

- Flying wing configuration
- Elevon control (pitch and roll)
- Outer 50% span, 25% chord elevons.
- Elevon maximum deflections: +/- 30°
- Trim conditions for steady-level flight:
  - Elevon: -10 deg deflection (AVL)
- Mass: 8.45 kg
- Aerodynamic center: 71.75 cm
  - Including wing and fuselage effects
- Center of gravity w/2 kg payload: 64.93 cm
- Static Margin: 22.4% (6.82 cm)
### CPE: Aerial Vehicle Design Key Requirements

**AVL Model Eigenvalues:**

- \( \lambda_i < 0 \ \forall \ i \)
  - Stable in the sense of Lyapunov
  - System is BIBS & BIBO stable
Aircraft Stability - AVL/Matlab

- Longitudinal eigenvalue locus plot
  - Range of C.G.: approx. 62.9 +/- 15 cm

  **Short period mode - very stable**

  **Phugoid mode - slightly stable for C.G. range of 50.7 cm - 76.3 cm**

  ∴ Feasible
Aircraft Stability- AVL/Matlab

- Lateral eigenvalue locus plot
  - Range of C.G.: approx. 62.9 +/- 15 cm

Roll mode - very stable

Dutch roll; Spiral modes - slightly stable for C.G. range of 50.7 cm - 76.3 cm

∴ Feasible
Launch System Backup
Launch Flow Chart

1. Bungee and restraining rope are anchored to the ground
2. Bungee and restraining rope are attached to the dolly
3. Dolly is set onto the rails
4. UAV is loaded into dolly
5. The dolly is halted by the restraining rope
6. Dolly brings UAV to designed launch speed (13.2 m/s)
7. Dolly is released and travels down the rails with the UAV
8. Dolly is pulled back into ready-for-launch position
9. UAV is launched out of the dolly into flight
Maximum Allowable Loading

- Factor of Safety = 2
- Maximum allowable force = 1700N
- 4 bungees used produce 2.6 in$^2$ of contact on front dolly bar
- Actual force on dolly bar from bungees = 343.33 N
- PVC tensile strength = 40.7 MPa
- PVC type Schedule 40
PVC Displacement

Max displacement = 1.5 mm
Force on Dolly From Restraining Rope

Dolly mass: 5.91 kg
Vf = 13.2 m/s
Max allowable force on dolly: 1700N

Stopping impulse force, $F_{\text{avg}} = m \cdot a_{\text{avg}} \cdot (\Delta V / \Delta t)$
- At max force $\Delta t = 0.046s$

Stopping distance, $x = V_0 \cdot t + 0.5 \cdot (-a) \cdot t^2$
- At max force $x = 0.310m$

Force safety increase stopping distance to 0.5m
- Time to stop, $t = 0.076s$
- Force on dolly, $F = 1026.5$ N
Restraining Rope

Material used: low stretch polyester rope
- Rated for 6% to 10% dynamic elongation
- 1556 N load capable
- FoS = 1.5

Recall stopping distance = 0.5 m
- Length of rope required for this stopping distance = 8.3 m to 5 m
Bungee and Restraining Rope Ground Anchors

Forces
- Bungee: 343.3 N
- Restraining rope: 1026.5 N

Anchors
- Bungee
  - 20 cm anchor
  - Holds 556 N
- Restraining rope
  - 41 cm anchor
  - Holds 1890 N
PVC Cement and Its Strength

Known: Same PVC cement is used for Schedule 40 and Schedule 80.

Assumption based off capped pipes. Since the area is the same for a 1 in diameter pipe for Sch 40 and Sch 80, the operating pressure of sch 80 pipe is used. Know that PVC cement should hold operating pressures of pipes.

Area of cap: 5.42 cm²
Operating pressure Sch 80: 2.61 MPa
Bursting pressure Sch 80: 13.93 MPa
Operating force of Sch 80, Area * pressure = 1412.5 N
Force that will burst Sch 80, F = 7548.4 N

Max force dolly experiences = 1026.5 N < 1412.5 N < 7548.4 N
Pictures of Dolly
Pictures of Dolly
Dolly Dimensions
CPE: Launch Design Key Requirements

DR 7.1
Launch and associated systems shall break down to fit in a 168 x 122 x 46 cm container for transportation.

Primary Concern:
Ramp rails are 5.8 meters (580 cm)

Solution:
Rail segments (<168cm) connected by a threaded, aluminum rod inside the pipe

Result:
4 rail segments at 1.47 meters each
3 threaded internal pipe connectors

Rail Segments 147 cm < 168 cm

DR 7.1 Satisfied
Finding the Spring Constant required for TO

Assumptions:
5 Hi-start Bungees
Max weight: 5 kg
Max elongation: 3 times original length
K found by hanging mass off ceiling (Mg = Kx)

Applied to Conservation of Energy for different bungee lengths,
Intersecting point will give K value for needed TO speed

Results:
Total Mass: 13.9657 kg
Force: 343.3333 N (5 Bungees)
Spring Constant: 86.0011 N/m
Initial Bungee length: 1.9961 m
Bungee-stretch: 3.9922 m
Assumptions:
Bungee Force will decrease as dolly moves
Bungees tied to ground in front of ramp

Accounted for change in bungee force and the change in direction.

Results:
Look at plots
Force the Dolly feels fades to zero
Gives effect of consistent pull by bungee
Speed model

Assumptions:
Total Mass: 13.9657 kg
Force: 343.3333 N (5 Bungees)
Spring Constant: 86.0011 N/m
Initial Bungee length: 1.9961 m
Bungee-stretch: 3.9922 m
Effective Bungee Force Data

Applied Newton’s first law and integrated to get equations of motion

Results:
Aircraft gets to speed 0.0405 after end of ramp, this is adjusted for, shown in plot
New ramp length: 5.2480 m
Time: 0.6851 s
Velocity at exit: 13.208 m/s
Beam Bending

\[
\delta_{\text{max}} = \frac{Fa(L^2 - a^2)^{3/2}}{9\sqrt{3}LEI}
\]

Assume:
- Two fixed supports
- Each point on ramp has load \( F \) shown by the blue line
- Load \( F \) is the effective Bungee Force plus the weight of UAV
- Material Properties of PVC schedule 40
- 5.25 m long 2” PVC pipe
Results:
Max Deflection of Beam: 3.857901 mm
At a Distance of: 2.4564 meters
Model stops when UAV is at speed~4 meters, the rest of the rail is there for stopping distance

Max Bending Stress = 153.0242 KPa

$\sigma_{\text{bend, max}} = 99.63 \text{ MPa}$

Safety Factor = 651.1
Reaction Forces

Assumptions:
- Two fixed supports
- Sum of the moments
- Effective Bungee Force data

Results:
First Support: Max compressive force of: 90.3230 N
Second Support: Max compressive force of: 52.1098 N
Compressive Stress: 155.3157 KPa
Max Compressive Force (PVC 40): 66.2 MPa
Safety Factor: 426.2
Recovery System Backup
# CPE: Recovery System Requirements

<table>
<thead>
<tr>
<th>FR 7</th>
<th>Aircraft and associated systems shall be modular to support future modifications, repairs, and to fit in a truck bed for transportation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR 7.1</td>
<td>Each capture system component fits within 168 x 122 x 46 cm container.</td>
</tr>
</tbody>
</table>

- Recovery System Structure made from 9cm outer diameter PVC pipe
- Max section length 168 cm
- Total sections required 34
- Smaller sections can be stored end-to-end
- 39+ sections will fit 22 lengthwise rows
- Stored 13 across, 2 up

fits 165x117x18 cm space < 168 x 122 x 46 cm space

.: FR 7, DR 7.1 Satisfied
Bungee Attachment, Cleat, And Double Pulley View

Swivel Pulley and Net attachment View
Connection Details

- Bungee/Pulleys are connected and rope is guided through ¼” eyebolts, 2200lb working load
- Connections between eyebolts/pulleys and between lines are made with ¼” quick links
- Rope and Bungee both have 3/16” diameter
- Rope has 400 N working load
- Cam Cleat has 850 N working load, accepts up to ¼” rope
- All pulleys and quick links have at least 1870 N working load
Tipping and Sliding Calculation

- CG location of net structure is 2.6 meters in front of and 0.61 meters above pivot
- If CG is tipped above pivot, CG will be raised to 2.3 meters
- Structure mass  69 kg
- 1135.5 J required to fully tip structure, > 572 J Capture force
- Tipping risk further mitigated with sandbags on forward supports

- 69 kg structure has 676 N normal force
- Expected coefficient of friction at least 1 (Helipad nonskid)
- $F_k = 676 \text{ N} > \text{ Maximum capture force of 395 N, Will not slide}$
Electronics Backup
Aerial Vehicle Design Requirement

**DR 2.3**
The aircraft shall have a climb rate of 5 m/s

5 m/s climb rate requires a motor with:
- 812 W Power
- 30.3 N Thrust

**Selected Electric Motor**
Model: PROPDRIVE v2 5060 380KV
Specifications
KV: 380 KV
Continuous Power: 1500 W

\[ T = C_t \rho n^2 D^4 \]

**Thrust for Model Aircraft**
- \( C_t \): coefficient of thrust (0.09, Garner reference)
- \( \rho \): air density (0.00238 slug/ft\(^3\), sea level)
- \( n \): revolutions per second (141 rev/s, spec. sheet)
- \( D \): diameter of the propeller (1.25 ft spec. sheet)

**Calculated Thrust**: 46.3 N > 30.3 N
- > 812 W
- Fulfills 5 m/s climb rate

∴ **DR 2.3 Satisfied**
Electronics Layout

- Battery
- Battery Eliminator Circuit
- Flight Controller
- RC Receiver
- Flight Computer
- Pitot Sensor
- GPS
- Servos
- Electronic Speed Controller
- Telemetry Radio
- Camera
- Motor

Legend:
- Power
- Control Signal
- Data
Climb Power

Given: Velocity = 20 m/s, Climb Rate = 5 m/s
Weight = 111.12 N, L/D = 12, t = 0.05 hr
Need: Power [W] = Thrust [N] * Velocity [m/s]

Climb Angle Equation:
\[ \sin(\gamma) = \frac{(\text{Thrust} - \text{Drag})}{\text{Weight}} \]

Aim for climb rate of 5 m/s and maintain speed at 20 m/s
From a): \[ \gamma = \sin^{-1}(5 / 20) = 14.5^\circ \]
Solve Climb Angle Equation for Thrust
\[ \text{Thrust} = \text{Weight} \cdot \sin(\gamma) + D \]
\[ = 30.43N \]
Power = 30.43 N * 20 m/s = 608.62 W
Assuming 0.75 efficiency
Power = 792 W

Energy Required = 792 * 0.05 = 39.6 Whr
Cruise Power

Power in Flight:
\[
\text{Power [W]} = \text{Thrust [N]} \times \text{Velocity [m/s]}
\]

Given L/D = 12

Assuming Steady Level Flight
\[
\text{Lift} = \text{Weight} = 89 \text{ N}
\Rightarrow \text{Thrust} = 7.4 \text{ N}
\]

Using Computed Thrust and Velocity
\[
\text{Power} = 7.4 \times 20 \text{ m/s} = 1748 \text{ W}
\]

Assuming propulsion efficiency of 0.75
\[
\text{Power} = 198 \text{ W}
\]

100 km range with 20 m/s speed \(\Rightarrow\) time = 1.4 hrs
\[
\text{Energy Required} = \text{Power [W]} \times \text{time [hr]}
\]
\[
= 198 \times 1.4 = 277 \text{ Wh}
\]
FR 6- Component Current Draw Tests
Verify advertised current draw in each component (Radio, GPS, Pixhawk, Servo etc.)

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Expected Result</th>
<th>Off-Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confirm Components’ Current Draw</td>
<td>Actual component current draw is within 10% error of advertised current draw</td>
<td>Reduce required range of mission.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Location</th>
<th>Requirements</th>
<th>Satisfied?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply</td>
<td>ITLL</td>
<td>Able to Supply 5V to component</td>
<td>Access to Power Supplies</td>
</tr>
<tr>
<td>Ammeter</td>
<td>ITLL</td>
<td>Able to measure up to 65A of current</td>
<td>Access to Ammeter</td>
</tr>
</tbody>
</table>
Electronics Diagram

- RC Receiver
- GPS
- Camera
- Telemetry Radio
- Flight Controller
- Flight Computer
- Sensor Board
- ESC
- BEC
- Motor
- Airspeed Sensor
- Port Servo
- Starboard Servo
- Battery
- 5V/.04 A
- 5V/.250 A
- 5V/.350 A
- 5V/1 A
- 5V
- 22.2V
- I = 14.6 - 65.6 A
From Electronic Layout

Needed Wire Gauge:
- Copper Size 4 between battery, sensor board, ESC, and motor.
- Copper Size 18 for everything else

Heat Generation:
- 6S Batteries typically have internal resistance of 6 milliohms. (Will verify during battery endurance test). At 15A → 1.35 W of heat generation.
- ESC internal resistance .0022 Ohms. At 15A → .495 W of heat generation.
- Motor is assumed to have 75% efficiency → 25% of energy supplied is heat. Supplied power is 22.2V at 15A is 333W → 83.25 W of heat generation.
- Total BOTE heat generation: 85W

\[ Q = IV = I^2R \]

- Q: heat generation
- I: Current
- V: Voltage
- R: Resistance
Nav/Comm Backup
DR 3.2  Aircraft shall capture and transmit images to ground station at 1/60 Hz.

- Image capture and transmission accomplished with mavimage.
  - Written in Python (to lower development time).
  - UML class diagram complete.
  - 22 classes in design.
- Ground station receiving of images and saving to disk also accomplished with mavimage.
- Images sent over telemetry link. mavtables used to mix image and telemetry packets.
  - Written in C++17 (to increase runtime speed).
  - UML class diagram complete.
  - 32 classes in design.
- Requires 70.0 kbps (95.0 kbps of download available)

UML diagrams in backup slides and can be provided at full resolution upon request.
Software Overview
mavimage Overview
mavimage UML Class Diagram
CPE: Nav/Comm Requirements

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UML diagrams in backup slides and can be provided at full resolution upon request.
mavimage UML Class Diagram (overview)
Mavtables Overview
mavtables UML Class Diagram (overview)
mavtables UML Class Diagram
mavlogger Overview

- UDP Socket
- pymavlink (MAVLink)
- Packet Decoder
- Log File
- Filesystem
mavlogger UML Class Diagram
Image Resolution

- 1920x1080 (2MP) - downsampled
- $62^\circ$ FOV (field of view)
- 0.6m x 0.6m pixel size
- Adult sperm whale: ~16m x 3m
- 1920x1080 is sufficient to see a whale sized object.

Modified from: http://a.abcnews.com/images/US/ap_ca_whales_3_141007_4x3_992.jpg
Image Transfer Rate

- 1920x1080 resolution.
- Compress images using WebP.
- 2 x the compression of JPEG.
- <70 kbps at 1/60 Hz frame rate.

895 (1920x1080) frames from https://youtu.be/0J3ctN-u2h4 used for compression analysis.
## Datalink Budget

<table>
<thead>
<tr>
<th>Group</th>
<th>Up (kbps)</th>
<th>Down (kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual Cockpit (telemetry)</td>
<td>0</td>
<td>10.5</td>
</tr>
<tr>
<td>Status Information</td>
<td>0</td>
<td>6.9</td>
</tr>
<tr>
<td>Image Transfer</td>
<td>0</td>
<td>70.0</td>
</tr>
<tr>
<td>Waypoints/Mission Editing</td>
<td>infrequent</td>
<td>0</td>
</tr>
<tr>
<td>Needed</td>
<td>N/A</td>
<td>87.2</td>
</tr>
<tr>
<td>Available</td>
<td>12.5</td>
<td>112.5</td>
</tr>
<tr>
<td>Remaining</td>
<td>N/A</td>
<td>25.3</td>
</tr>
</tbody>
</table>

Can upload ~330 mission items (waypoints) per second with 12.5 kbps.
Testing Backup
## Aircraft Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Test set-up</th>
<th>Facilities/equipment</th>
<th>Off ramps</th>
<th>So What?</th>
<th>Safety</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Loading test</td>
<td>Wing Spar experiences loading similar to flight/Whiffle tree configuration</td>
<td>ITLL/ Weights</td>
<td>Rethink wing materials</td>
<td>Validate the wing loading model during flight, wings won’t snap off</td>
<td>Unpredictable behavior of wing snap</td>
<td>Pre TRR</td>
</tr>
<tr>
<td>Half scale flight test</td>
<td>Launch half scale</td>
<td>Open space, camera</td>
<td>Adjust model</td>
<td>Validate stability models and L/D</td>
<td>Crashing</td>
<td>Week of 1/15/18</td>
</tr>
<tr>
<td>Magnet Pull Test</td>
<td>Apply different load to winglets</td>
<td>ITLL, Force gauge</td>
<td>Rethink solution</td>
<td>Validate the wing tips will stay secure during flight but may fall off in recovery</td>
<td>Strong magnets</td>
<td>Pre TRR</td>
</tr>
</tbody>
</table>
## Launch Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Test set-up</th>
<th>Facilities/equipment</th>
<th>Off ramps</th>
<th>So What?</th>
<th>Safety</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bungee/Rope Test</td>
<td>Tensile machine</td>
<td>Tensile machine/ITLL</td>
<td>Can add more or less bungees</td>
<td>The Bungee will provide enough force for the aircraft to get into the air and fly without LOV</td>
<td>Talk to Dan about testing specimens such as this</td>
<td>Week of 1/15/18</td>
</tr>
<tr>
<td>Dolly speed test</td>
<td>Set dummy weight and launch</td>
<td>Open space, camera, tripod</td>
<td>Can add more or less bungees</td>
<td>Prove the speed is sufficient after all launch components are integrated</td>
<td>Dummy weight launched</td>
<td>Post TRR</td>
</tr>
<tr>
<td>Dolly rope test</td>
<td>Drop weight from height to simulate jerking force</td>
<td>ITLL, weights, camera</td>
<td>Stronger material for Dolly</td>
<td>Validates the dolly force model</td>
<td>Dropping weights can be unpredictable</td>
<td>Week of 1/15/18</td>
</tr>
<tr>
<td>Rails bending test</td>
<td>Apply expected loads to rails</td>
<td>ITLL, potentiometers, camera (First iteration)</td>
<td>Stronger material for Dolly</td>
<td>Validate deflection model</td>
<td>Rail can snap, but highly unlikely</td>
<td>Week of 1/15/18</td>
</tr>
</tbody>
</table>
## Recovery Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Test set-up</th>
<th>Facilities/equipment</th>
<th>Off ramps</th>
<th>So What?</th>
<th>Safety</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hook Test</td>
<td>Hook thrown into net with dummy payload</td>
<td>ITLL</td>
<td>Rethink hook design</td>
<td>Critical for hook to grab on to the net</td>
<td>Sharp hook</td>
<td>Week of 1/15/18</td>
</tr>
<tr>
<td>PVC Tensile Test</td>
<td>Tensile machine</td>
<td>Tensile machine/ ITLL</td>
<td>Rethink material</td>
<td>The PVC will provide enough structure for recovery</td>
<td>Talk to Dan about testing specimens such as this</td>
<td>Week of 1/15/18</td>
</tr>
<tr>
<td>Bungee Test</td>
<td>Bungee tied to fish scale</td>
<td>ITLL, weights, camera</td>
<td>Can add more or less bungees</td>
<td>Validates the elastic bungee model for recovery</td>
<td>High bungee tension can snap</td>
<td>Week of 1/15/18</td>
</tr>
<tr>
<td>Net Test (First iteration)</td>
<td>Set up net system</td>
<td>ITLL, accelerometers, camera (First iteration), Dummy weight</td>
<td>Stronger net, New configuration</td>
<td>Validate recovery g force model</td>
<td>Net can throw back dummy weight</td>
<td>Post TRR</td>
</tr>
</tbody>
</table>

### So What?
- **Hook Test**: Sharp hook is critical for the hook to grab on to the net. A week of 1/15/18 for tests.
- **PVC Tensile Test**: The PVC will provide enough structure for recovery. Week of 1/15/18.
- **Bungee Test**: Validates the elastic bungee model for recovery. Week of 1/15/18.
- **Net Test (First iteration)**: Validates recovery g force model. Post TRR.
## Communication Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Test set-up</th>
<th>Facilities/equipment</th>
<th>Off ramps</th>
<th>So What?</th>
<th>Safety</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data-Link Range Test</td>
<td>radios 12 km apart, ground station config involving rfd900+, Yagi, and PC. UAV config involving rfd900+ and power supply. Radios configured to day-in-the-life settings</td>
<td>Laptop, 2 rfd900+ 900 Mhz 10 element yagi antenna 2 900Mhz 1/4 wave monopole antennas 5V power supply FTDI cable</td>
<td>If the required data rates fail to function at 12 km, the range of the mission shall be decreased to achievable levels</td>
<td>By successfully transferring an image at the required data rates qualifies the comm system for being able to operate successfully abiding by mission requirements.</td>
<td>Travel locations could be hazardous</td>
<td>Week of 2/1/18</td>
</tr>
<tr>
<td>Test</td>
<td>Test set-up</td>
<td>Facilities/equipment</td>
<td>Off ramps</td>
<td>So What?</td>
<td>Safety</td>
<td>Date</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------------------</td>
<td>-----------------------------------------------</td>
<td>------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Component Testing</td>
<td>Circuit board laid out</td>
<td>Multimeter Banana clips Oscilloscope Power supply</td>
<td>Power budget can adjust</td>
<td>Must confirm power budget, range of aircraft could be reduced</td>
<td>Can fry a component, blow up</td>
<td>Post TRR</td>
</tr>
<tr>
<td>Motor Test</td>
<td>Motor hooked up to power source</td>
<td>Oscilloscope Multimeter Power supply</td>
<td>Change motor, decrease range</td>
<td>Need to validate the thrust output</td>
<td>Can blow up</td>
<td>Pre TRR</td>
</tr>
<tr>
<td>Battery Endurance Test</td>
<td>Battery hooked up to resistor load and voltmeter</td>
<td>Oscilloscope Multimeter Power Supply Resistors</td>
<td>Decrease range</td>
<td>Need to validate battery endurance</td>
<td>Can blow up</td>
<td>Pre TRR</td>
</tr>
</tbody>
</table>
## Software Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Test set-up</th>
<th>Facilities/equipment</th>
<th>Off ramps</th>
<th>So What?</th>
<th>Safety</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autopilot HIL Test</td>
<td>Connect Pixhawk to computer with FTDI cable. Connect Pixhawk with XPlane. Connect QGroundControl to Pixhawk.</td>
<td>Pixhawk 2.1, USB cable, XPlane, QGroundControl</td>
<td>Adjust software</td>
<td>Validate the autopilot can control the aircraft</td>
<td>Eye strain</td>
<td>Post TRR</td>
</tr>
<tr>
<td>Full Software Integration Test</td>
<td>Requires all electronics and communications to be fully integrated and setup.</td>
<td>All electronics and a laptop</td>
<td>Remove image capture</td>
<td>Software works as expected</td>
<td>Eye strain</td>
<td>Post TRR</td>
</tr>
<tr>
<td>mavtables/image Unit Tests</td>
<td>Built in unit testing of classes</td>
<td>N/A</td>
<td>Fix it</td>
<td>Testing every interface of every class</td>
<td>Eye strain</td>
<td>On going</td>
</tr>
</tbody>
</table>
OLD SLIDES
Baseline Design

Purpose/Objectives
Design Solutions
Critical Project Elements
Requirements Satisfaction
Project Risks
Verification and Validation
Project Planning
# Baseline Design Selection

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Takeoff</th>
<th>Landing</th>
<th>Autopilot</th>
<th>Flight Computer</th>
<th>RF Comm.</th>
<th>Power / Electronics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and Validate Airframe</td>
<td>Bungee Launch with Rail</td>
<td>Net with Extending Posts</td>
<td>PX4 Pro with Pixhawk 2.1</td>
<td>Raspberry Pi 3 Model B</td>
<td>RFD900+ Datalink OpenLRS RC</td>
<td>Batteries (Electric)</td>
</tr>
</tbody>
</table>
Landing System

- **Net** suspended between two poles
- **Pulley connections**
- **Extension of net reduces forces** upon landing and **closes the net to capture aircraft**
- **Hook on nose** of aircraft will **catch the net to prevent impact** with ground
- **Tension** is required in net to *slow the aircraft* to a stop

- Tension is provided to lines by *friction* from a *weight* being *dragged along the deck*

- Weight will be *guided by rails* placed behind the net

- Weight will be *provided by seawater* to provide *easier transportation*
Nav/Comm Requirements

NCR.1: Autonomous mission (follow waypoints).

NCR.2: Stream captured (1920x1080) images to the ground station at a rate of at least 1/60 Hz.

NCR.3: Virtual cockpit (for beyond line of sight operations).
Antennas - Ground Station

- **900 Mhz 15 element Yagi directional antenna** (datalink)
  - Long range
  - 25 dbi gain
  - 30 degree horizontal beamwidth
  - Manually pointed

- **900 Mhz Omnidirectional Antenna** (datalink)
  - Short Range
  - Vertical linear polarization

- **433 Mhz ¼ wave monopole** (RC)
  - Plug and play with Open LRS
Antennas - UAV

- 900 Mhz ¼ wave monopole (x2)
  - Vertical and horizontal linear polarization
  - RP-SMA connectors
  - 2.1 dBi gain

- 433 Mhz ¼ wave monopole
  - Plug and play with OpenLRS
GNC comm

- How is each element communicating?
- ** Data rates
Aircraft Sizing

Known: battery mass (2.65 kg), payload weight (2.27 kg), mass fraction of structure, motor, small electronics

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass Fraction</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>.35</td>
<td></td>
</tr>
<tr>
<td>Electric Motor</td>
<td>.05</td>
<td></td>
</tr>
<tr>
<td>Autopilot, Flight Computer, RC electronics, Communication System</td>
<td>.05</td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td></td>
<td>2.65 kg</td>
</tr>
<tr>
<td>Payload</td>
<td></td>
<td>2.00 kg</td>
</tr>
</tbody>
</table>

Remaining Mass Fraction: 0.55
Current Mass: 4.65 kg
### Aircraft Sizing

**Requirement:** The aircraft shall have a maximum takeoff weight at or under 22.7 kg.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass Fraction</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>0.35</td>
<td>2.96 kg</td>
</tr>
<tr>
<td>Electric Motor</td>
<td>0.05</td>
<td>0.42 kg</td>
</tr>
<tr>
<td>Autopilot, Flight Computer, RC electronics, Communication System</td>
<td>0.05</td>
<td>0.42 kg</td>
</tr>
<tr>
<td>Batteries</td>
<td>0.31</td>
<td>2.65 kg</td>
</tr>
<tr>
<td>Payload</td>
<td>0.24</td>
<td>2.00 kg</td>
</tr>
</tbody>
</table>

\[
\text{mass} = \frac{4.65 kg}{0.55} = 8.45 kg
\]

The aircraft mass 8.45 kg < 22.7 kg maximum \( \therefore \text{Feasible} \)
**Requirement:** Aircraft supports downward-facing 2.0 kg simulated instrument payload with 15 cm x 15 cm x 23 cm dimensions.

Payload Bay has access to downward panel and has dimensions 15 cm x 15 cm x 23 cm. Previous slide shows 2.0 kg mass in weight budget.

∴ Feasible
Center of Gravity & Fuselage Layout

- **Neutral Point**: 72.8 cm from nose (25% Mean aerodynamic chord)

- **Need CG in front of neutral point**

- Components can be moved into tailcone, giving a CG range of 9 cm (61.6 cm - 70.6 cm)

\[
CG = \frac{\sum (\text{weight}_{\text{component}} \times \text{distance from nose})}{\text{weight}_{\text{total}}}
\]
Center of Gravity & Fuselage Layout

Side View

92 cm
31 cm 23 cm 23 cm 15 cm

15 cm

Nose Cone Payload Bay Battery Tail Cone Electronics Bay

Center of Gravity (65.7 cm)

Neutral Point (72.7 cm)

Center of Gravity
Neutral Point
Wing Area and Aspect Ratio

- Wing area $S = 0.93 \text{ m}^2$
  - $W = 84.9 \text{ N}$ (Total aircraft mass = 8.45 kg)
  - Stall speed $V_s = 11.0 \text{ m/s}$
  - $(C_L)_{\text{max}} \approx 1.2$
    - Reynolds number

- Aspect ratio based on span limit of 3 m $\rightarrow$ AR = 10.0

Wing area and coefficient of lift satisfy stall requirement of 11 m/s
Wing Sweep

- Helps satisfy stability and controllability requirements
- Similar aircraft with similar flight missions
**Critical Project Elements**

- **Purpose/Objectives**
- **Design Solution**
- **Project Risks**
- **Requirements Satisfaction**
- **Project Planning**
- **Verification and Validation**

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**L/D**

**Requirement:** The aircraft shall have an L/D of at least 12.

- Historical data (RECUV aircraft and AAA)
- OpenVSP model: $L/D_{\text{cruise}} = 16.2$ (Hoerner estimation)
- $C_L$ at cruise speed:
  \[
  C_L = \frac{W}{0.5\rho V^2 S} = 0.38
  \]
- $L/D$ at cruise:
  \[
  \frac{L}{D} = \frac{C_L}{C_{D0} + \frac{C_L^2}{\pi e A R}} = 16.2
  \]

The aircraft L/D is $16.2 >> 12$, comfortable safety factor considering calculation fidelity

∴ Feasible
Modular Design

Requirement: The aircraft shall be designed to disassemble into a 46 cm x 122 cm x 168 cm shipping container.

- Design will be transported in 5 pieces: Fuselage, 2 separate wings, 2 separate winglets.

<table>
<thead>
<tr>
<th>Part</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage</td>
<td>15 cm x 15 cm x 92 cm</td>
</tr>
<tr>
<td>Half-Wing</td>
<td>5 cm x 41 cm x 152 cm</td>
</tr>
<tr>
<td>Winglet</td>
<td>0.5 cm x 29 cm x 38 cm</td>
</tr>
</tbody>
</table>

Fit together, dimensions are 25.5 cm x 41 cm x 152 cm (less than 46 cm x 122 cm x 168 cm) \(\therefore\) Feasible
Aircraft Stability (half scale)- AVL/Matlab

- Longitudinal eigenvalue locus plot (half scale model)
  - Range of C.G.: approx. 31.5 +/- 7 cm

  Short period mode - very stable

  Phugoid mode - slightly stable for C.G. range of 25.3 cm - 38.2 cm.

  ∴ Half-scale has similar longitudinal stability as full scale, Feasible
Aircraft Stability (half scale) - AVL/Matlab

- Lateral eigenvalue locus plot (half scale model)
  - Range of C.G.: approx. 31.5 +/- 7 cm

Roll mode - very stable

Dutch roll; Spiral modes - slightly stable for C.G. range of 25.3 cm - 38.2 cm.

∴ Half-scale has similar lateral stability as full scale, Feasible
Airfoil

- Thickness
  - Need to get a spar through the wing
  - $C_{L_{\text{max}}}$ required
  - $\Rightarrow \geq 12\%$ thick airfoil
- Reflexed camber
  - Alternative: large wing twist (difficult to get right, little available data)
- Examined most well-known reflexed and low-moment airfoils.
- Examined some custom airfoil modifications
  - Small number of available reflexed airfoils
  - “Does this airfoil perform well with reflex?”
Airfoil

- Joukowski with Horten camber line (12% thickness, 2% camber)
Aircraft Stability- XFLR5

- Longitudinal eigenvalue plot
Aircraft Stability - XFLR5

- Lateral eigenvalue plot
\[ E = mg \Delta h \]
\[ \eta_p E = \frac{mgr}{L/D} \]
\[ \eta_p d_{bat} m_{bat} = \frac{mgr}{L/D} \]

\[ m_{bat} = \frac{mgr}{\eta_p d_{bat} L/D} \]
\[ \frac{m_{bat}}{m} = \frac{rg}{\eta_p d_{bat} L/D} \]
\[ M_{BF} = \frac{rg}{\eta_p d_{bat} L/D} \]

Glide ratio = L/D
Wing Structure Modeling

Requirement: The aircraft shall have an operational limit of 5 g.

- Wing load distribution at 5 g (Prandtl Lifting Line Theory) → 4th order method.
- Looking at carbon spar, EPP foam core, plastic skin.
  - Considering composite skin.
Spring Constant Calculation model

\[ k \Delta x = m_{\text{max}} g \]
\[ k = m_{\text{max}} g / \Delta x \]