CETI | SHAMU

Cetacean **E**cholocation **T**ranslation **I**nitiative

Search and **H**elp **A**quatic **M**ammals **U**AS

Critical Design Review

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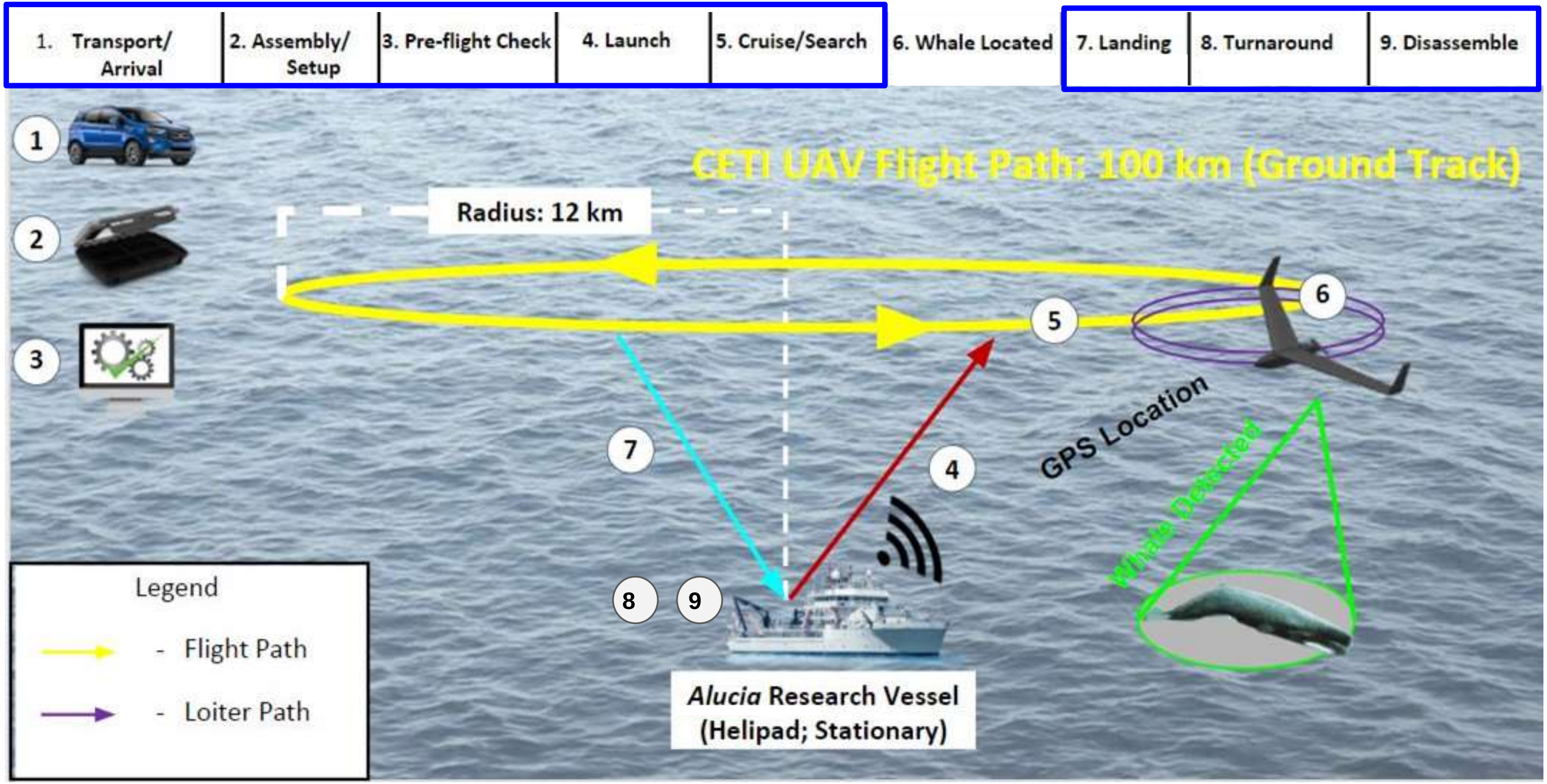
Project Description

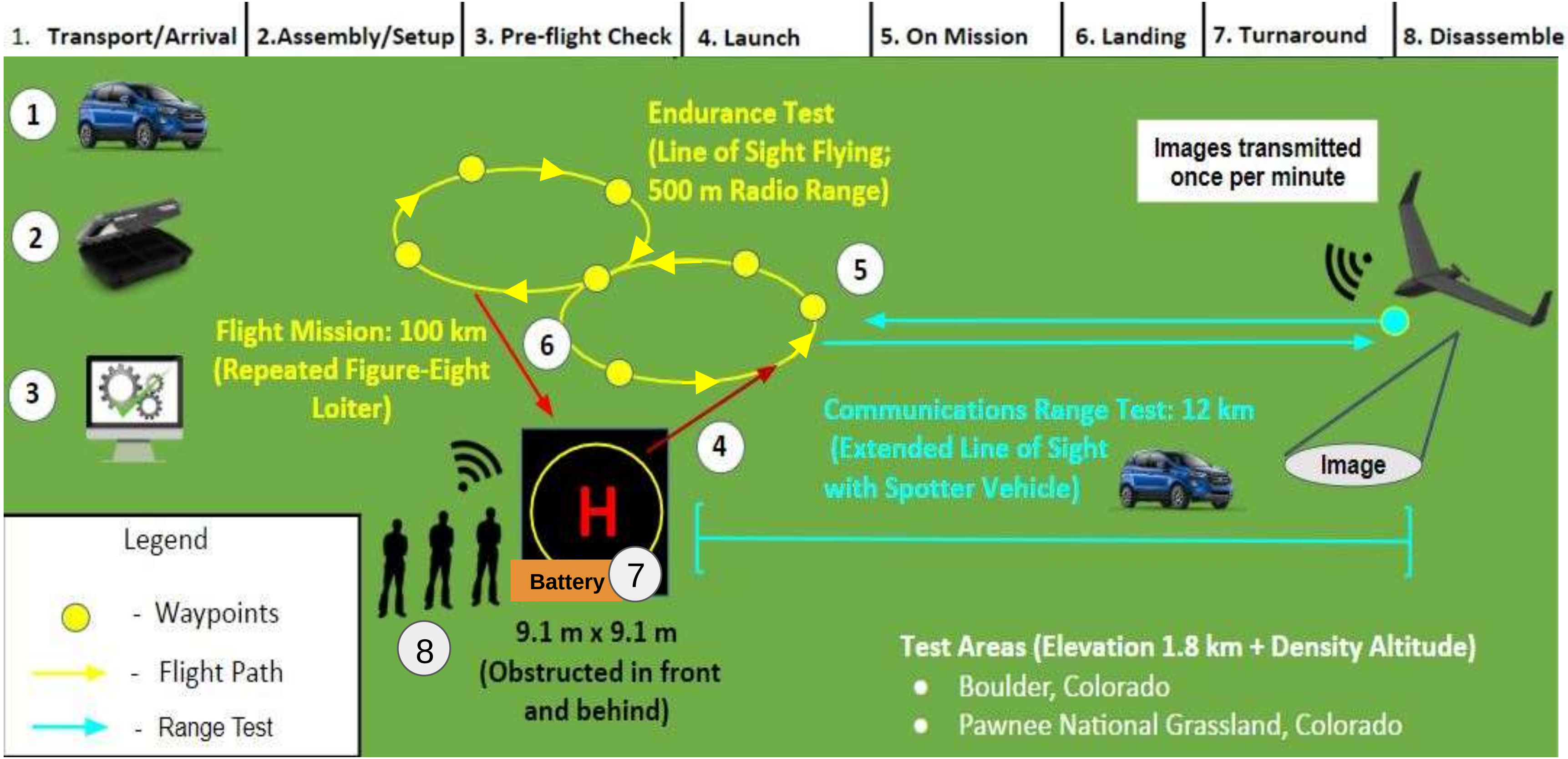
Search and **H**elp **A**quatic **M**ammals **UA**S

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



SHAMU Test CONOPS



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**.

Functional Requirements

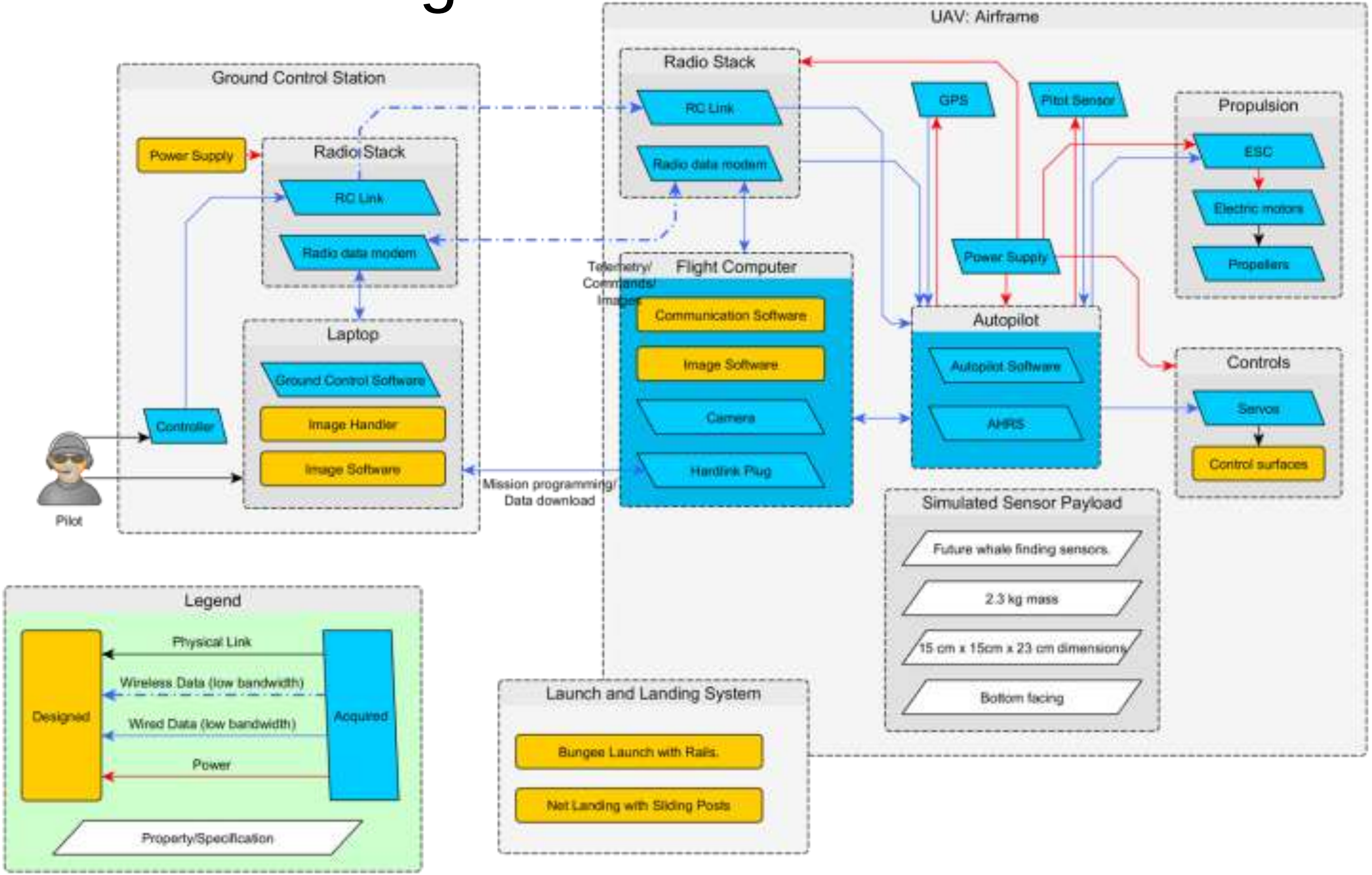
4.	Aircraft shall support **downward-facing 2.0 kg simulated instrument payload** with 15 cm x 15 cm x 23 cm dimensions.
5.	Aircraft shall be **operable and recoverable** onto stationary platform in **winds up to 10 m/s.**
6.	Aircraft shall have **100 km ground track range endurance.**

Design Solutions

Design Solutions

Aircraft	Takeoff	Recovery	Autopilot	Flight Computer	RF Comm.	Electronics
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

Functional Block Diagram



Design Solution

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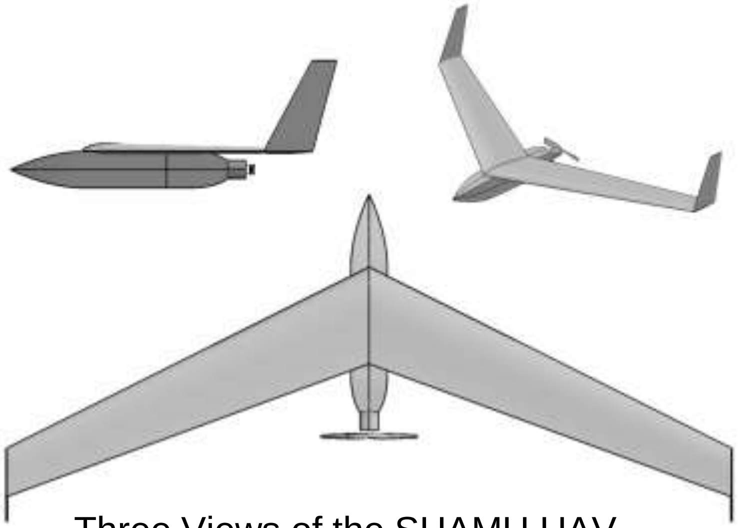
Aircraft Design: Specifications

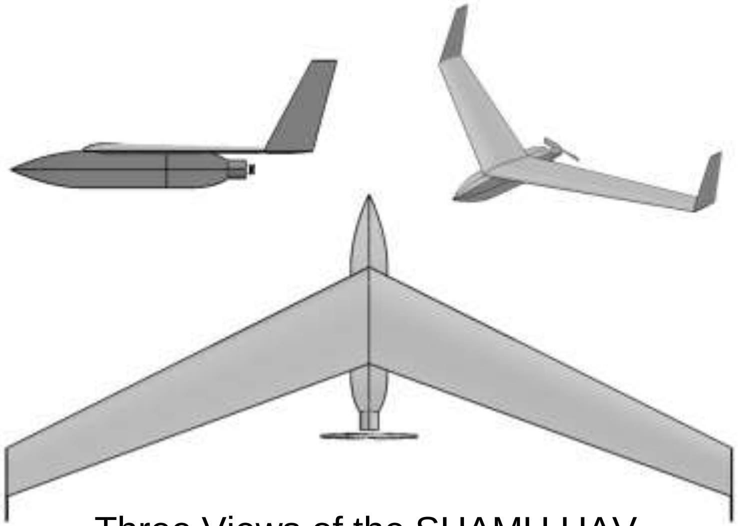
Wing Span	3.0 m (10 ft)
Length	1.4 m (4.5 ft)
Height	0.53 m (1.8 ft)
Wing Area	0.93 m^2 (10 ft^2)
Wing Aspect Ratio	10
Empty Weight	4.5 kg (10 lbs)
Payload Weight	2.0 kg (4.4 lbs)
Gross Weight	8.45 kg (19 lbs)
Motor Power	1300 W (1.74 hp)



Three Views of the SHAMU UAV

Aircraft Design: Performance

Cruise Speed	20 m/s (38 kts)
Stall Speed	11 m/s (20 kts)
Range	100 km (62 mi)
Climb Rate	>5.1 m/s (>1000 ft/min)
Cruise L/D	12 - 16.2
Wing Loading	9.8 kg/m^2 (2.0 lbs/ft^2)

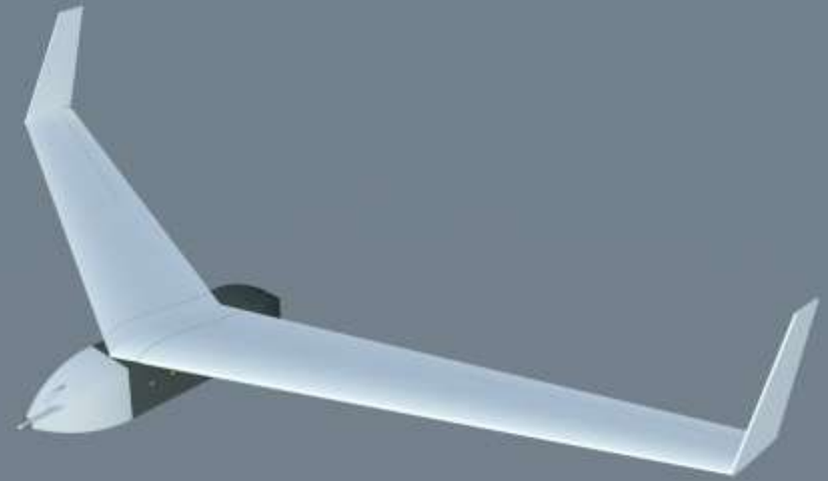


Three Views of the SHAMU UAV

Aircraft Design

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



SolidWorks Rendering of SHAMU Aircraft

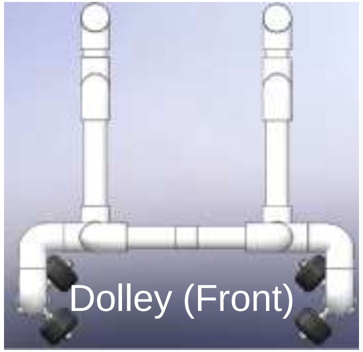
Design Solution

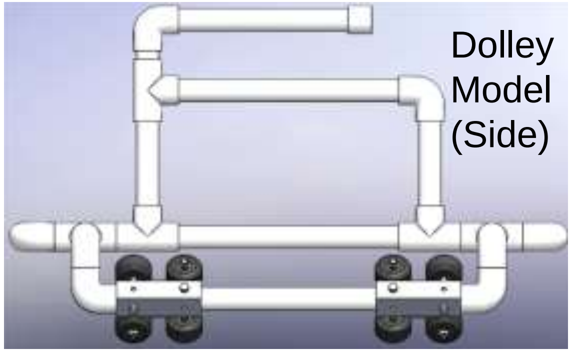
Aircraft	Takeoff	Recovery	Autopilot	Flight Computer	RF Comm.	Electronics
Design and Validate Airframe	Bungee Launch with Rail	Net with Extending Lines	PX4 Pro with Pixhawk 2.1	Raspberry Pi 3 Model B	RFD900+ Datalink OpenLRS RC	Component List

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 (Front)

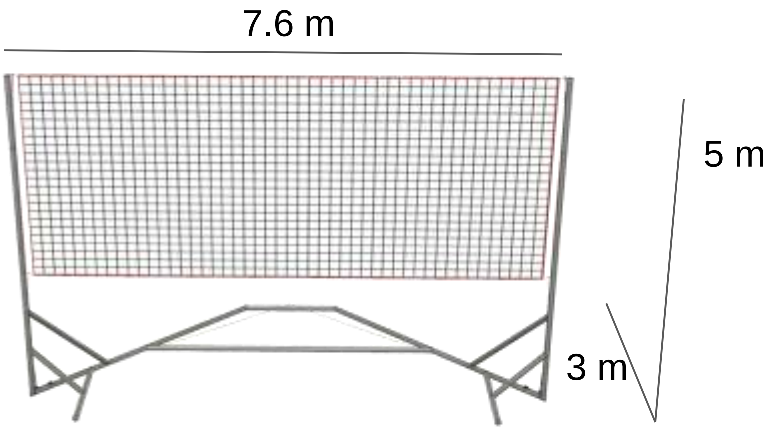

Dolley Model (Side)

Design Solution

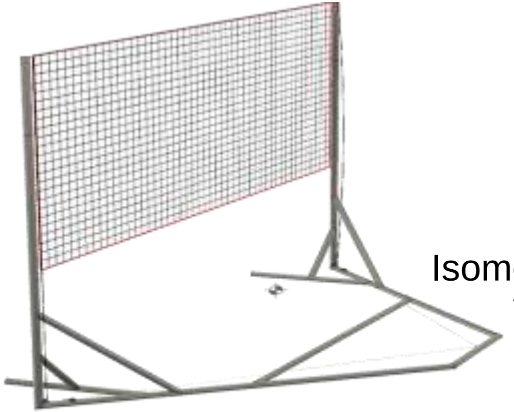
Aircraft	Takeoff	Recovery	Autopilot	Flight Computer	RF Comm.	Electronics
Design and Validate Airframe	Bungee Launch with Rail	Net with Extending Lines	PX4 Pro with Pixhawk 2.1	Raspberry Pi 3 Model B	RFD900+ Datalink OpenLRS RC	Component List

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**



Net Front View

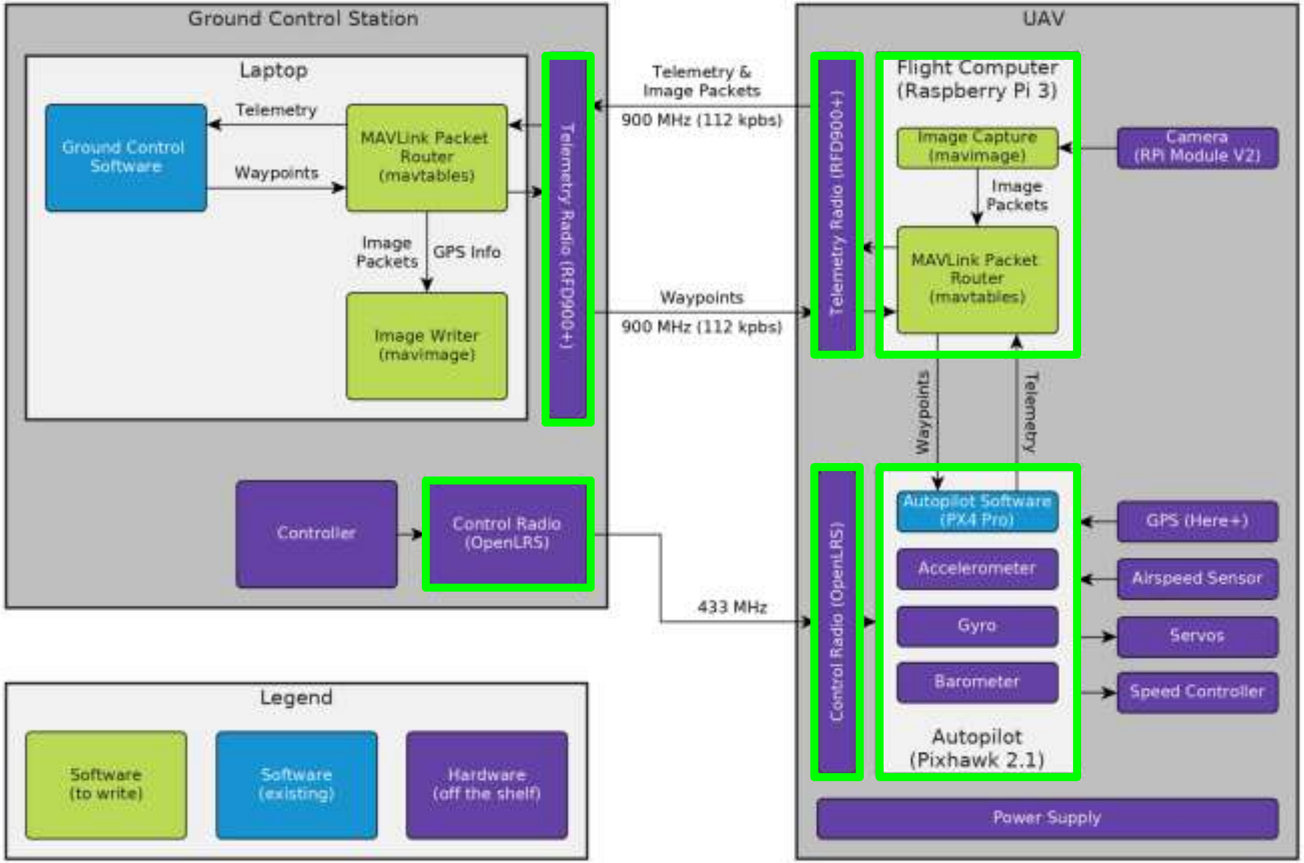


Isometric Back View

Design Solution

Aircraft	Takeoff	Recovery	Autopilot	Flight Computer	RF Comm.	Electronics
Design and Validate Airframe	Bungee Launch with Rail	Net with Extending Lines	Pixhawk 2.1 with PX4-Pro	Raspberry Pi 3 Model B	RFD900+ Datalink OpenLRS RC	Component List

Navigation Hardware/Software Design



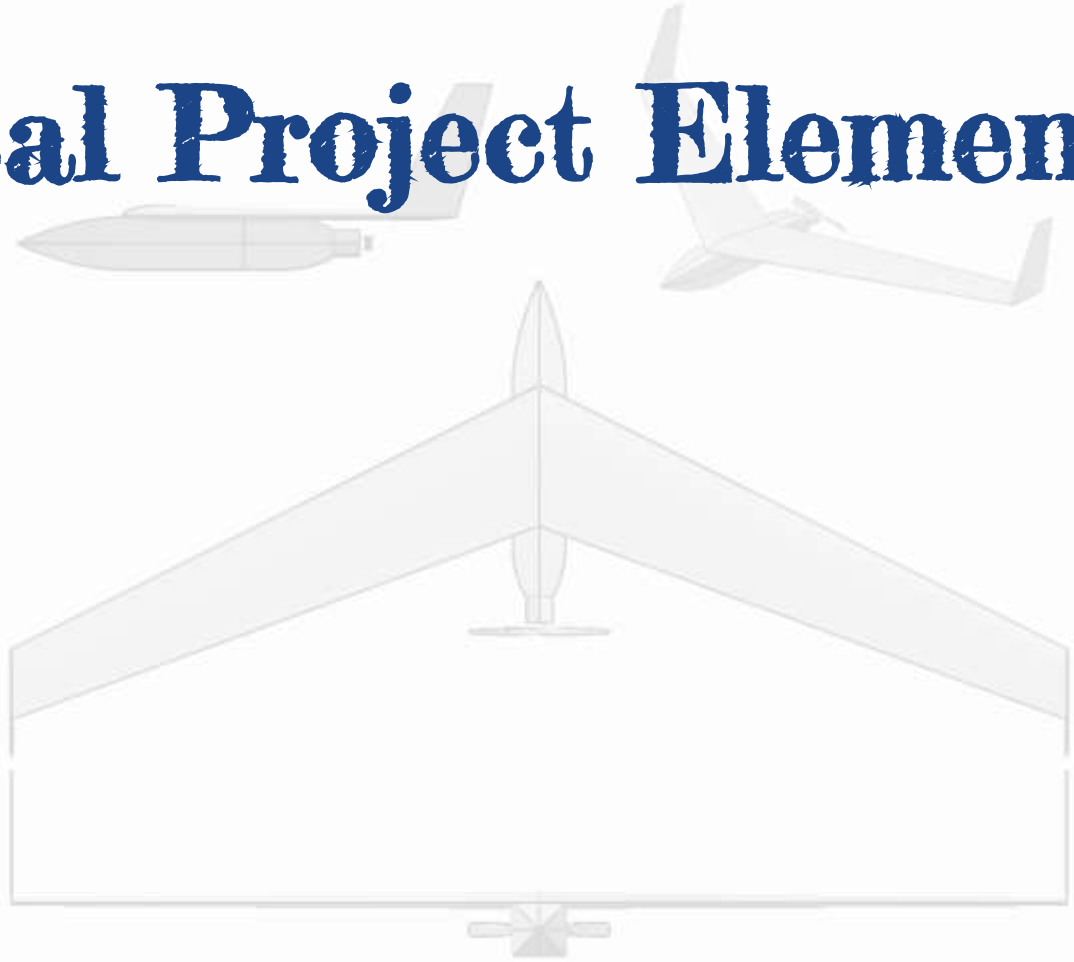
Design Solution

Aircraft	Takeoff	Recovery	Autopilot	Flight Computer	RF Comm.	Electronics
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

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

Critical Project Elements



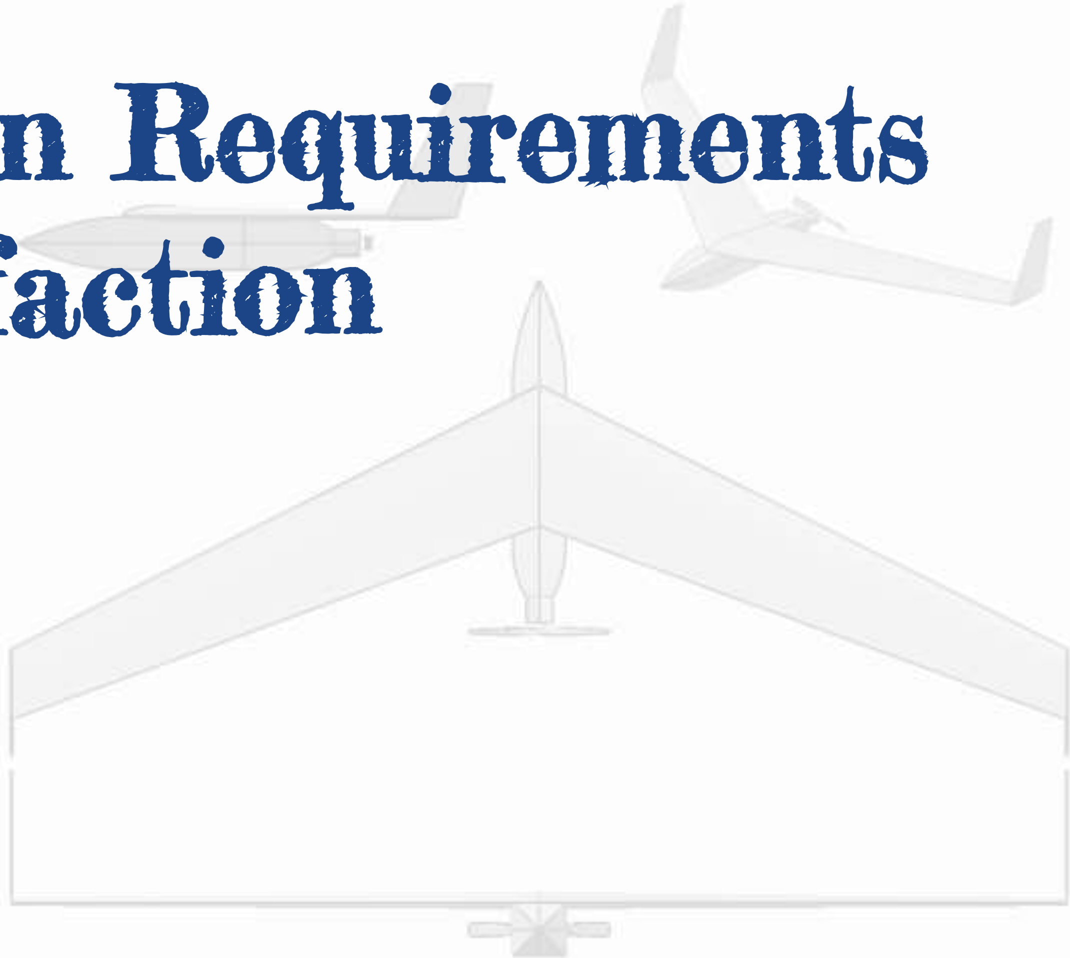
Critical Project Elements

CPE	Requirement Considerations
Aerial Vehicle Design	• **Stability and control** • **Future sensor payload** • **Tradeoff** between **maximizing lift-to-drag** ratio and **structural/manufacturing complexity**
Takeoff and Recovery	• Accelerate/decelerate aircraft under **maximum structural load** • Capability to transport and setup on **9.1m x 9.1m helipad**

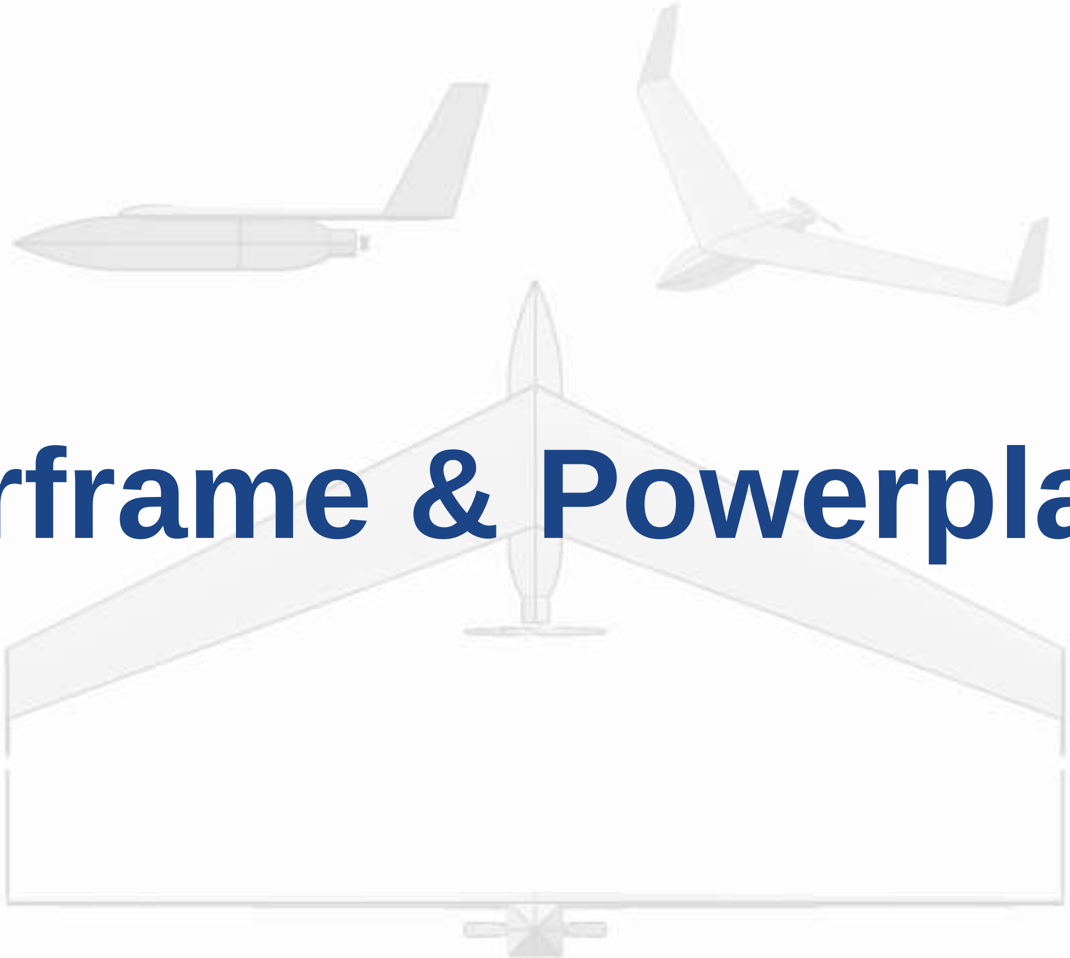
Critical Project Elements

CPE	Requirement Considerations
Communication with Ground Station	• **Communication range of 12 km** from ground station • Transmit images at **one per minute** • Piloted **manual control** • Transmit **updated flight waypoints** • Transmit **telemetry** to ground station
Flight Computer / Autopilot	• Collects **sensor data** for virtual cockpit • Autopilot keeps aircraft in **steady, level flight** • Accepts **flight waypoints** and **executes**

Design Requirements Satisfaction



Airframe & Powerplant



CPE: Aerial Vehicle Design Key Requirements

FR 1	The aircraft shall operate in remotely piloted and fully autonomous modes throughout all phases of flight.
DR 1.1	The aircraft shall have static longitudinal stability.
DR 1.2	The control system shall provide required control surface deflections for aircraft longitudinal and lateral stability throughout all phases of flight.

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).
DR 2.1	The aircraft shall have a nose hook that sustains 5 g net recovery forces.
DR 2.2	The aircraft wings shall sustain 5 g forces for maneuvers and net recovery.

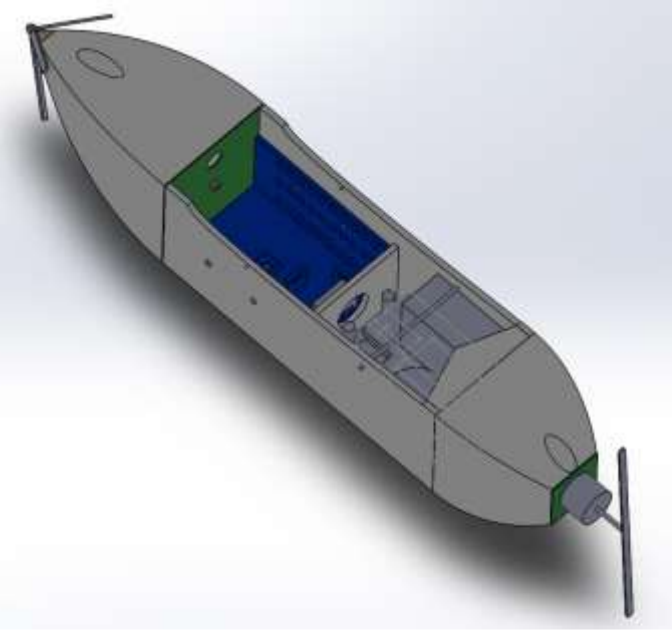
FR 4	Aircraft supports downward-facing 2.0 kg simulated instrument payload with 15 cm x 15 cm x 23 cm dimensions.

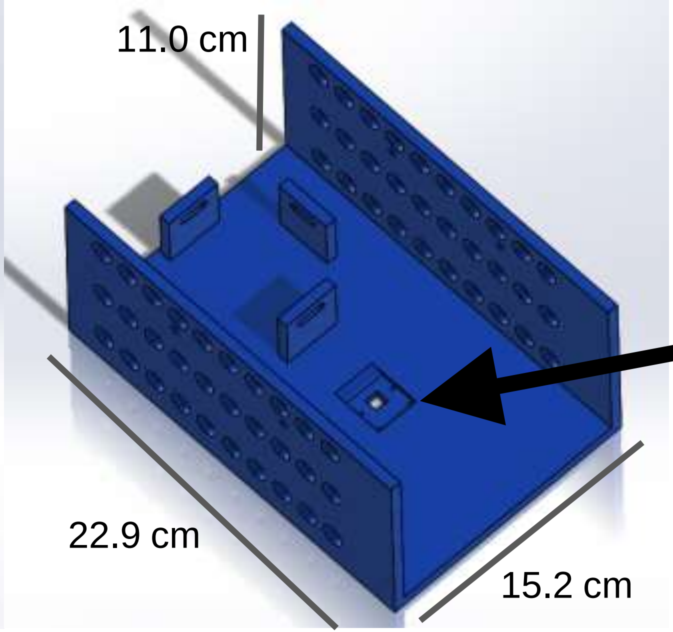
CPE: Aerial Vehicle Design Key Requirements

FR 6	The aircraft shall have a 100 km ground track range.
DR 6.1	The aircraft shall have a lift-to-drag ratio of 12.
DR 6.2	Battery shall have 1.4 hr endurance

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.





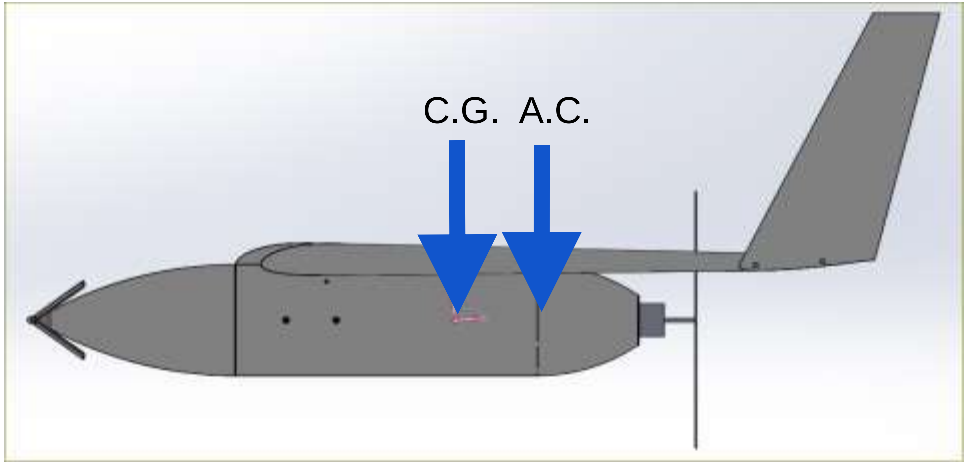
Downward facing RPi Cam mount

∴ **FR 4 Satisfied** ✓

CPE: Aerial Vehicle Design Key Requirements

DR 1.1	The aircraft shall have static longitudinal stability.

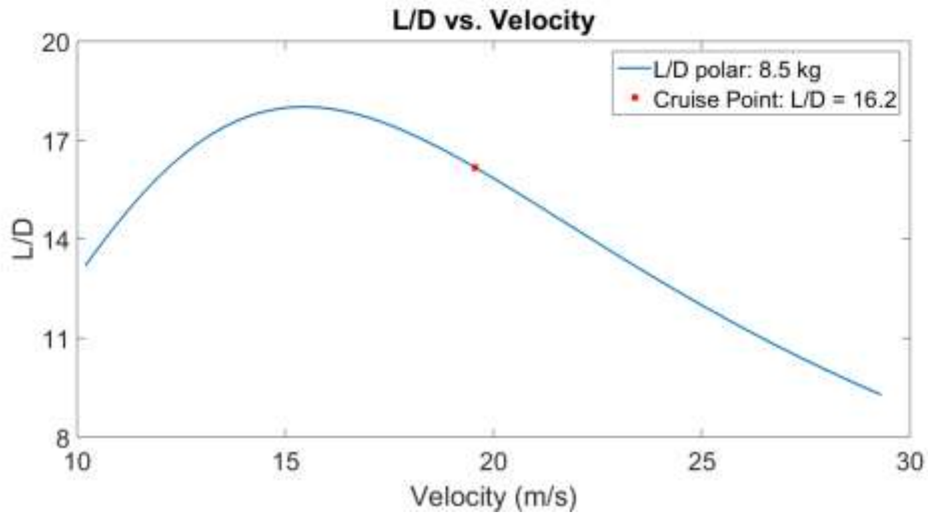
- Aerodynamic center: 71.75 cm behind the nose
    - Including wing and fuselage effects
- Center of gravity w/ 2 kg payload: 64.93 cm behind the nose
- Static Margin: 22.4% (6.82 cm)



∴ **DR 1.1 Satisfied** ✓

CPE: Aerial Vehicle Design Requirements

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



MATLAB L/D prediction

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*

∴ **DR 6.1 Satisfied** ✓

* To be verified by L/D tests in half-scale

CPE: Aerial Vehicle Design Requirements

DR 6.2	Battery shall have 1.4 hr endurance

Component	Power Needed
Motor (Steady Flight)	277 Wh
Motor (Climb)	39.6 Wh
Pixhawk	1.75 Wh
RFD 900+	5.6 Wh
OrangeRX Open LRS	0.28 Wh
Raspberry π w/ Camera	2.45 Wh
Servo	14 Wh
Total Required Energy:	375 Wh

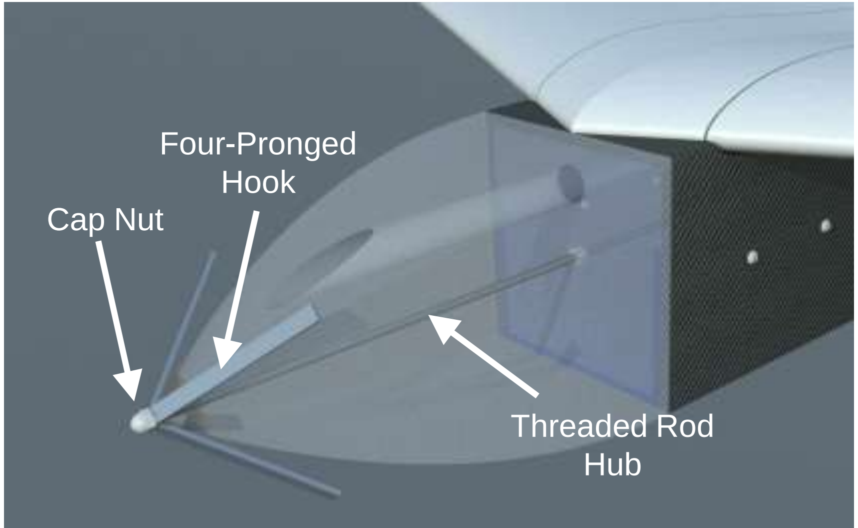
Selected Battery Pack

Tattu 22000mAh 6S 25C 22.2V Lipo Battery Pack
Capacity: 22000 mAh
Voltage: 22.V
Watt-hours: 488 Wh
Available Energy: 390 Wh
Weight: 2.65 kg

390 Wh > 375 Wh
∴ DR 6.2 is satisfied ✓

CPE: Aerial Vehicle Design Key Requirements

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



SolidWorks Rendering: Nose Hook and Threaded Rod Through Nose Cone

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

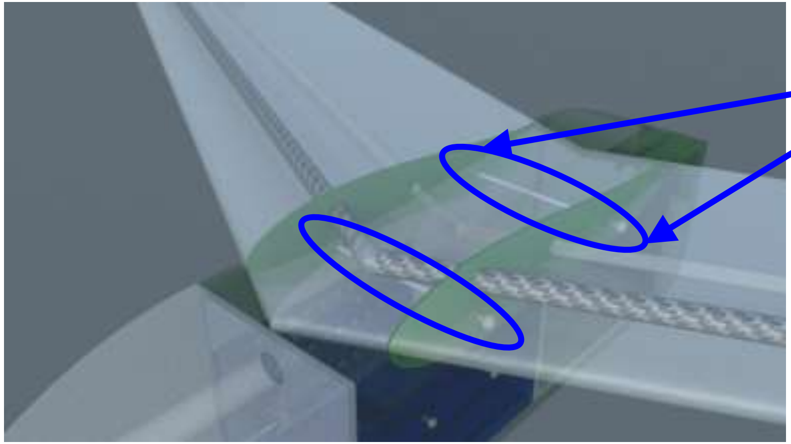
Solution

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

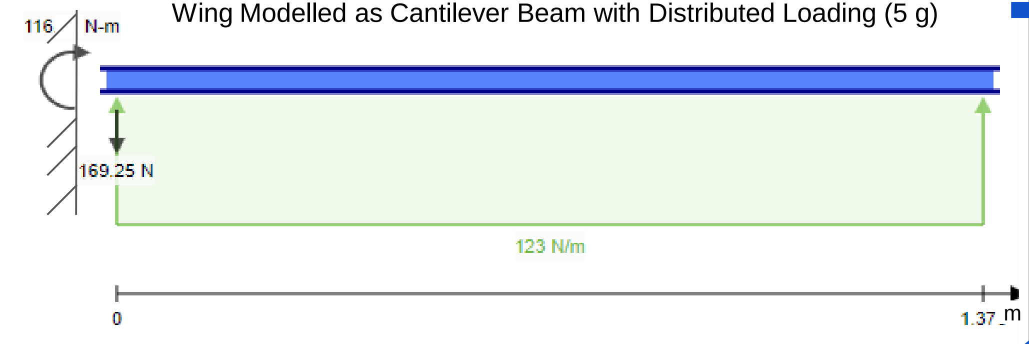
Aluminum (6061) rod:
Shear Strength is 204 MPa

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 Modelled as Cantilever Beam with Distributed Loading (5 g)



Wing spar must sustain

Bending Moment : 116 Nm
Shear Force : 169 N

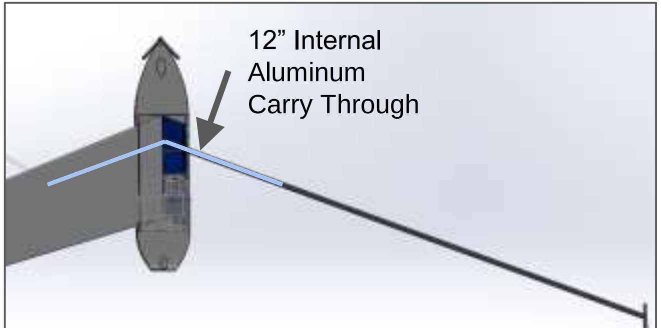
For a (20mm x 18mm Tube)

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** ✓



SolidWorks Rendering: Carbon Spar Along Quarter Chord

CPE: Aerial Vehicle Design Key Requirements

DR 1.2	The control system shall provide required control surface deflections for aircraft longitudinal and lateral stability throughout all phases of autonomous flight.

Controllability:

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

Controllability Matrices

$$\mathcal{C}_{long} = \begin{bmatrix} B_{long} & A_{long}B_{long} & A_{long}^2B_{long} & A_{long}^3B_{long} \end{bmatrix}$$

$$\mathcal{C}_{lat} = \begin{bmatrix} B_{lat} & A_{lat}B_{lat} & A_{lat}^2B_{lat} & A_{lat}^3B_{lat} \end{bmatrix}$$

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

FR 1	The aircraft shall operate in remotely piloted and fully autonomous modes throughout all phases of flight. ✓
DR 1.1	The control system shall provide required control surface deflections for aircraft longitudinal and lateral stability throughout all phases of flight. ✓
DR 1.2	The control system shall provide required control surface deflections for aircraft longitudinal and lateral stability throughout all phases of flight. ✓
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). ✓
DR 2.1	The aircraft shall have a nose hook that sustains 5 g landing forces. ✓
DR 2.2	The aircraft wings shall sustain 5g landing forces. ✓
FR 4	Aircraft supports downward-facing 2.0 kg simulated instrument payload with 15 cm x 15 cm x 23 cm dimensions. ✓

CPE: Aerial Vehicle Design Key Requirements Recap

FR 6	The aircraft shall have a 100 km ground track range.	✓
DR 6.1	The aircraft shall have a lift-to-drag ratio of 12.	✓
DR 6.2	Battery shall have a 1.4 hr endurance	✓

Launch System

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).
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.

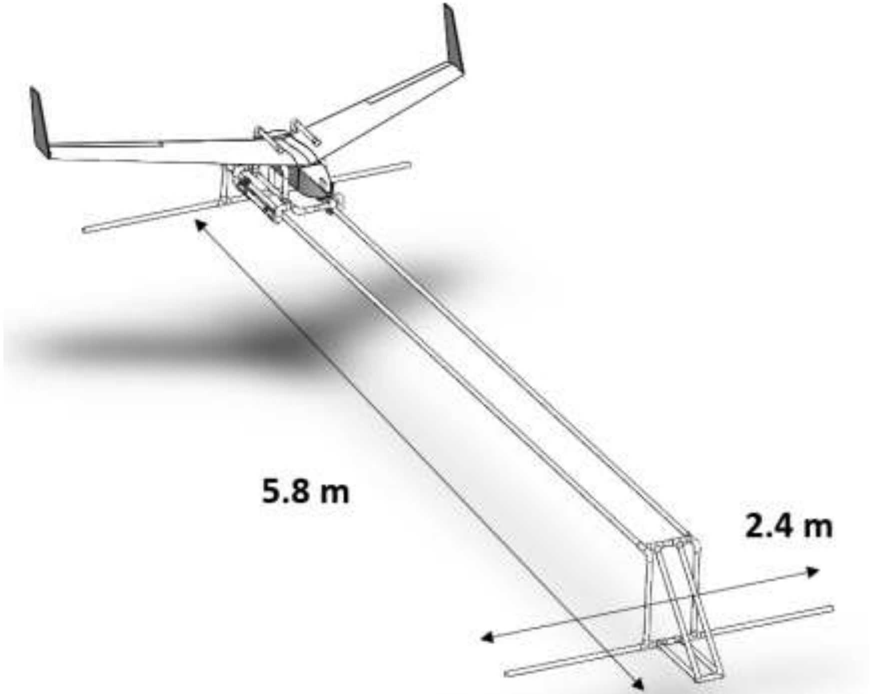
CPE: Launch Design Key Requirements

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 < 9.1m

FR 2 Satisfied ✓



CPE: Launch Design Key Requirements

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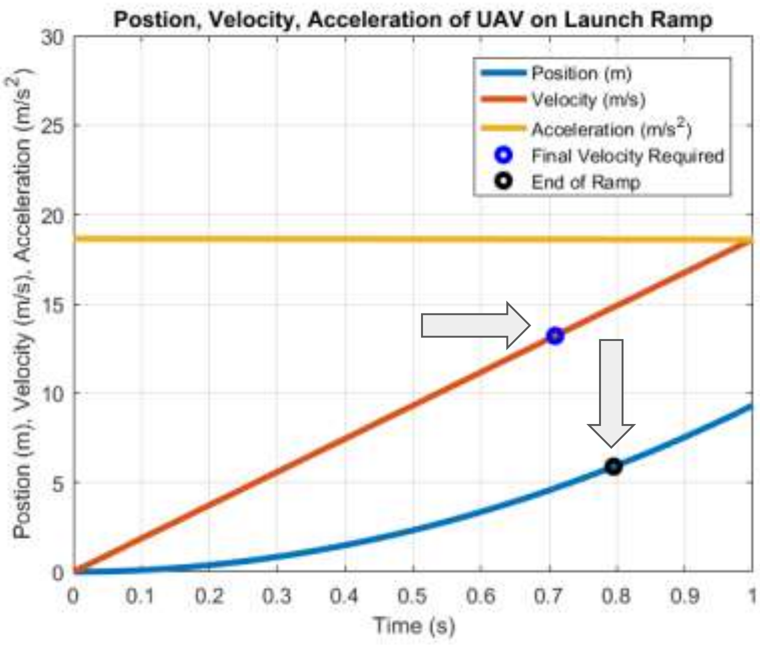


Concerns:
G-force on launch needs to be **< 5 g**
UAV/Cradle speed **≥13.2 m/s by end of ramp** (5.25 m)

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** ✓

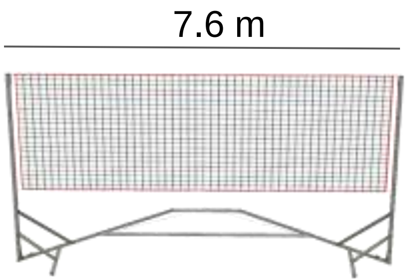
CPE: Launch Design Key Requirements Recap

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).	✓
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.	✓

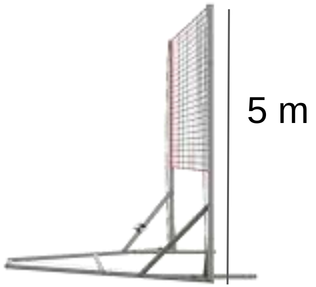
Recovery System

CPE: Recovery System Requirements

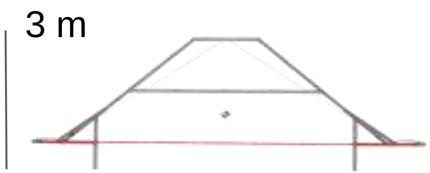
FR 2	Takeoff and land from/to a stationary 9.1 m x 9.1 m platform obstructed fore (represents ship superstructure) and aft (represents ship crane).
DR 2.1	The recovery system shall exert forces on the aircraft under 5 g.
DR 2.2	Capture system shall sustain 5 g aircraft recovery forces.



Front View



Side View



Top View

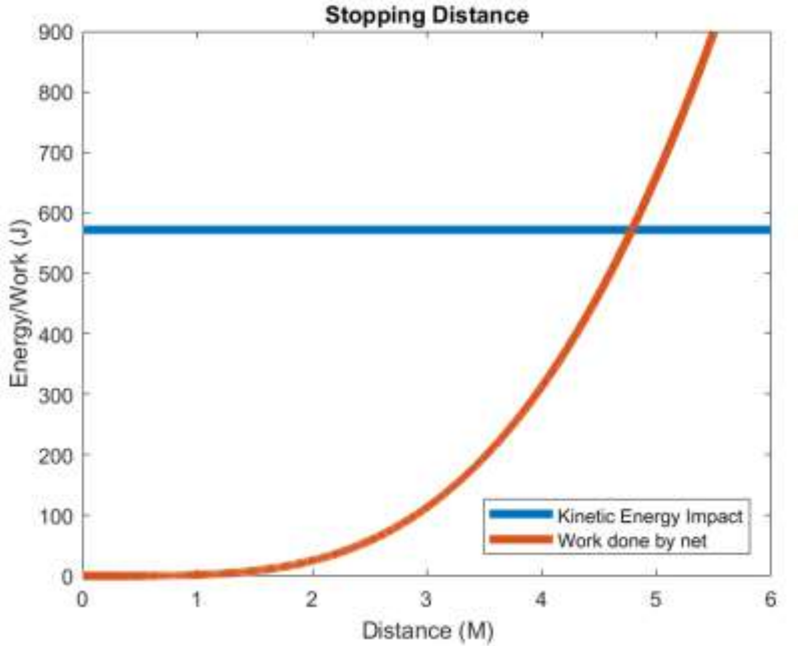
CPE: Recovery System Requirements

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

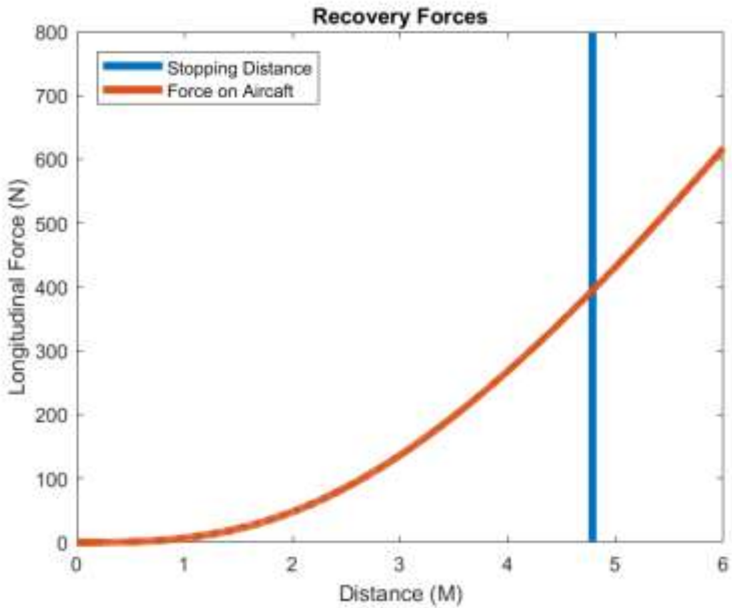
FR 2	Takeoff and land from/to a stationary 9.1 m x 9.1 m platform obstructed fore (represents ship superstructure) and aft (represents ship crane).
DR 2.1	The recovery system shall exert forces on the aircraft under 5 g.

- Recovery System Dimensions:
  7.6 m x 3.0 m < 9.1 m x 9.1 m

∴ FR 2 Satisfied ✓

- Maximum Line Tension 130 N
- Maximum force on aircraft
  395 N = 4.4 g < 5g

∴ DR 2.1 Satisfied ✓



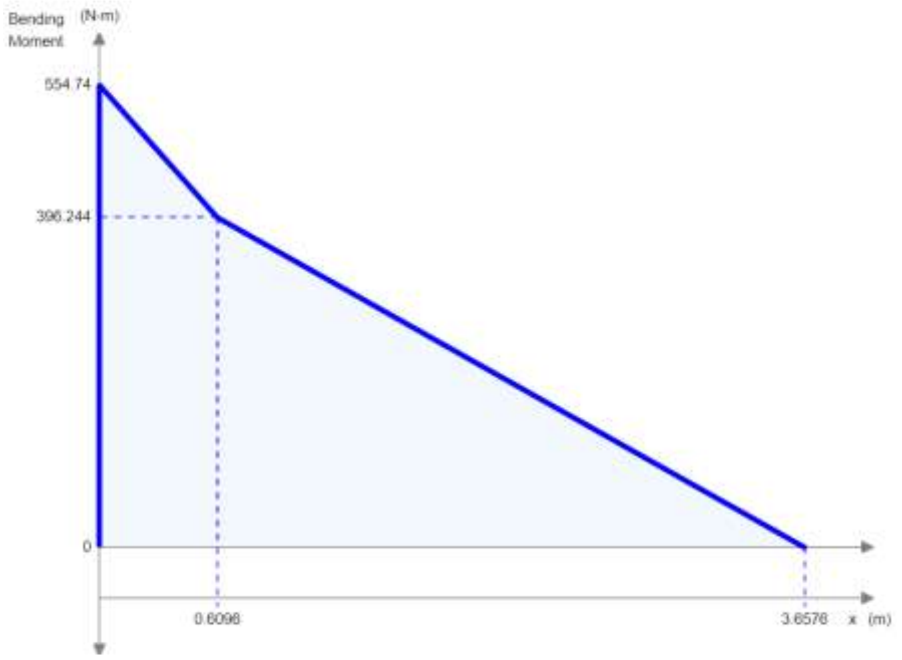
CPE: Recovery System Requirements

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

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).	✓
DR 2.1	The recovery system shall exert forces on the aircraft under 5 g.	✓
DR 2.2	Capture system shall sustain 5 g aircraft recovery forces.	✓

Navigation & Communication

CPE: Nav/Comm Design Key Requirements

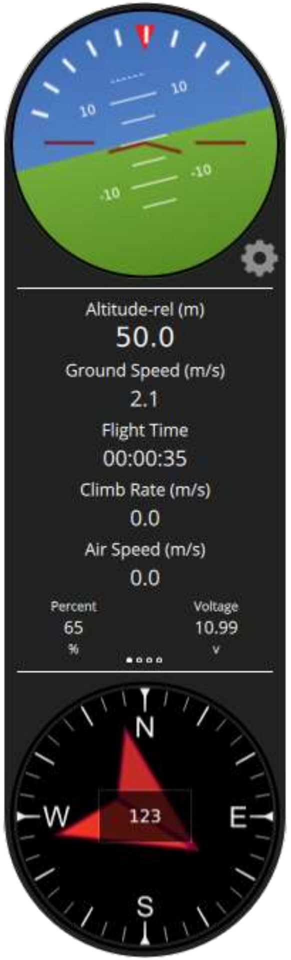
FR 1	Operate in manually piloted mode throughout all phases of flight with autonomous mode capability at cruise altitude.
DR 1.1	Aircraft shall transmit telemetry to ground station.
DR 1.2	Ground control station shall provide virtual cockpit.
DR 1.3	Aircraft shall fly autonomous missions based on waypoints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

FR 3	12 km communication range for telemetry, images, and RC control from ground control station.
DR 3.1	Telemetry radio shall have a range of 12 km at 90+ kbps.
DR 3.2	Aircraft shall capture and transmit images to ground station at 1/60 Hz.

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

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

CPE: Nav/Comm Requirements

DR 3.1	Telemetry radio shall have a range of 12 km at 90+ kbps. ✔

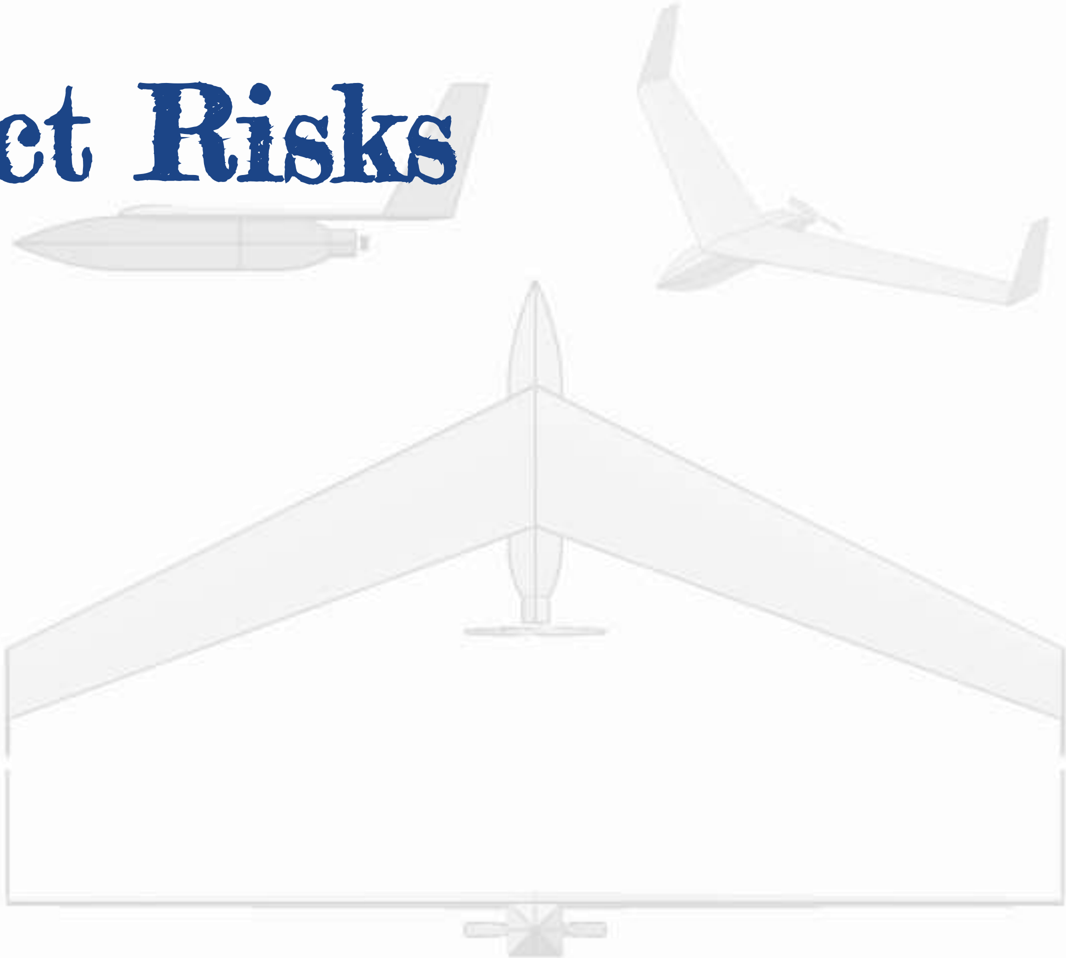
Datalink Link Budget Contributors	Gain/Loss	Associated Component
TX Power	30 dBm	RFD900+ specification
TX Antenna Gain	2.1 dBi	UAV ¼ wave monopole
Free Space Path Loss	-113.1 dB	900 Mhz @ 12 km
RX Antenna Gain	25 dBi	Yagi Ground Station Antenna
SNR	-30 dB	Rayleigh Fading Model for 99.9% time availability
RX Sensitivity (for 125 kbps)	90 dB	RFD900+ Specification
Link Budget	**3.59 dB**	DR 3.1 satisfied.

CPE: Nav/Comm Design Key Requirements Recap

FR 1	Operate in manually piloted mode throughout all phases of flight with autonomous mode capability at cruise altitude.	✓
DR 1.1	Aircraft shall transmit telemetry to ground station.	✓
DR 1.2	Ground control station shall provide virtual cockpit.	✓
DR 1.3	Aircraft shall fly autonomous missions based on waypoints and loiter points.	✓
DR 1.4	Mission shall be reprogrammable during flight.	✓

FR 3	12 km communication range for telemetry, images, and RC control from ground control station.	✓
DR 3.1	Telemetry radio shall have a range of 12 km at 90+ kbps.	✓
DR 3.2	Aircraft shall capture and transmit images to ground station at 1/60 Hz.	✓

Project Risks



Project Risks

Risk	Pre mitigation likelihood/ impact	Mitigation Plan	Post mitigation likelihood/ impact
1) Software delay	3 / 3	Extra manpower	2 / 3
2) Comm system failure during test flight	5 / 5	Extensive testing, autopilot failsafe mode	2 / 2
3) Manufacturing time delay	3 / 4	Detailed plan, add manpower	2 / 4
4) Crash during testing	4 / 4	Pilot preparation, shock absorbent airplane, half-scale	3 / 3
5) Shipping delays	2 / 4	Order parts with long lead times before break	1 / 4

Legend

- Red = High Risk
- Orange = Mitigated Risk

1 = lowest likelihood/impact (desired)

5 = highest likelihood/impact (undesired)

Project Risks

Risk	Pre mitigation likelihood/ impact	Mitigation	Post mitigation likelihood/ impact
6) Wing failure during sandbag test	2 / 3	Buy 2 sets of wings, Produce extra	2 / 2
7) Battery overheating	3 / 5	Test components and circuit	1 / 5
8) Injury during testing	2 / 5	Safety plan	1 / 5
9) Over-budget	4 / 4	Budget plan, half-scale testing	2 / 4
10) Insufficient battery duration during flight	3 / 4	Battery testing, autopilot safeguard	2 / 3
11) Bad weather	3 / 2	Plan ahead, have multiple options	3 / 1

Legend

[red] = High Risk

[orange] = Mitigated Risk

1 = lowest likelihood/impact (desired)

5 = highest likelihood/impact (undesired)

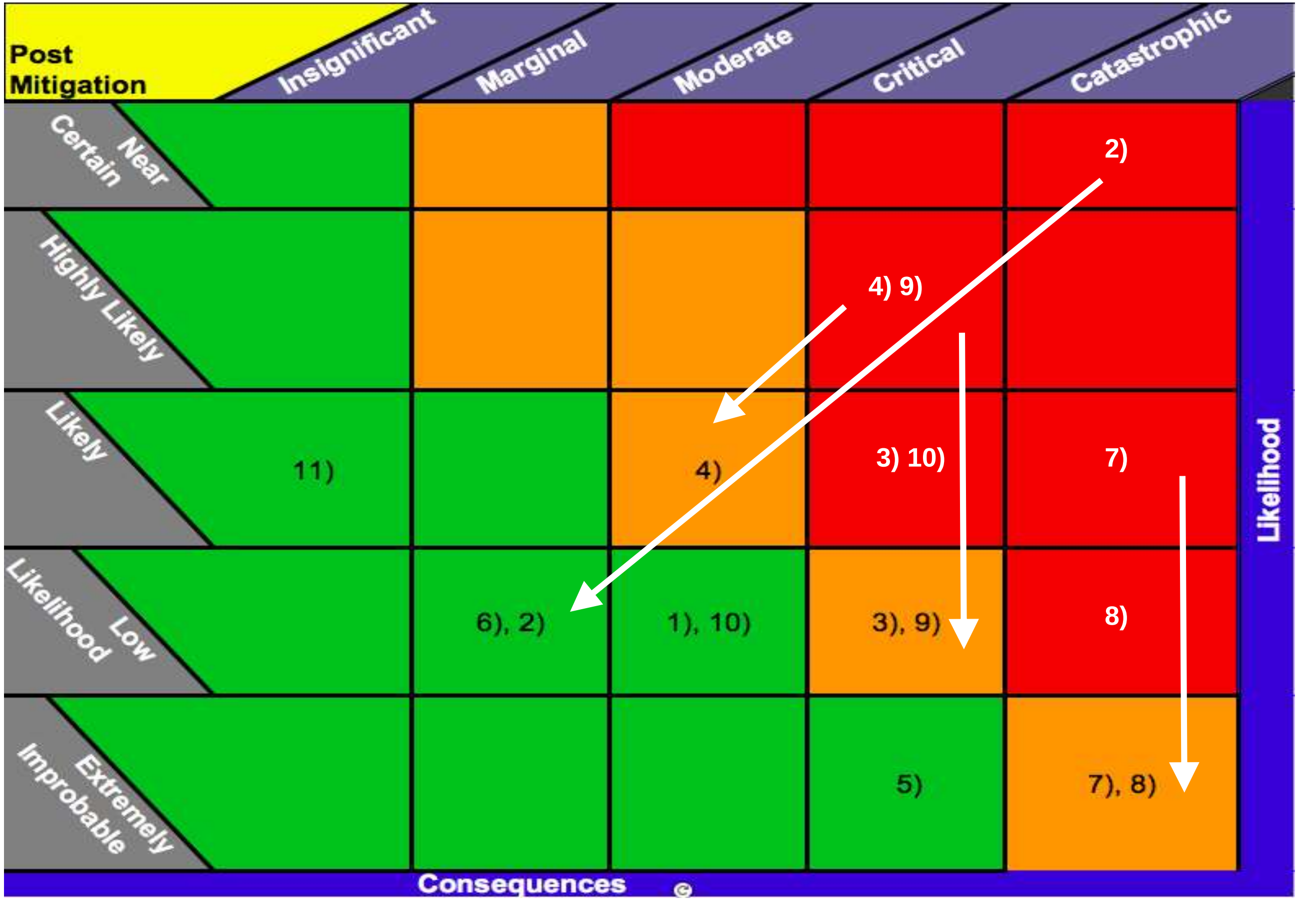
Pre Mitigation Risk Matrix

Pre Mitigation	Insignificant	Marginal	Moderate	Critical	Catastrophic
Near Certain					2)
Highly Likely				4), 9)	
Likely		11)	1)	3), 10)	7)
Low Likelihood			6)	5)	8)
Extremely Improbable					

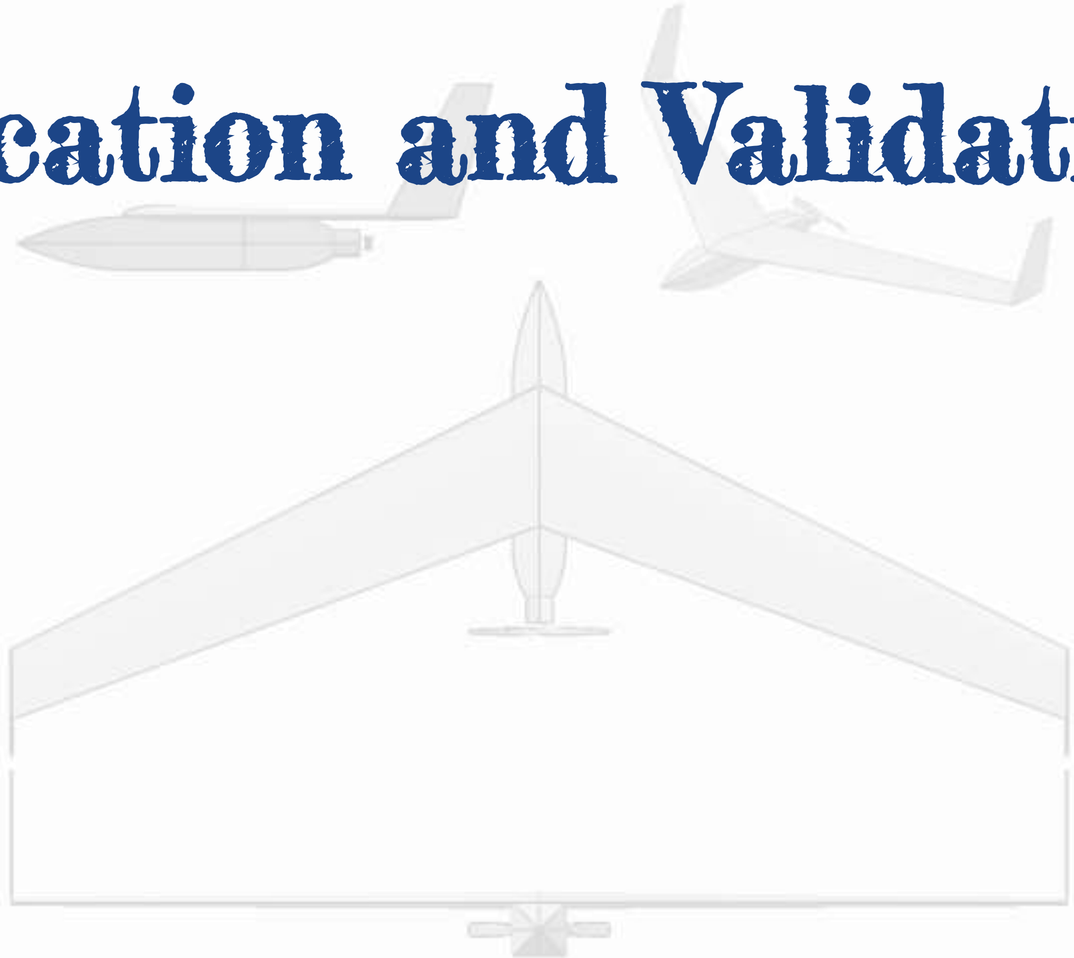
Likelihood

Consequences ©

Post Mitigation Risk Matrix



Verification and Validation



DR 1.1- Half Scale Stability Test

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

Motivation	Expected Result According to Models	Off-Ramp
Validate stability model	Use accelerometers to confirm predicted behavior	Iteration of model

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

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

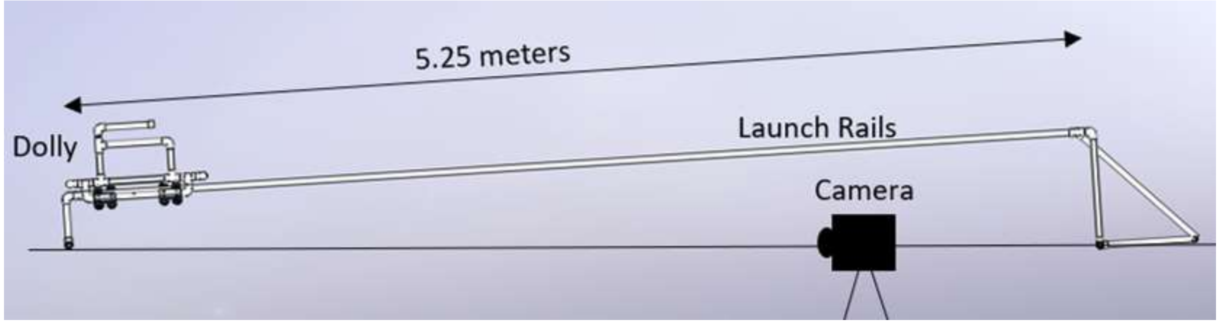
Key Measurements Issues: Accelerometer resolution

DR 2.1 - Launch Speed Test

Anticipated Date: After TRR

Motivation	Expected Result According to Models	Off-Ramp
Validate Speed Model	Dolly speed is 13.2 m/s	Add or remove bungees, vary pull back distance on ramp.

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

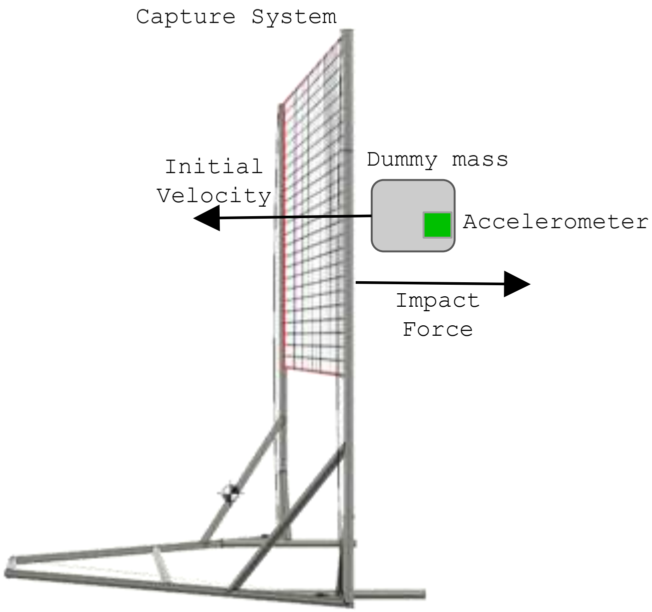
Equipment	Availability	Capabilities	Requirements	Satisfied?
Camera	ITLL	60 fps camera Launch time: 0.766 s	> 20 frames for track time	45 frames in launch time ✓
Tripod/Stand	ITLL	Any height is achievable	0.25 m height	Any Height ✓
Logger Pro Software	ITLL	Frame by frame tracking of dolly to find position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

Key Measurements Issues: Error in height of camera leading to issues in software

DR 2.1 - Recovery System Force Test

Anticipated Date: After TRR

Motivation	Expected Result According to Models	Off-Ramp
Validate Recovery Force Model	Accelerometer on dummy mass will experience < 5g	Redesign of bungees



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

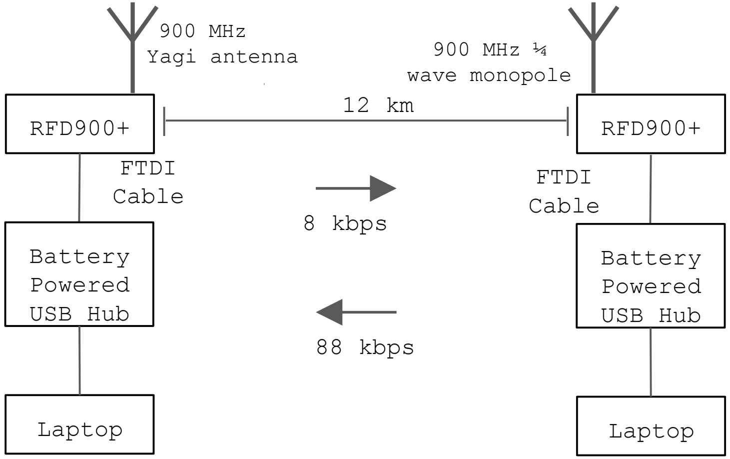
Equipment	Availability	Capabilities	Requirements	Satisfied?
Accelerometer	COTS	Range: 0-14.2 g Resolution: 16 bit	5 g	Available ✓
High Speed Camera	ITLL	120 fps	Record dummy mass to find net extension	Available ✓
Dummy Mass	ITLL	N/A	8.45 kg	Available ✓

Key Measurements Issues: Consistent throw speeds, error in measurements from accelerometer.

DR 3.1 - Datalink Range Test

Anticipated Date: February 1, 2018

Motivation	Expected Result According to Models	Off-Ramp
Verify 12 km communication range	Successful image transfer Uplink rate of 8 kbps Datalink rate of 88 kbps.	Implementation of ground station tracking system



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

Equipment	Availability	Capabilities	Requirements	Satisfied?
2 FTDI Cables	Acquired through funds	Communicate between radio and laptop	5V capacity	Can be purchased with budget ✓
2 Battery Powered USB Hubs	Acquired through funds	Provide extra power to radio	At least 88 kbps transfer rate	Can be purchased with budget ✓

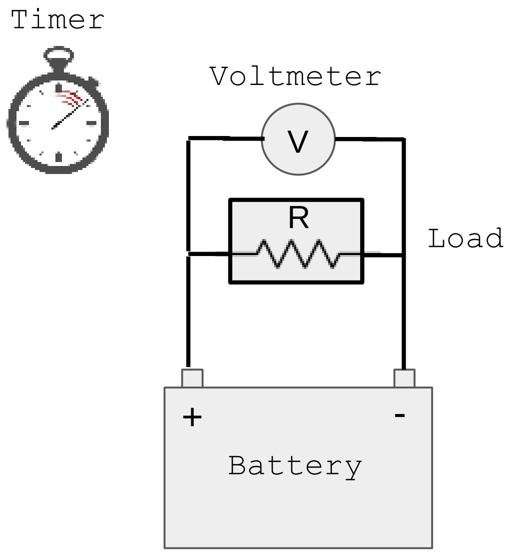
Key Measurements Issues: Ground station pointing angle of antenna.

DR 6.2 - Battery Endurance Test

Verify the battery can reach the mission time requirement

Anticipated Date: Before TRR

Motivation	Expected Result According to Models	Off-Ramp
Validate Power Budget	Battery holds charge for: 3 min at 65.6A 81 min at 15.6A	Reduce required range of mission.



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

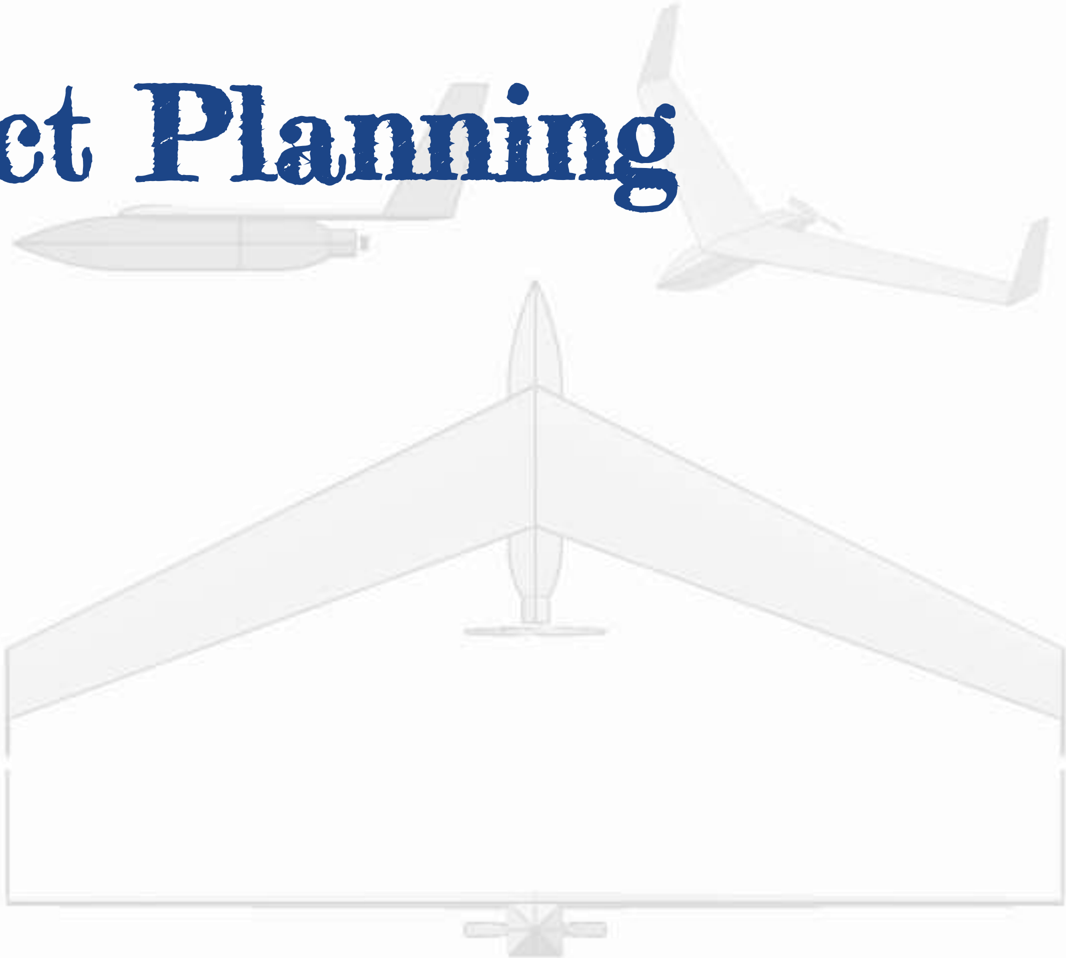
Equipment	Availability	Capabilities	Requirements	Satisfied?
Motor, Autopilot, Flight Computer	Acquired through funds	Simulate mission load on battery	Components chosen for project	Components to be ordered ✓
Compact DAQ	ITLL	Verify the battery voltage over time and measure the cutoff voltage	84 min measurement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

Key Measurements Issues: Error in DAQ measurements.

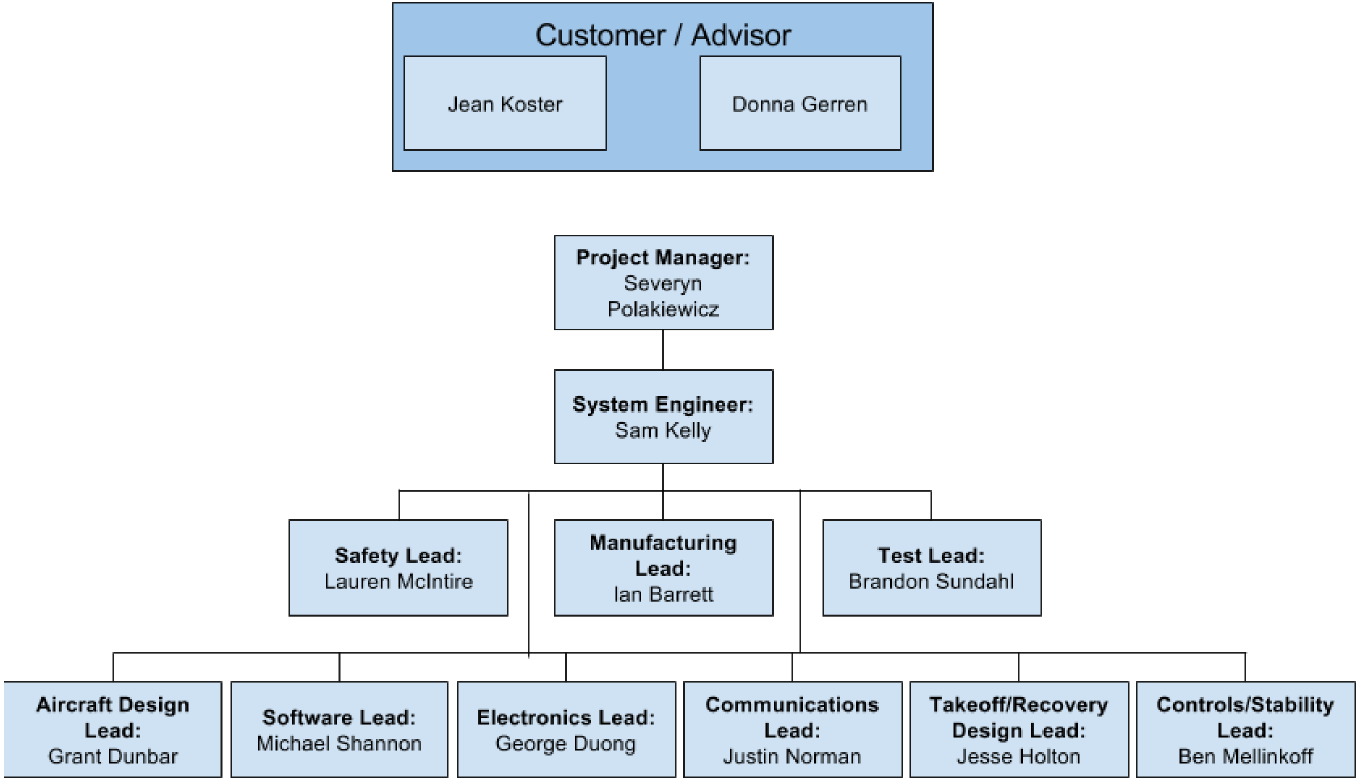
Verification & Validation Summary

Models Validated	Requirements verified
Stability model	Aircraft stability during flight
Launch system speed model	Capability of launch system to deliver necessary energy to UAV
Recovery system force model	Capability of landing system to capture UAV with forces in under 5g
Battery depletion model	Battery shall have 1.4 hour endurance between climb and cruise
Link Budget	Capability of ground system to communicate with UAV at range

Project Planning



Organizational Chart



Work Breakdown Structure

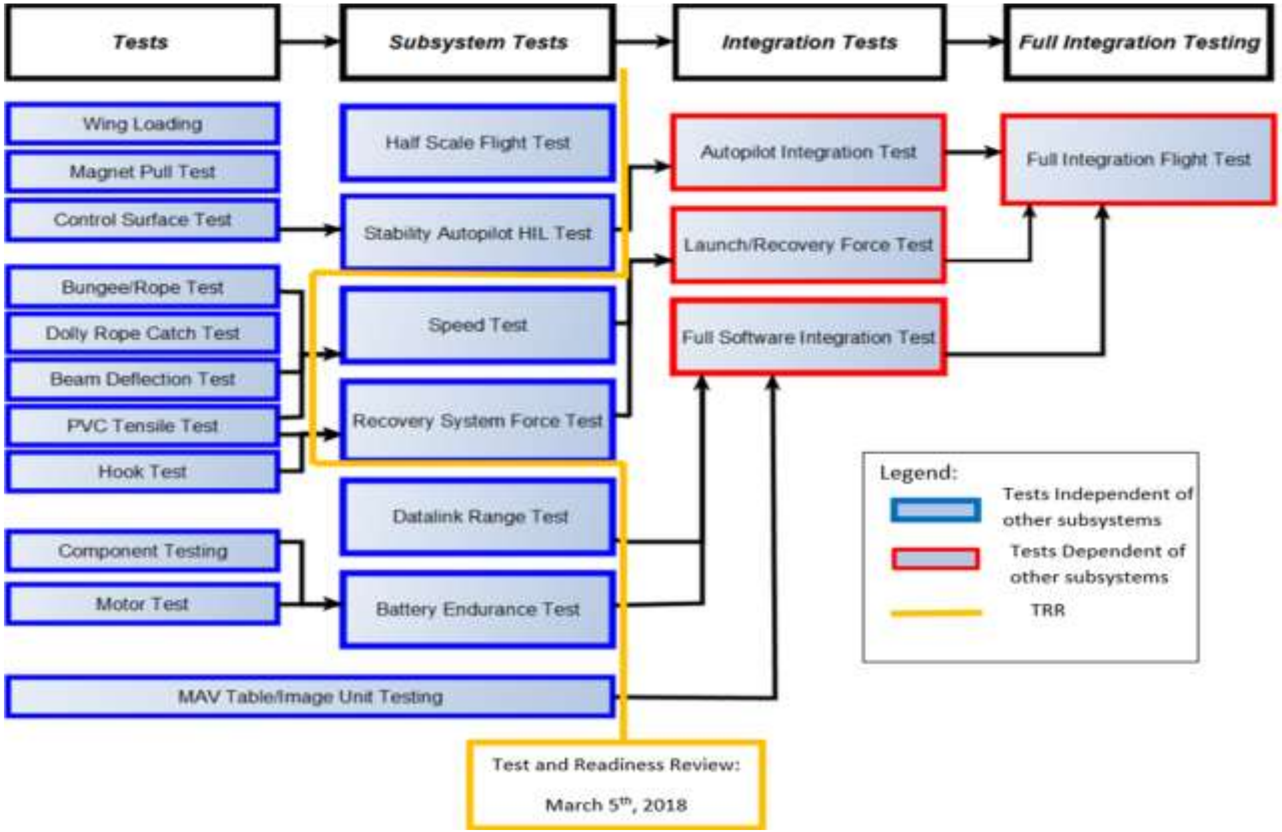
SHAMU

Aircraft	Launch/Recovery	Manufacturing/ Development	Testing	Deliverables	Crowdfunding
Control and Stability Model	Dimension Components	Overview Plan	Overview Plan	Project Definition	Project Outline
Wing Design	Stress/Deflection Analysis	Determine Components	Hook Concept	Conceptual Design	Storyboard
Fuselage Design	Launch Energy Model	Order Components	Launch Velocity	Preliminary Design	Website Page
Material Selection	Recovery Energy Model	Construct Launch System	Net Recovery	Critical Design	Film/Edit Video
Structural Load Analysis	Material Selection	Construct Landing System	Communication Range Test	Fall Final Report	
CAD Model	Reaction Force Analysis	Aircraft Composites	Wing Loading	Manufacturing Status	
Modularity	Dolley Tipping Analysis	Construct Aircraft Structures	Power Endurance	Test Readiness	
Electronics Design	CAD Model	Software	Aircraft Stability	Spring Final Review	
		Communications System	Software	Project Final Report	
			Hardware Integration		

Completed

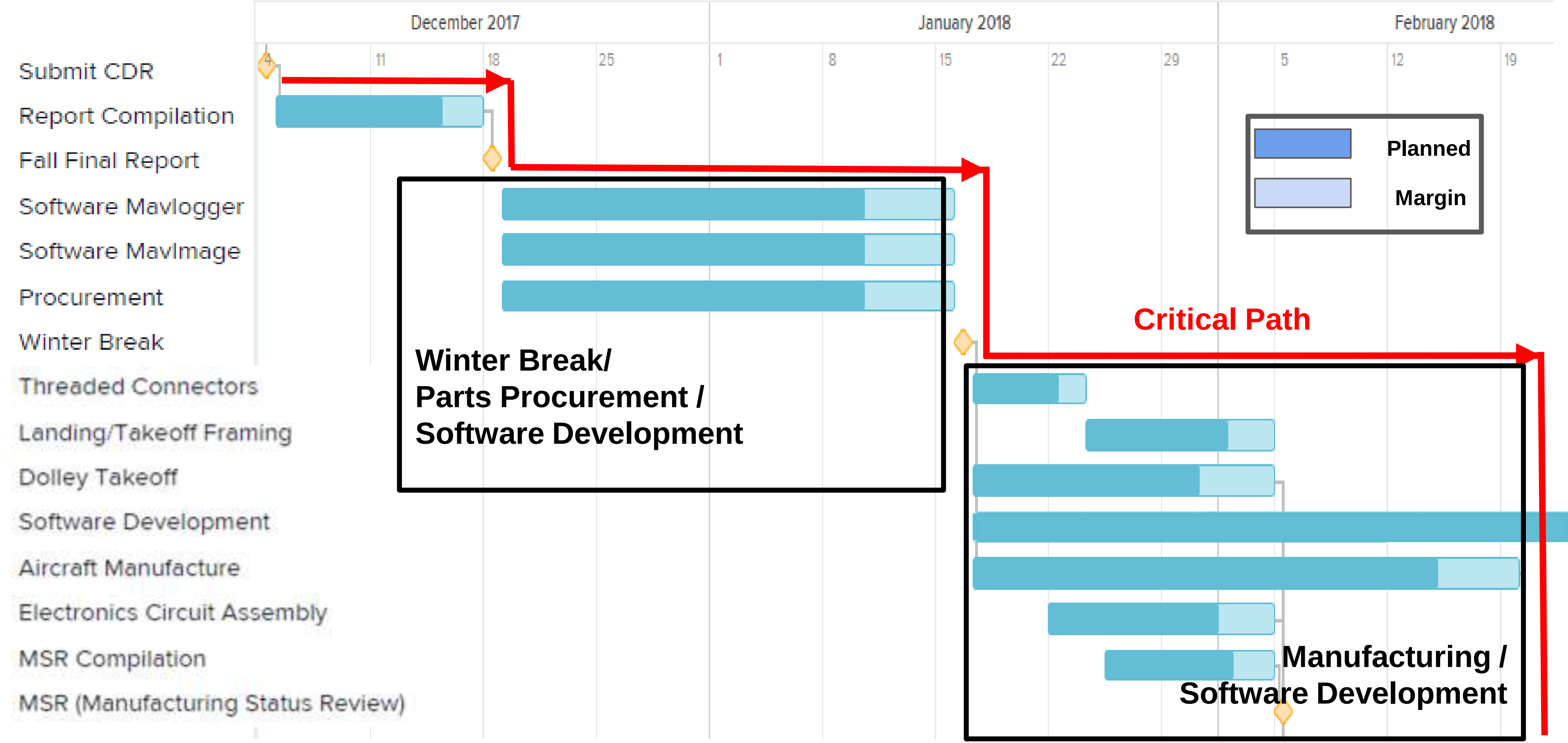
To Be Completed

Test Plan

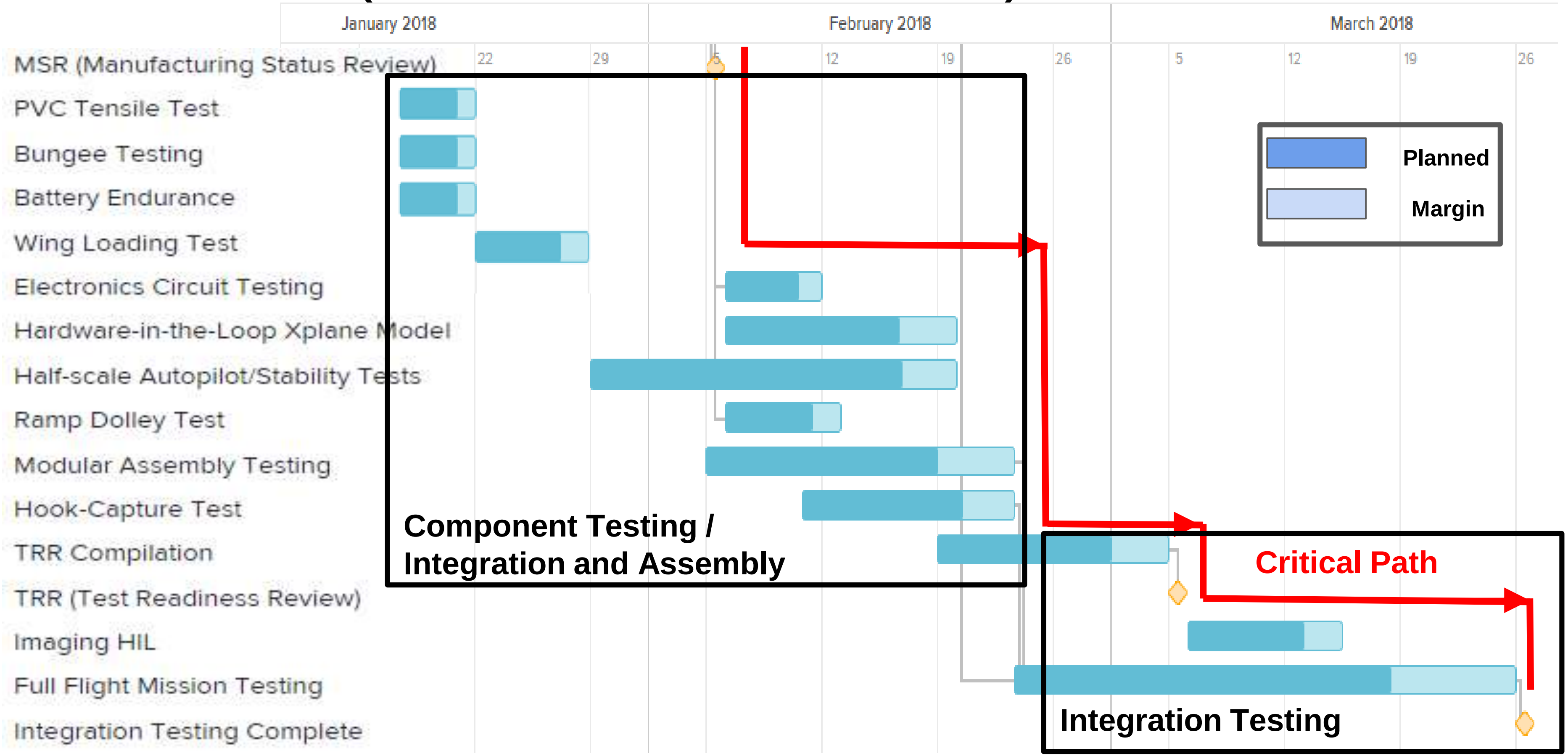


Tests
Subsystem Tests
Integration Tests
Full Integration Testing
Wing Loading
Magnet Pull Test
Control Surface Test
Bungee/Rope Test
Dolly Rope Catch Test
Beam Deflection Test
PVC Tensile Test
Hook Test
Component Testing
Motor Test
MAV Table/Image Unit Testing
Half Scale Flight Test
Stability Autopilot HIL Test
Speed Test
Recovery System Force Test
Datalink Range Test
Battery Endurance Test
Autopilot Integration Test
Launch/Recovery Force Test
Full Software Integration Test
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)



Work Plan (Gantt Chart Continued)

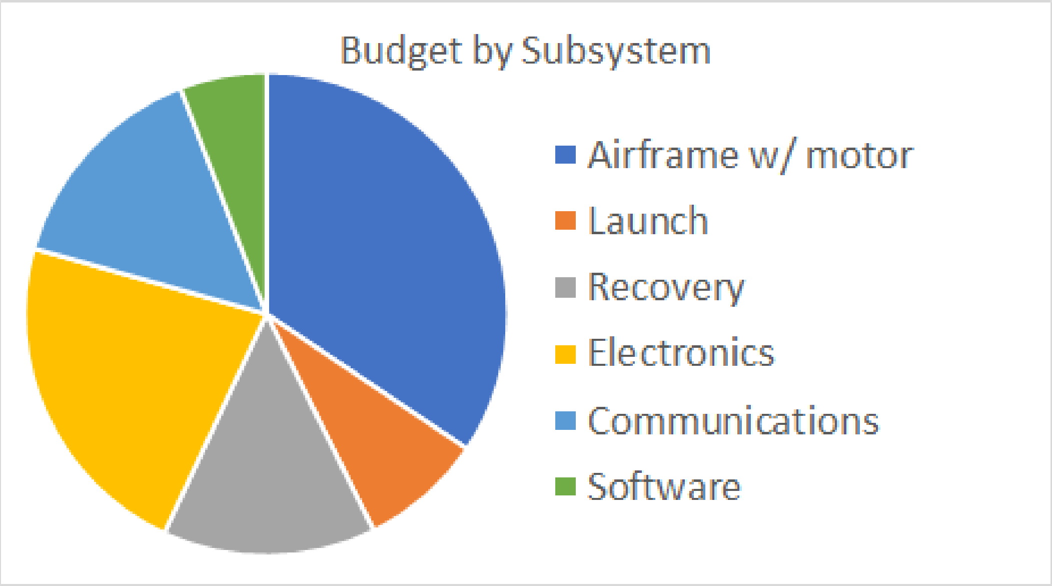


Budget Estimations

Airframe w/ motor:	$1230
Communications:	$530
Electronics:	$800
Launch system:	$295
Recovery system:	$510
Software	$320

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

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- Pixhawk 2.1 Feature Overview: http://www.proficnc.com/index.php?controller=attachment&id_attachment=5 (retrieved 12/3/17)
- PX4 Pro: http://px4.io/ (retrieved 12/3/17)
- QGroundControl: http://qgroundcontrol.com/ (retrieved 12/3/17)
- Model Aircraft Propellers: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=6&cad=rja&uact=8&ved=0ahUKEwjO8MLoh-_XAhVD6oMKHduWDCsQFghrMAU&url=http%3A%2F%2Fdc-rc.org%2Fpdf%2FModel%2520Propellers%2520Article.pdf&usg=AOvVaw1CxfDyyhN4K5DlHAanXPPt (retrieved 12/3/17)
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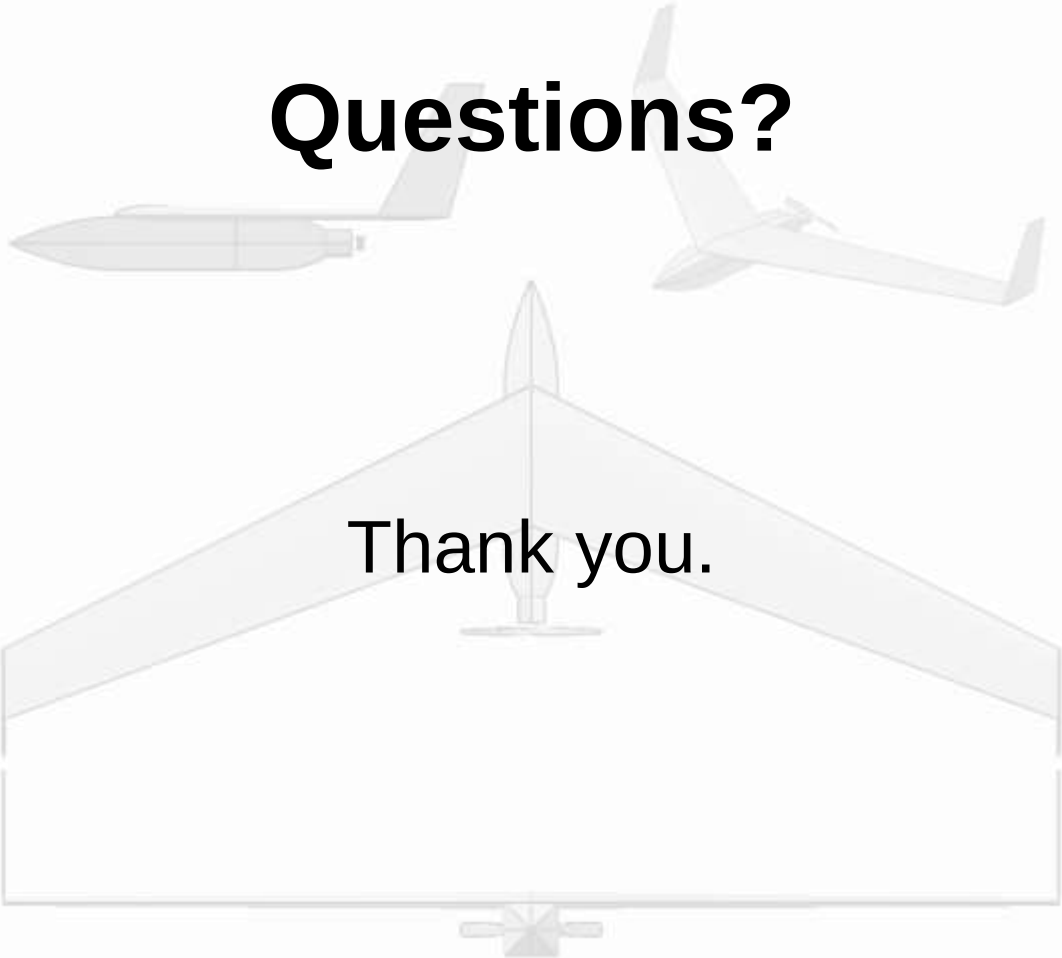
- OrangeRx Open LRS Receiver: https://hobbyking.com/en_us/orangerx-open-lrs-433mhz-9ch-receiver.html (retrieved 12/13/17)
- UIAA climbing rope: http://www.theuiaa.org/safety-standards/
- Solidworks: http://www.solidworks.com/
- PVC porperties: https://www.engineeringtoolbox.com/physical-properties-thermoplastics-d_808.html
- PVC pressure ratings: https://www.engineeringtoolbox.com/pvc-cpvc-pipes-pressures-d_796.html

Questions?



Thank you.

Backup Slides Directory

Airframe & Powerplant Backup

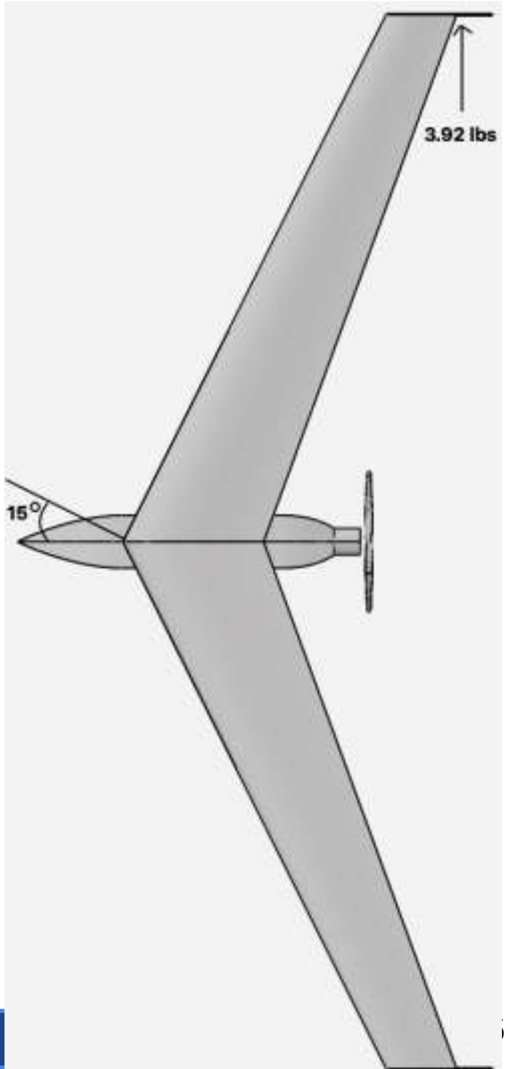
Propeller backup slide

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 ($C_{M\alpha} < 0$) 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 ($C_{M\alpha} < 0$) in all flight conditions with 3° wing twist
  - Dynamically stable

- Will be used for hardware in the loop simulations with autopilot.

X-Plane Rendering of SHAMU UAV

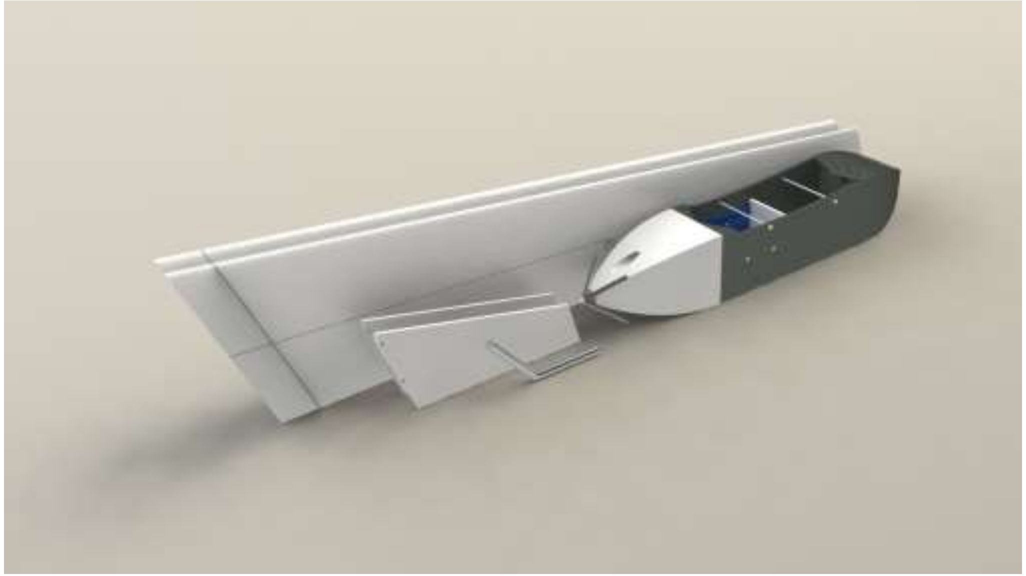
Aerial Vehicle Design Key Requirements

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

<u>Design Decisions for modularity</u>

- 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

https://hobbyking.com/en_us/hobbykingtm-coreless-digital-hv-mg-bb-servo-20kg-0-16sec-66g.html

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:

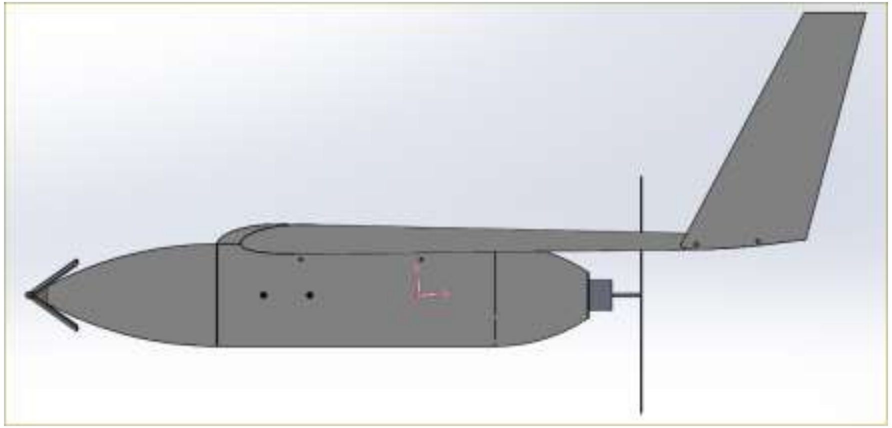
- Maximum pitch and roll rates: 30 - 360°/s at minimum controllable airspeed.
- $C_{M\alpha} < 0$ through flight regime (angles of attack from zero to stall) → **statically stable**.
- Real component of phugoid/short period/dutch roll/rolling modes must be less than zero → **dynamically stable**.

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)

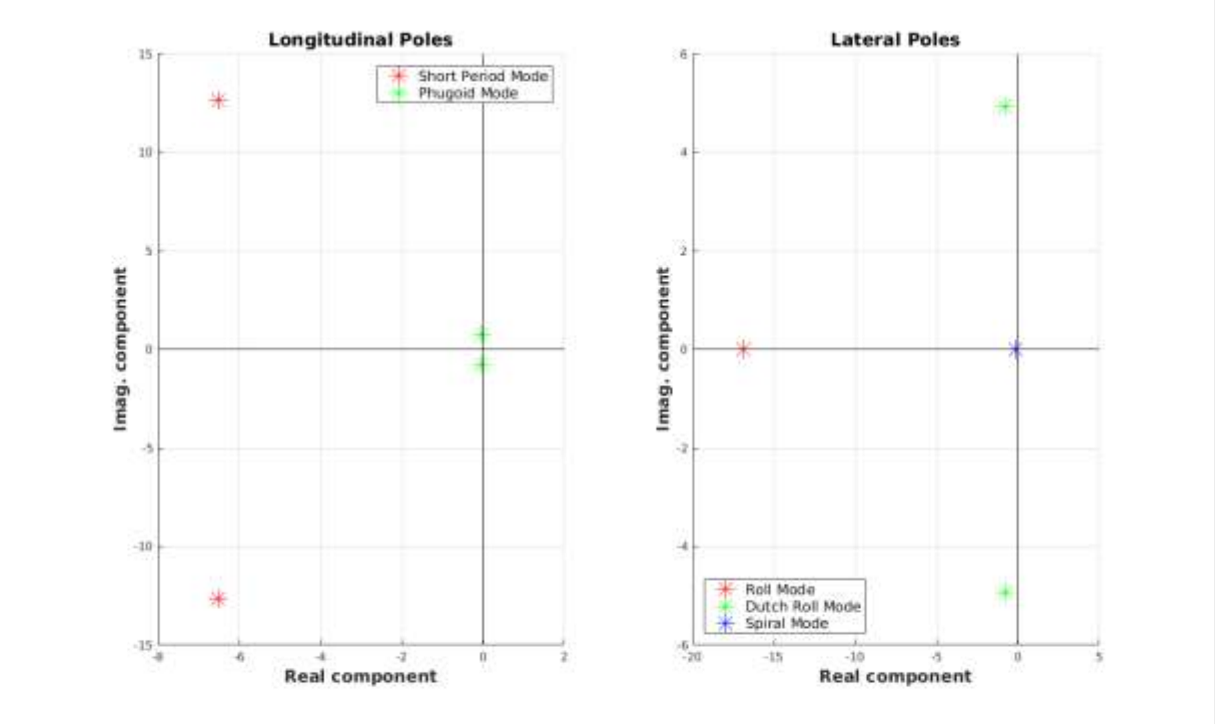
Aircraft side view



CPE: Aerial Vehicle Design Key Requirements

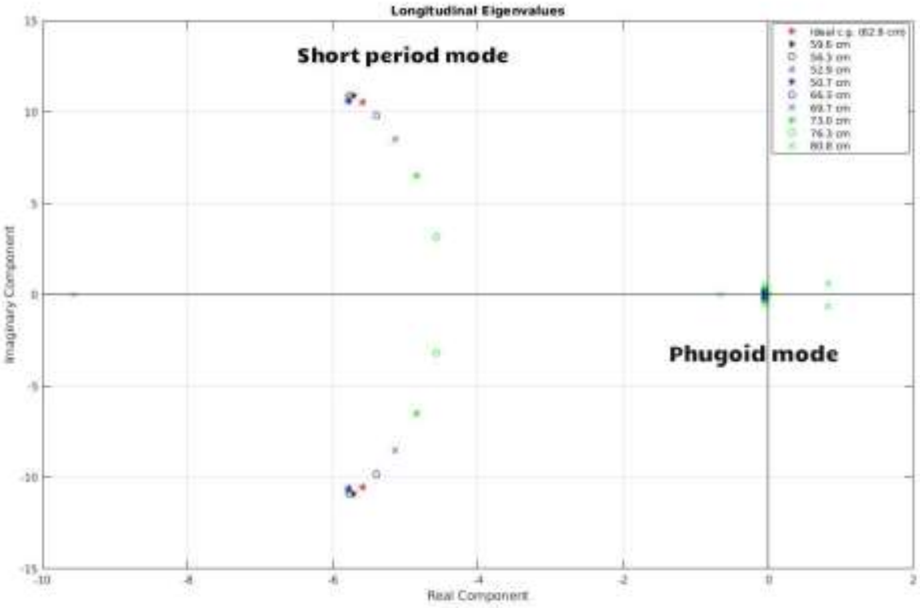
AVL Model Eigenvalues:

- $\lambda_i < 0 \; \forall \; i$
  - 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

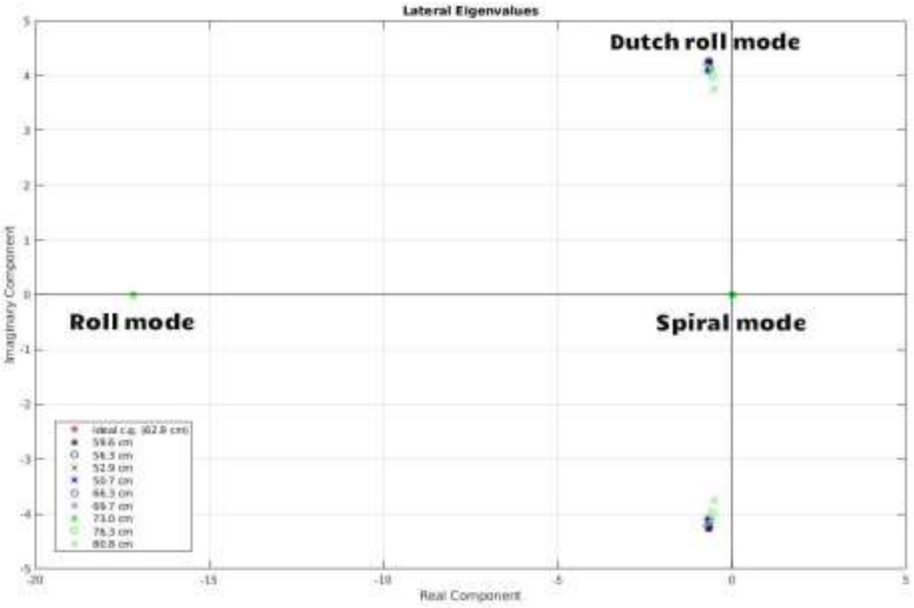
Aircraft Stability- AVL/Matlab

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

Roll mode - very stable

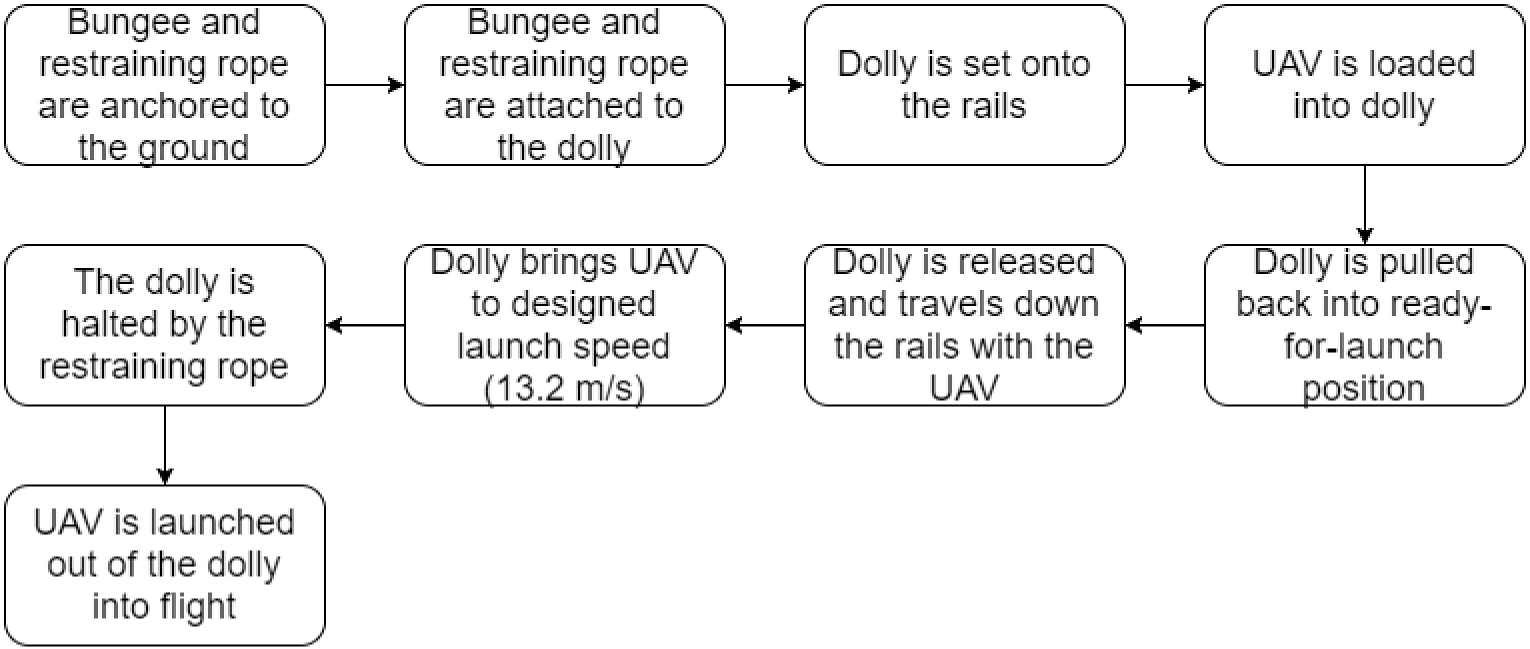
Dutch roll; Spiral modes - slightly stable for C.G. range of 50.7 cm - 76.3 cm

∴ Feasible



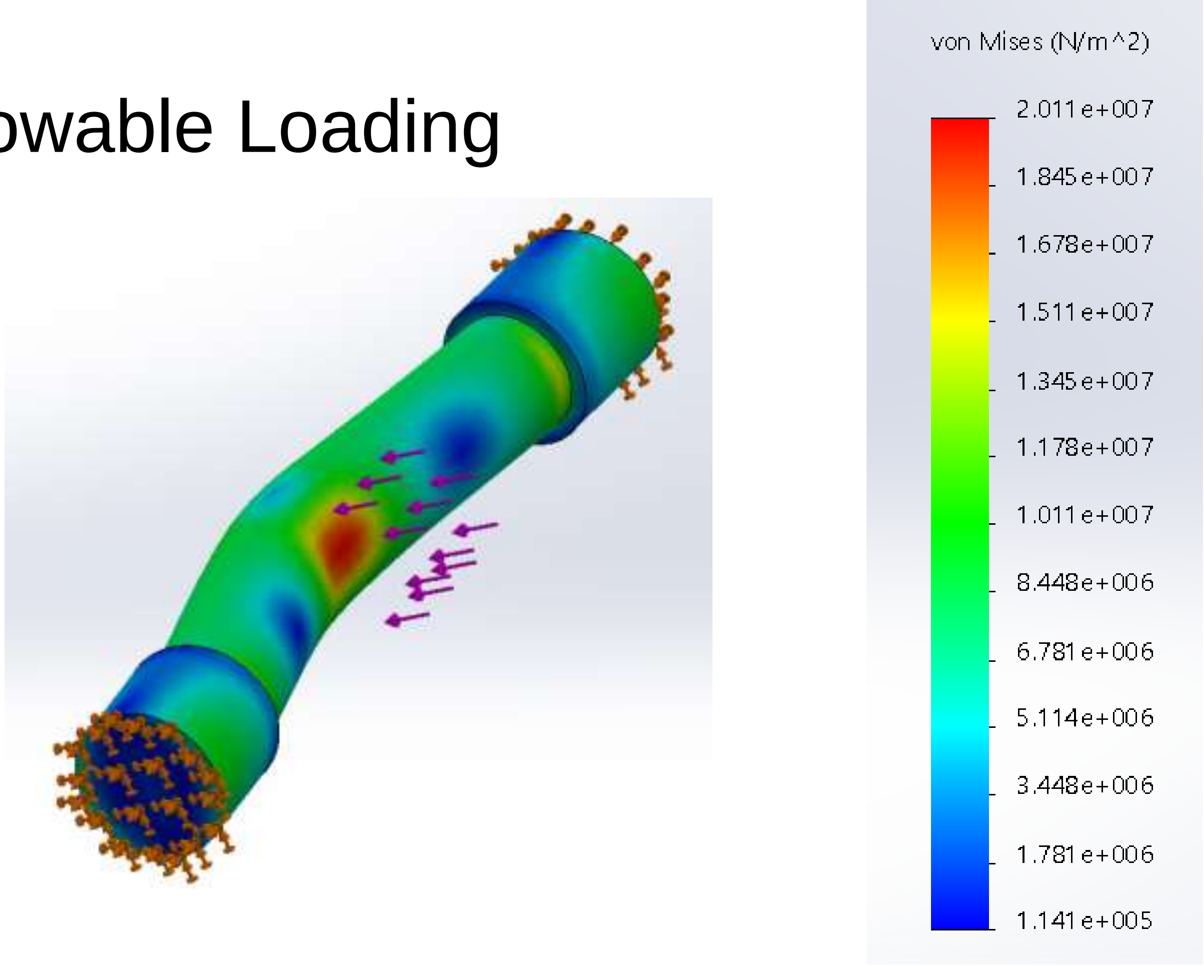
Launch System Backup

Launch Flow Chart



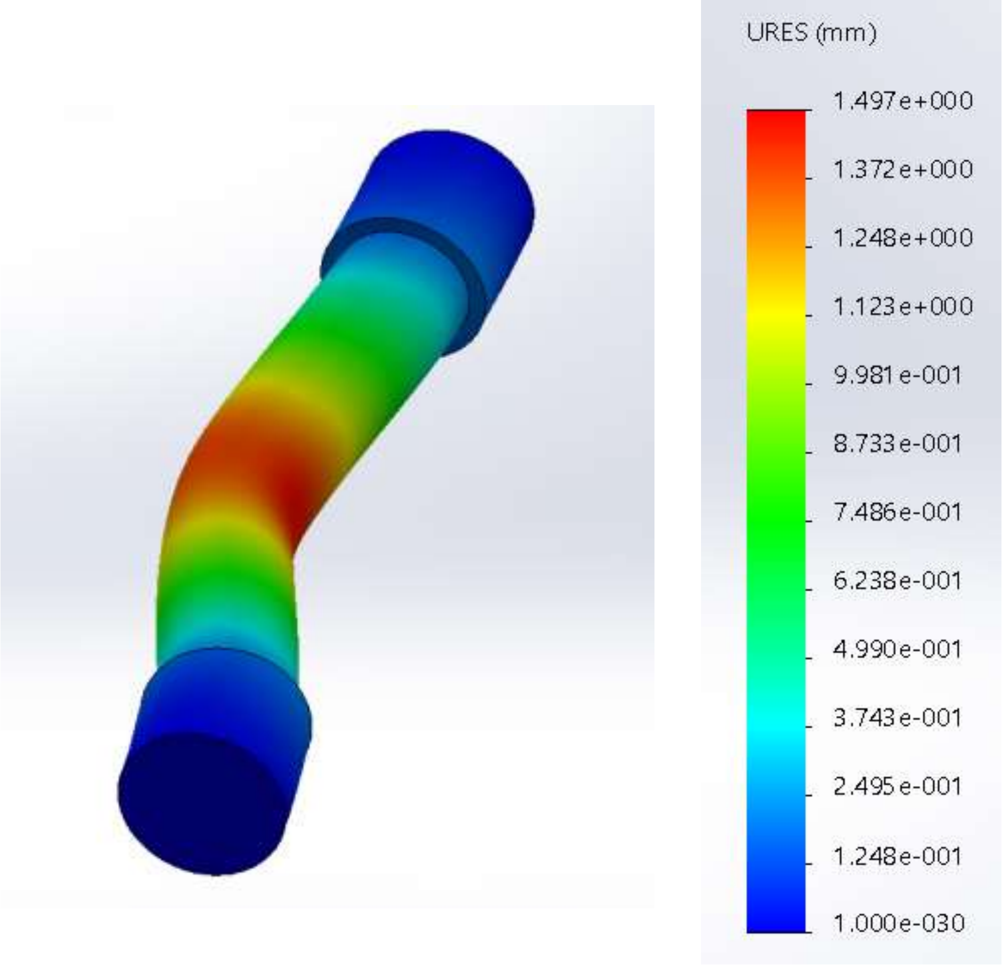
Maximum Allowable Loading

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

Stopping distance, $x = V_o*t + 0.5*(-a)*t^2$
- 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

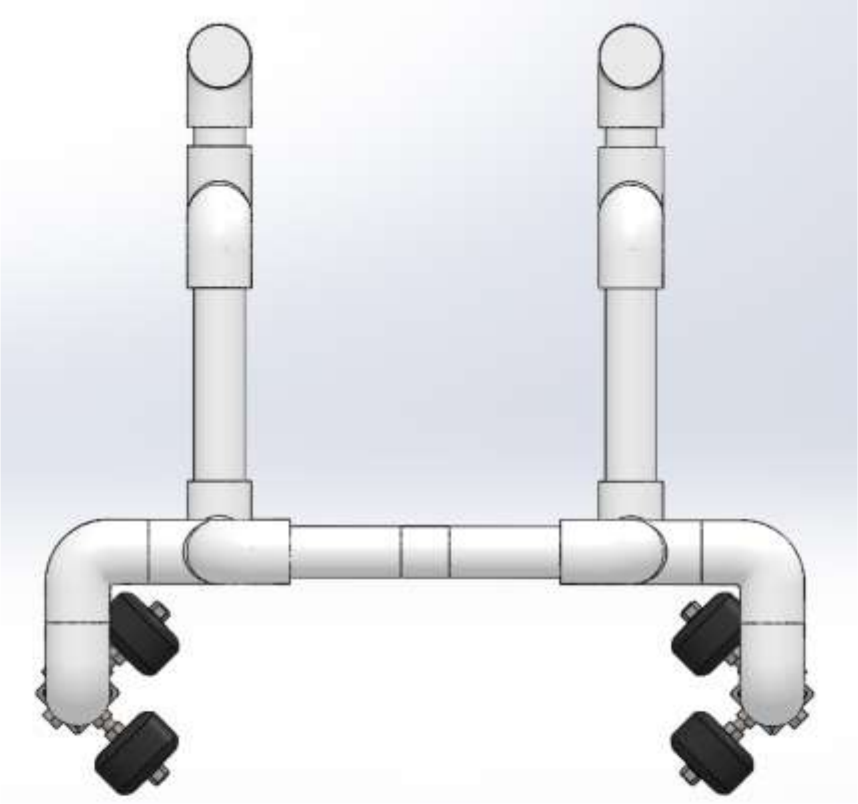
Known: Same PVC cement is used for Schedule 40 and Schedule 80.

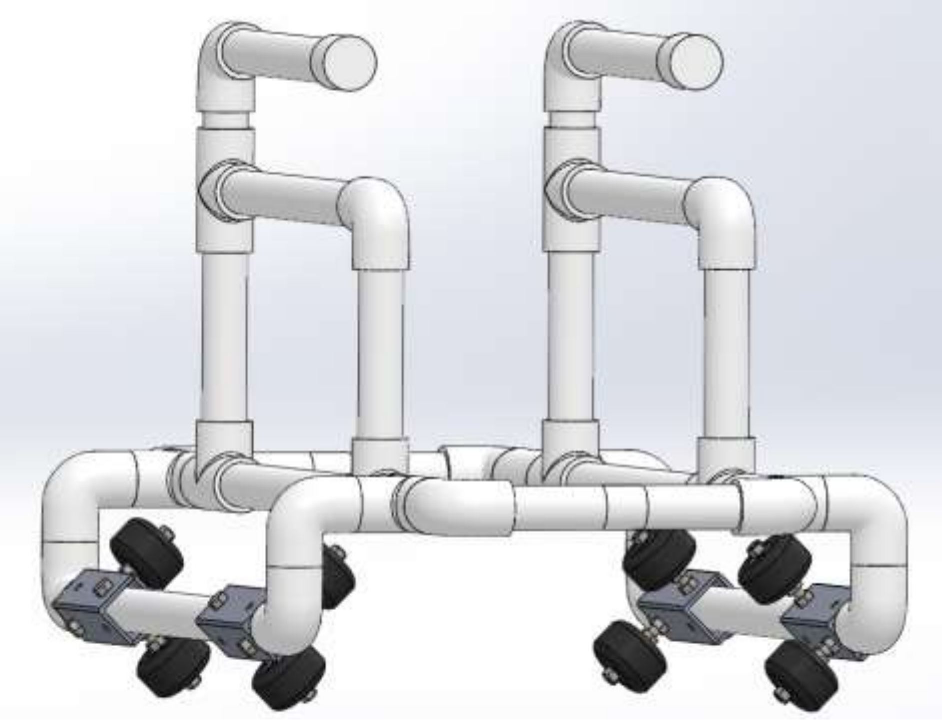
Assumption based off capped pipes. Since the area is the same for a 1 in diameter pipe for Sch 40 and Sch 80, the operating pressure of sch 80 pipe is used. Know that PVC cement should hold operating pressures of pipes.

Area of cap: 5.42 cm^2
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

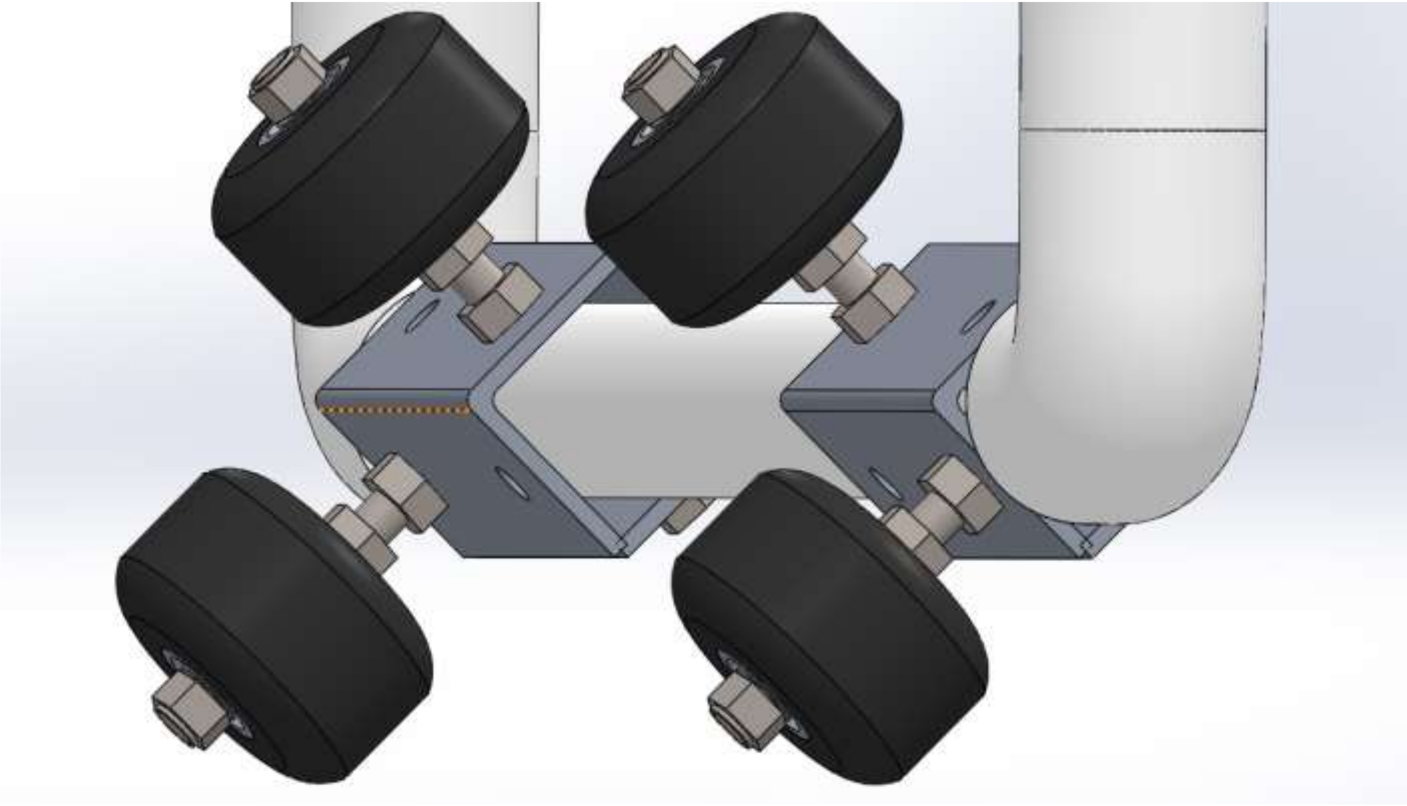
Max force dolly experiences = 1026.5 N < 1412.5 N < 7548.4 N

Pictures of Dolly

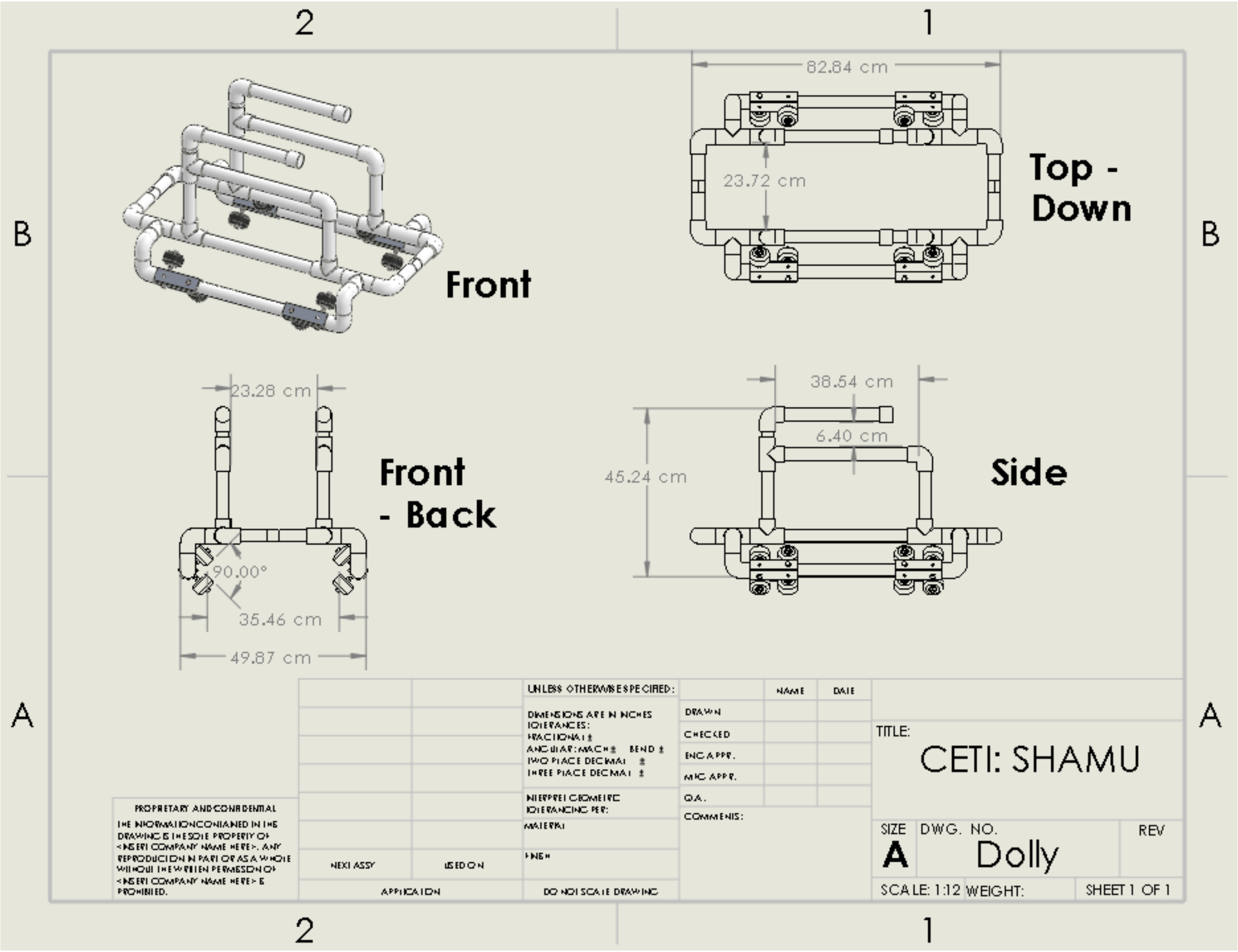




Pictures of Dolly

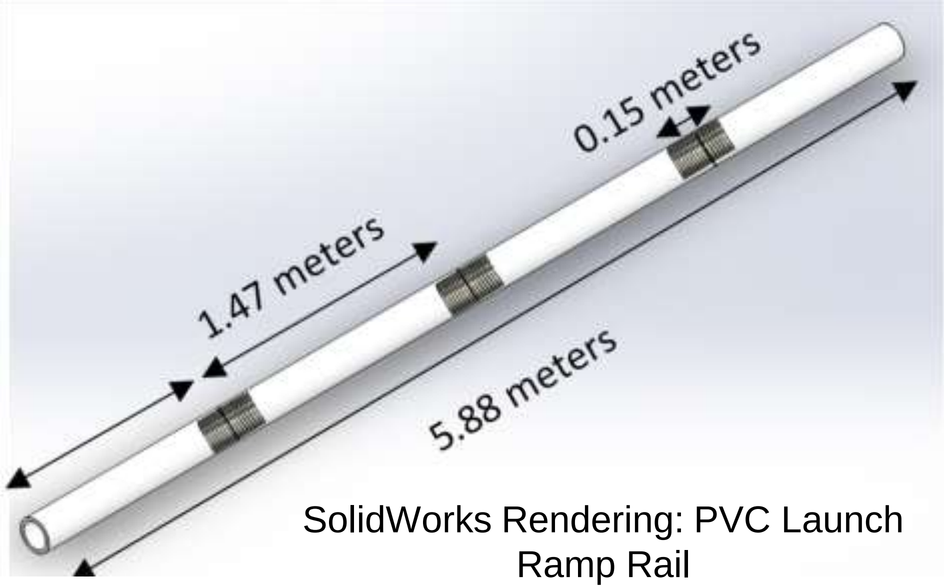


Dolly Dimensions



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.



SolidWorks Rendering: PVC Launch Ramp Rail

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

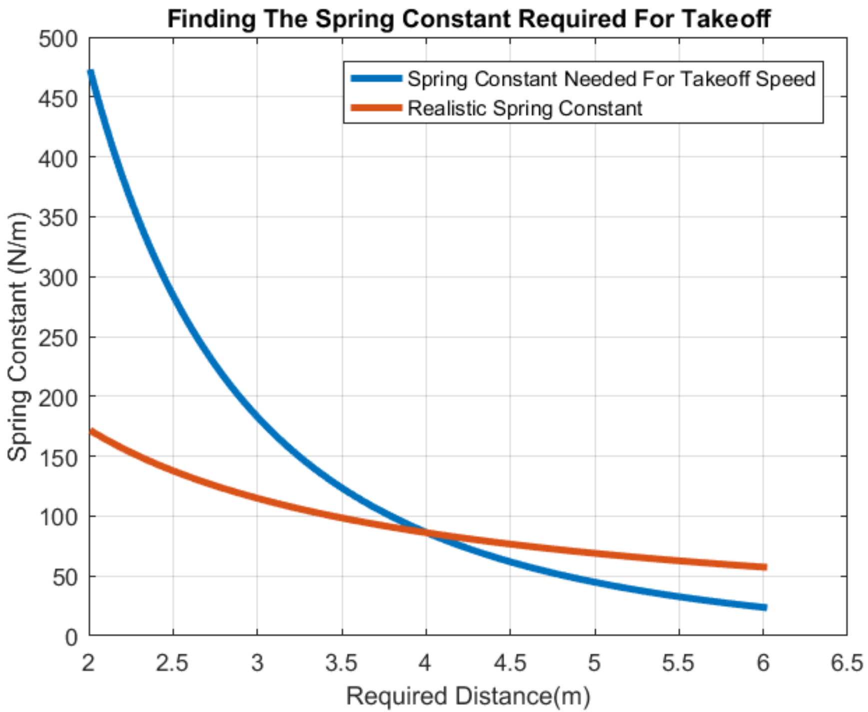
Solution:
Rail segments (<168cm) connected by a threaded, aluminum rod inside the pipe

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

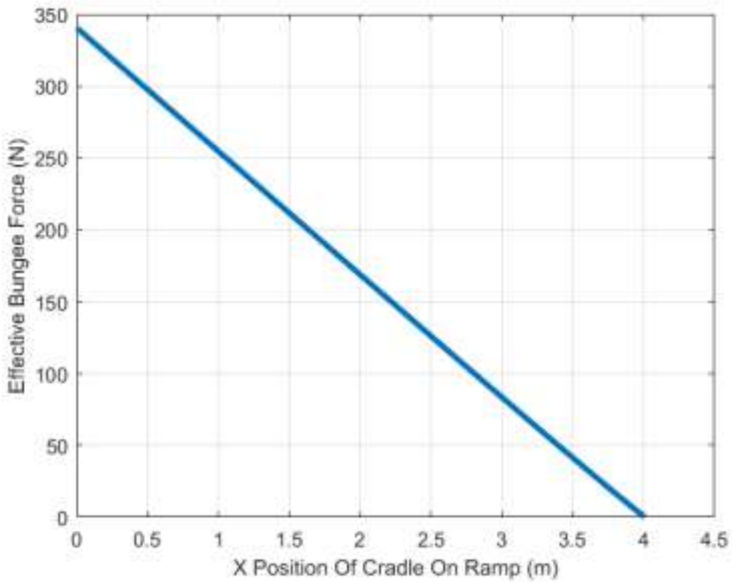


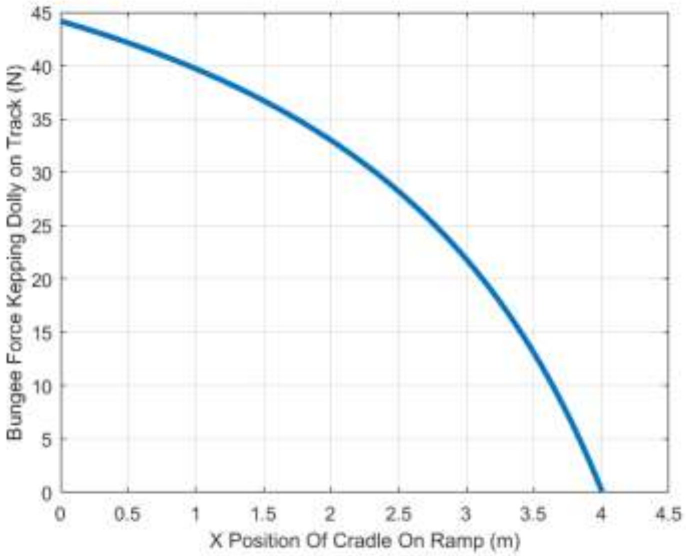
Assumptions:
5 Hi-start Bungees
Max weight: 5 kg
Max elongation: 3 times original length
K found by hanging mass off ceiling (Mg = Kx)

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

Effective Bungee Force



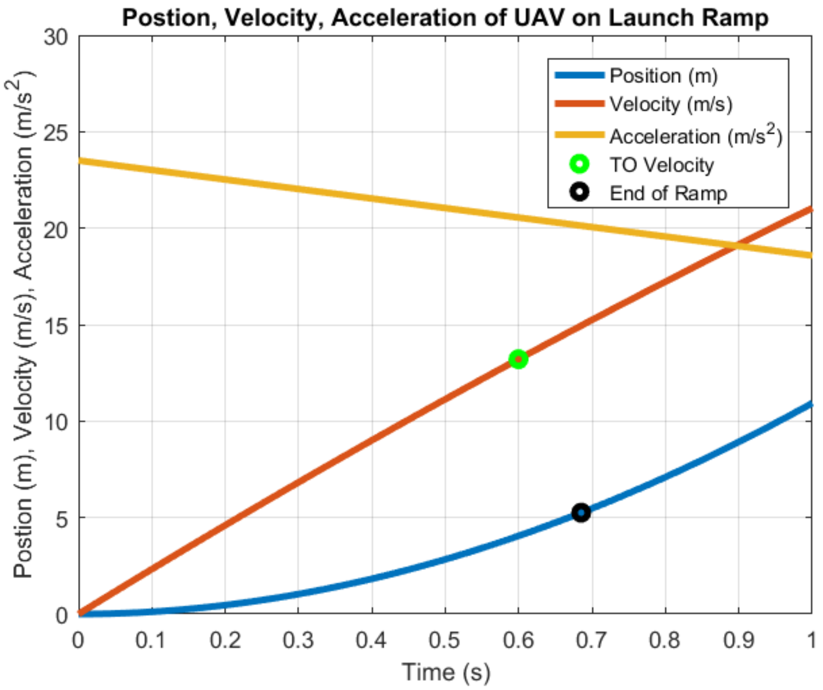


Assumptions:
Bungee Force will decrease as dolly moves
Bungees tied to ground in front of ramp

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

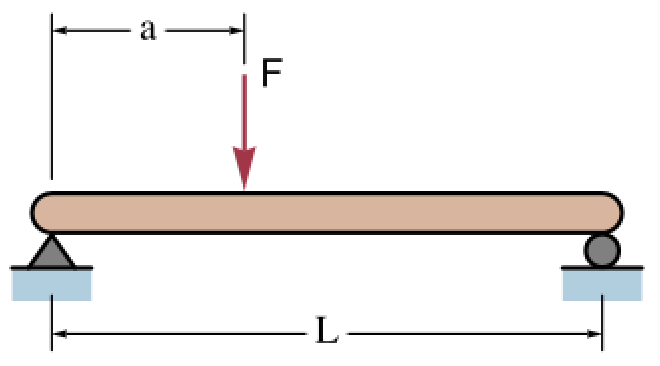


Assumptions:
Total Mass: 13.9657 kg
Force: 343.3333 N (5 Bungees)
Spring Constant: 86.0011 N/m
Initial Bungee length: 1.9961 m
Bungee-stretch: 3.9922 m
Effective Bungee Force Data

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

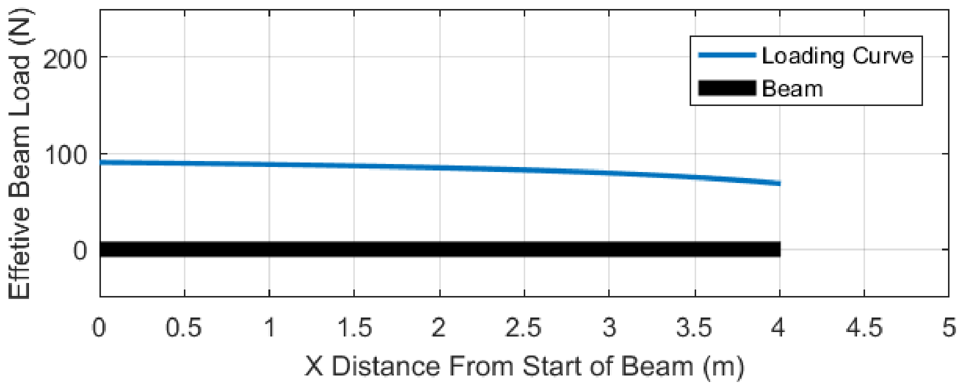
Beam Bending



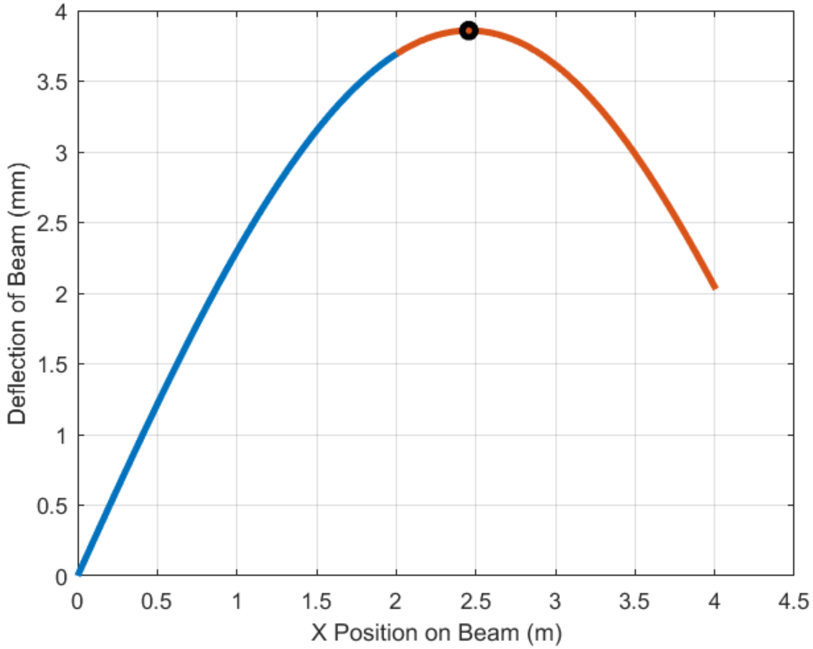
Assume:

- 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

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



Beam Bending (Continued)



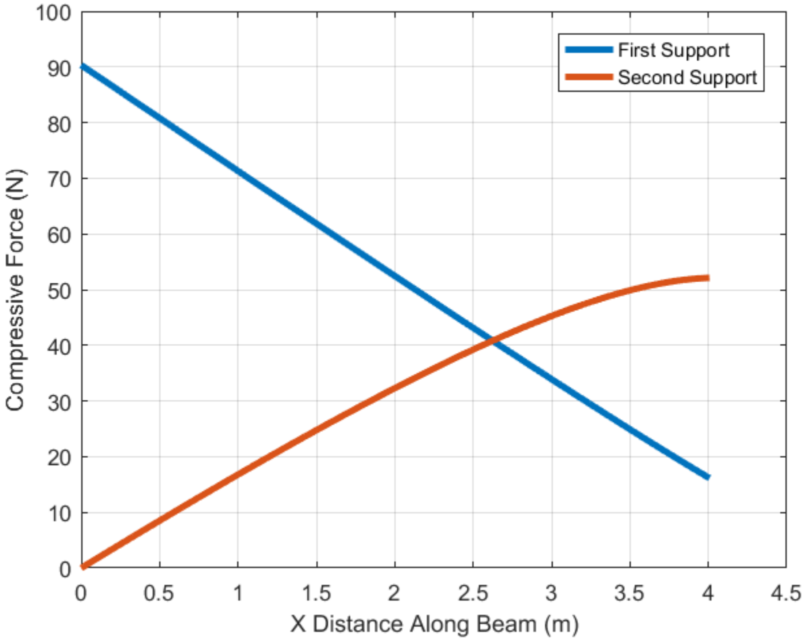
Results:
Max Deflection of Beam: 3.857901 mm
At a Distance of: 2.4564 meters
Model stops when UAV is at speed~4 meters, the rest of the rail is there for stopping distance

Max Bending Stress =153.0242 KPa

σ bend,max = 99.63 MPa

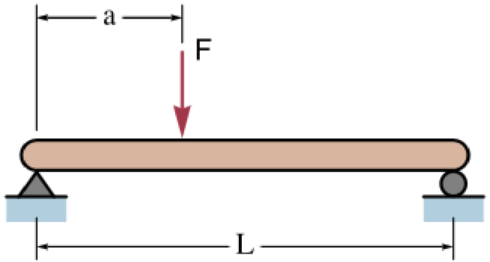
Safety Factor = 651.1

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

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

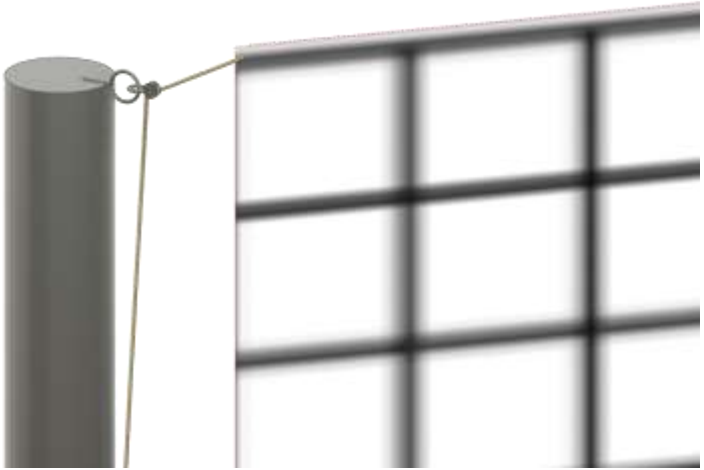
- Recovery System Structure made from 9cm outer diameter PVC pipe
- Max section length 168 cm
- Total sections required 34
- Smaller sections can be stored end-to-end
- 39+ sections will fit 22 lengthwise rows
- Stored 13 across, 2 up

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

∴ **FR 7, DR 7.1 Satisfied** ✔

Pulley/Cleat System CAD

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

Cam Cleat

Quick Link

Eyebolt

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 foreward supports

- 69 kg structure has 676 N normal force
- Expected coefficient of friction at least 1 (Helipad nonskid)
- F_k = 676 N > 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)

ρ: 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)

PROPDRIVE (selected motor)

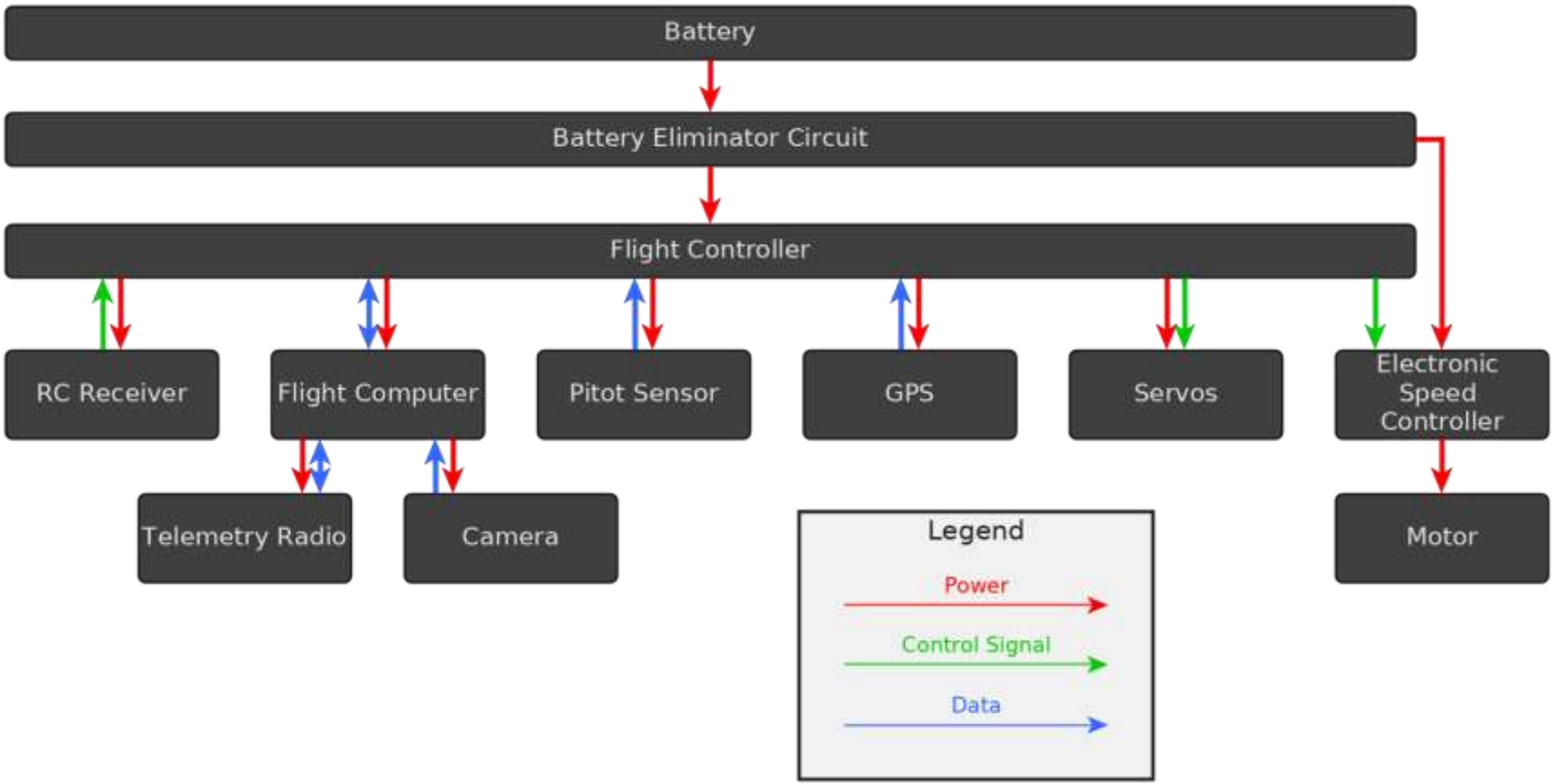
Calculated Thrust: 46.3 N > 30.3 N

Power: 1500 W > 812 W

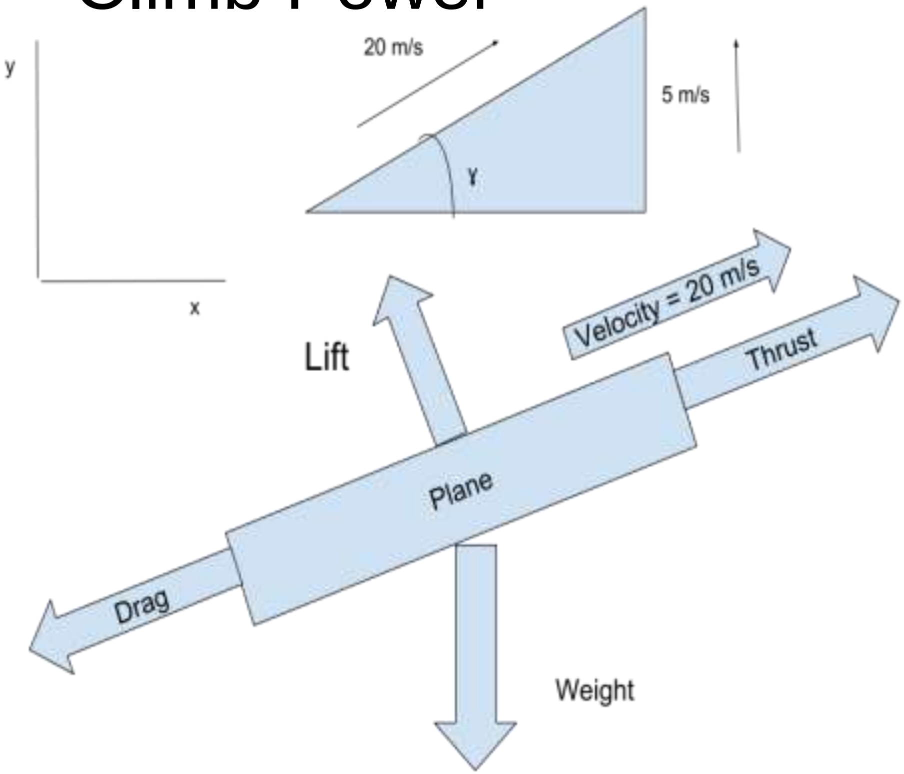
Fulfills 5 m/s climb rate ✓

∴ DR 2.3 Satisfied

Electronics Layout



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]
Thrust

Climb Angle Equation:
sin(ɣ) = (Thrust - Drag)/ (Weight)

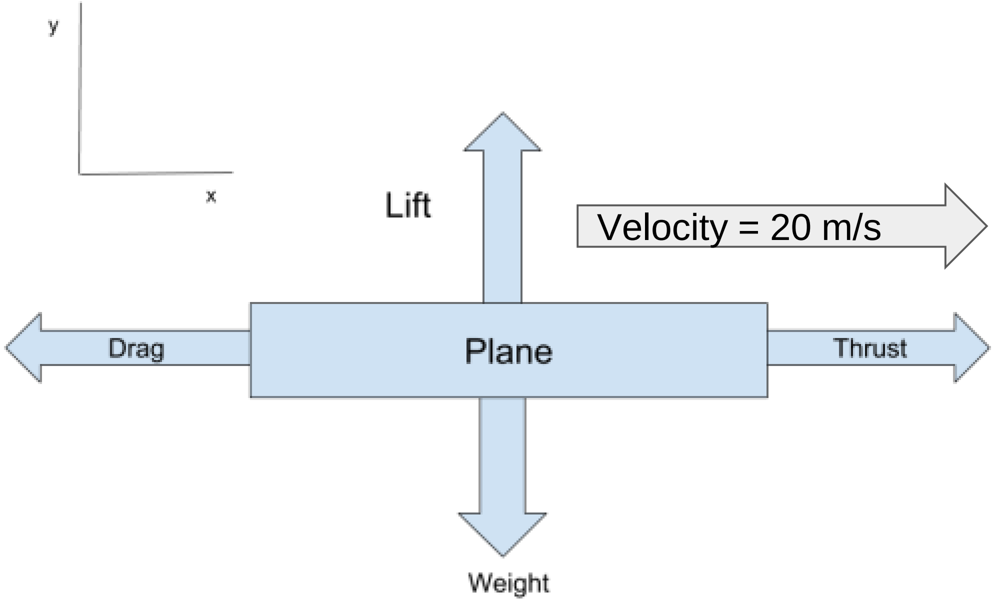
Aim for climb rate of 5 m/s and maintain speed at 20 m/s
From a): $\gamma = \sin^{-1}(5 / 20) = 14.5°$

Solve Climb Angle Equation for Thrust
Thrust = Weight*sin(ɣ) + 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:

Power [W] = Thrust [N] * Velocity [m/s]

Given L/D = 12

Assuming Steady Level Flight

Lift = Weight = 89 N

⇒Thrust = 7.4 N

Using Computed Thrust and Velocity

Power = 7.4 * 20 m/s = 1748 W

Assuming propulsion efficiency of 0.75

Power = 198 W

100 km range with 20 m/s speed ⇒time = 1.4 hrs

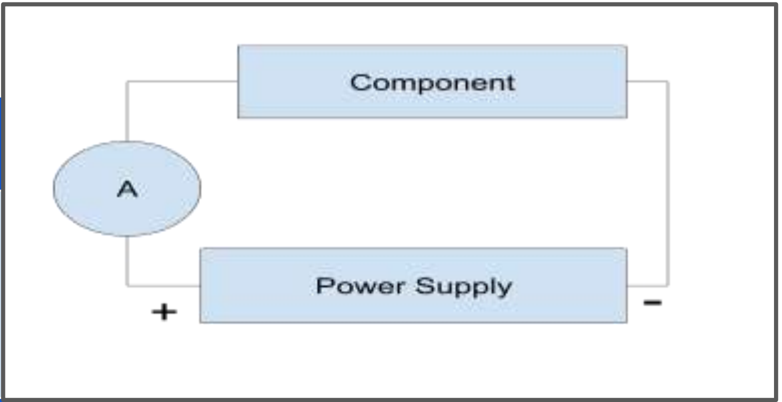
Energy Required = Power [W] * time [hr]

= 198 * 1.4 = 277 Wh

FR 6- Component Current Draw Tests

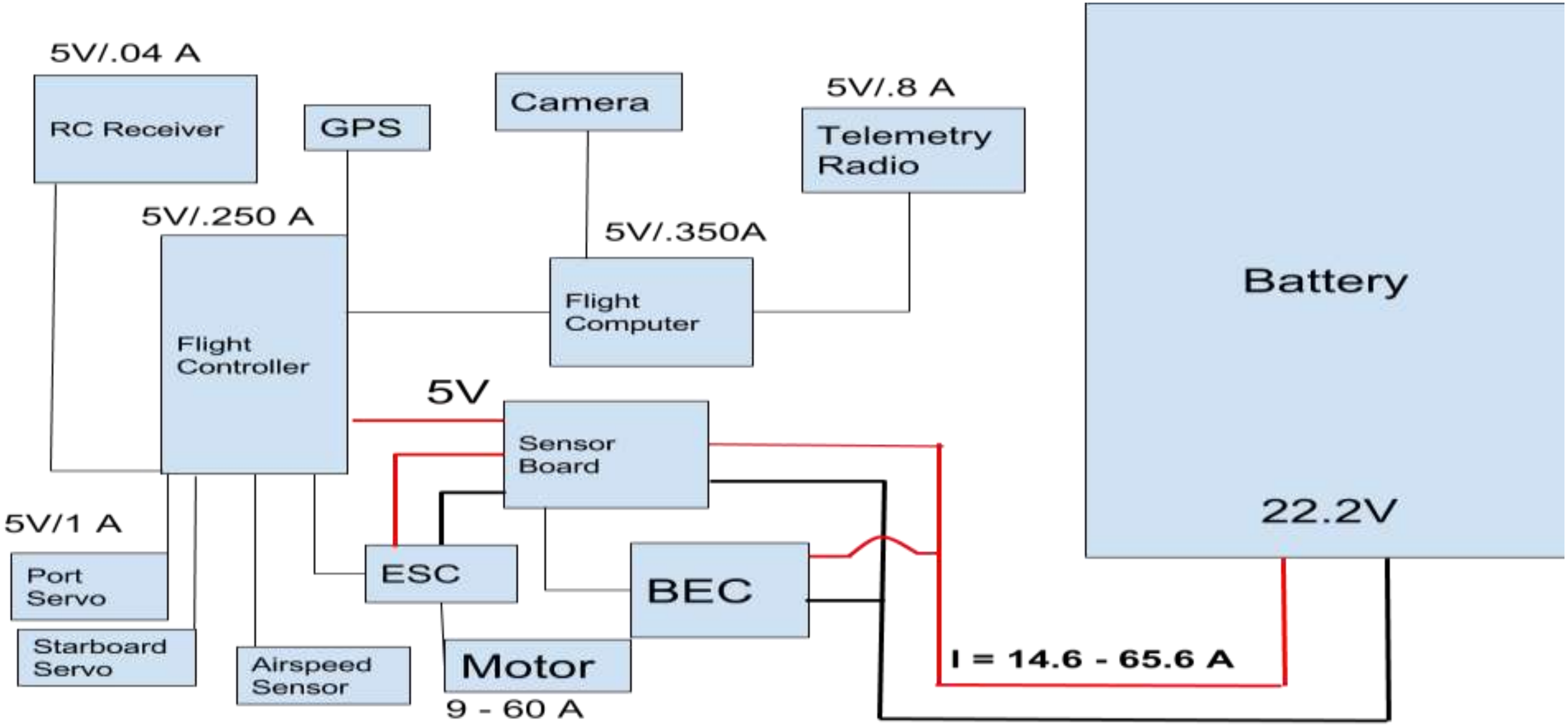
Verify advertised current draw in each component (Radio, GPS, Pixhawk, Servo etc.)

Motivation	Expected Result	Off-Ramp
Confirm Components' **Current Draw**	Actual component current draw is within 10% error of advertised current draw	Reduce required range of mission.



Equipment	Location	Requirements	Satisfied?
Power Supply	ITLL	Able to Supply 5V to component	Access to Power Supplies
Ammeter	ITLL	Able to measure up to 65A of current	Access to Ammeter

Electronics Diagram



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

CPE: Nav/Comm Requirements

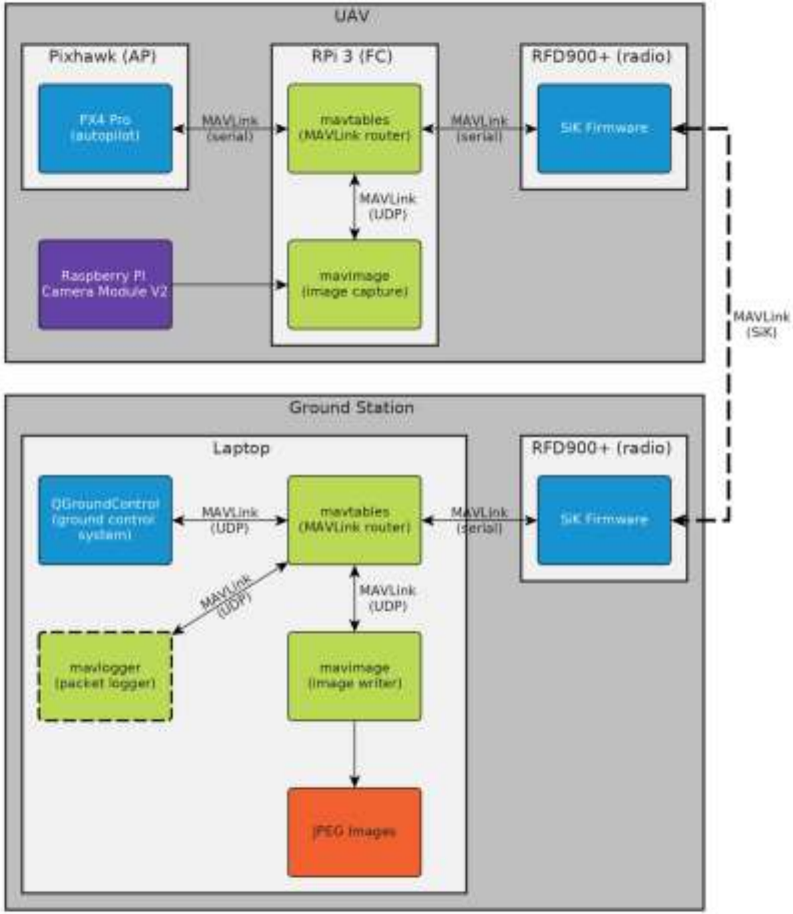
DR 3.2	Aircraft shall capture and transmit images to ground station at 1/60 Hz.

- 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)

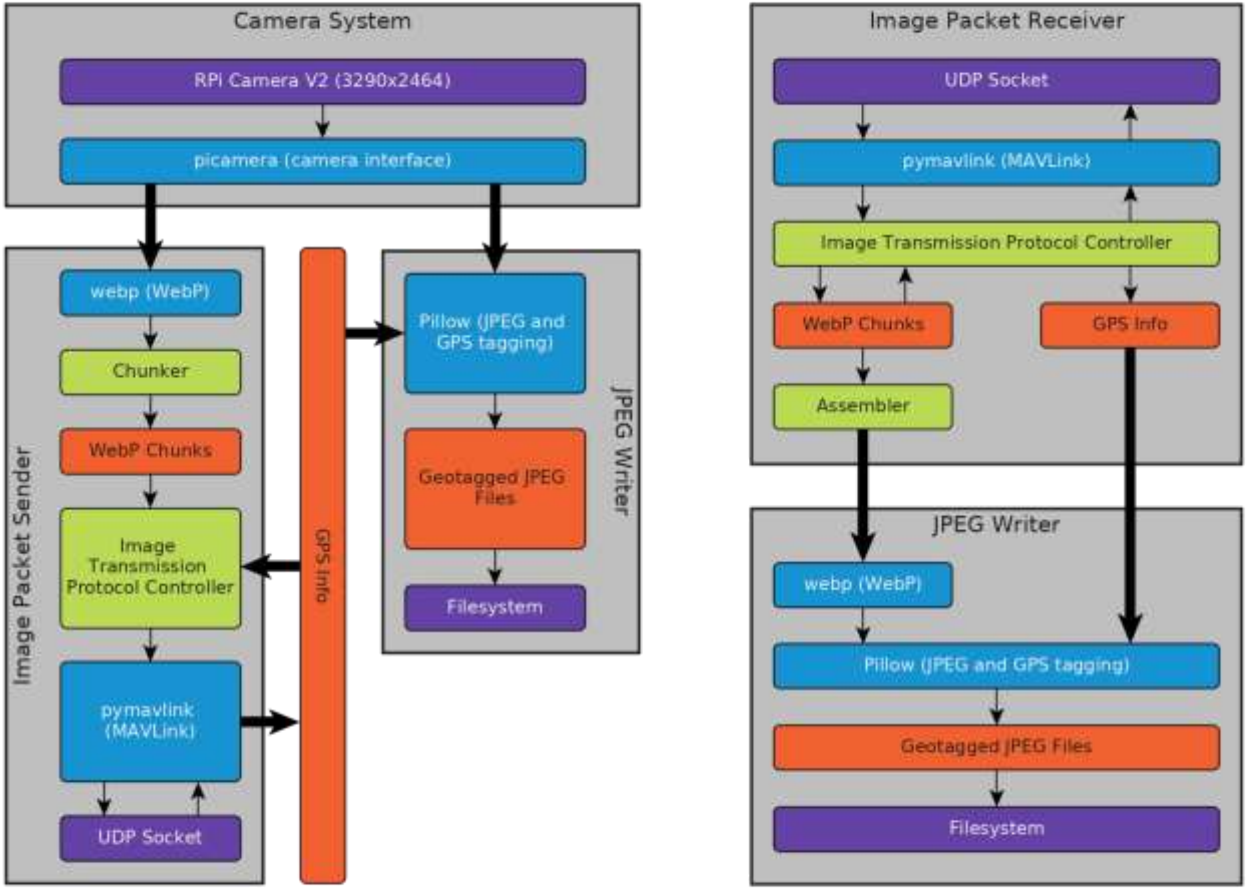
UML diagrams in backup slides and can be provided at full resolution upon request.

From UML class diagrams.

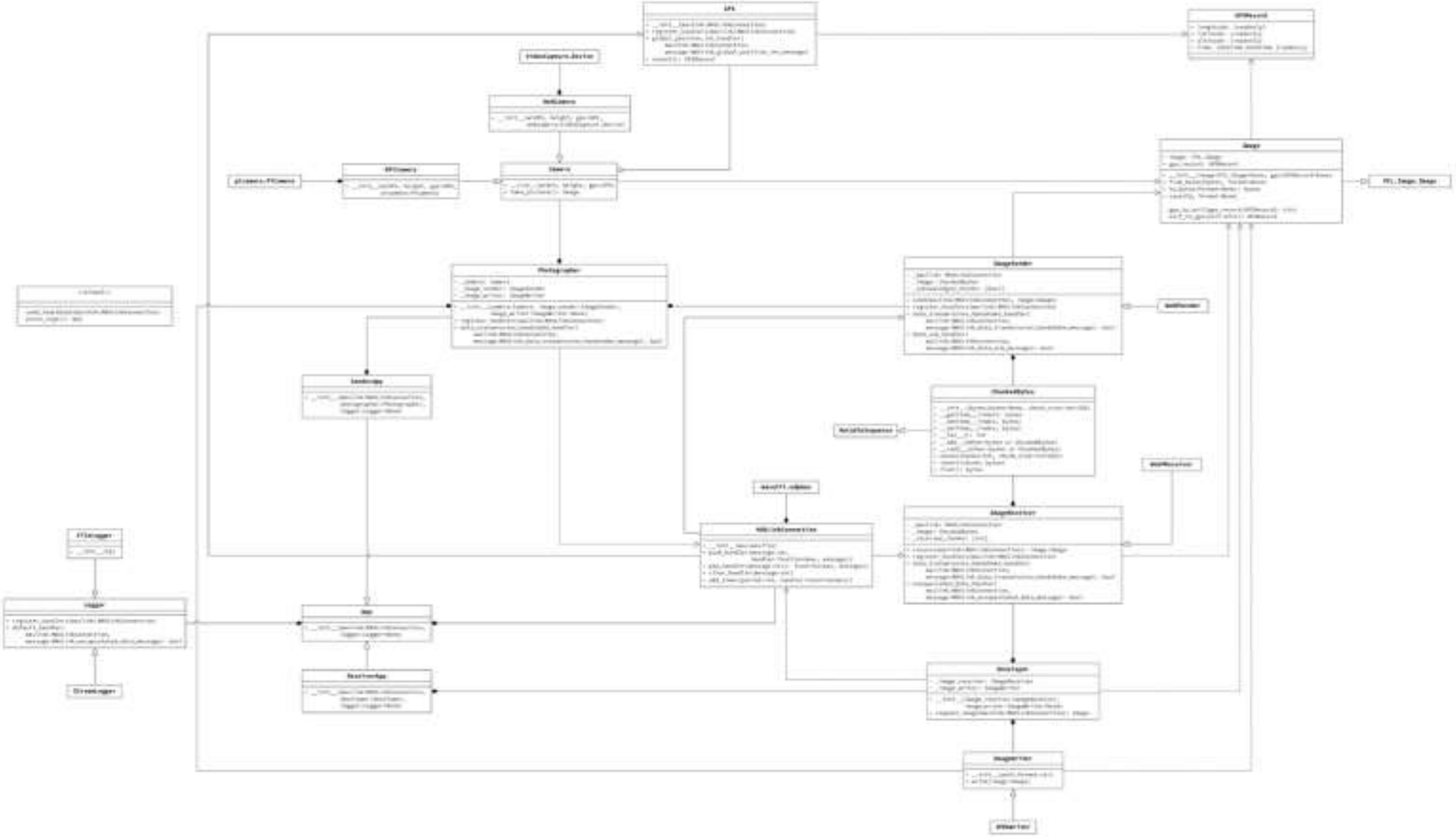
Software Overview



mavimage Overview



mavimage UML Class Diagram



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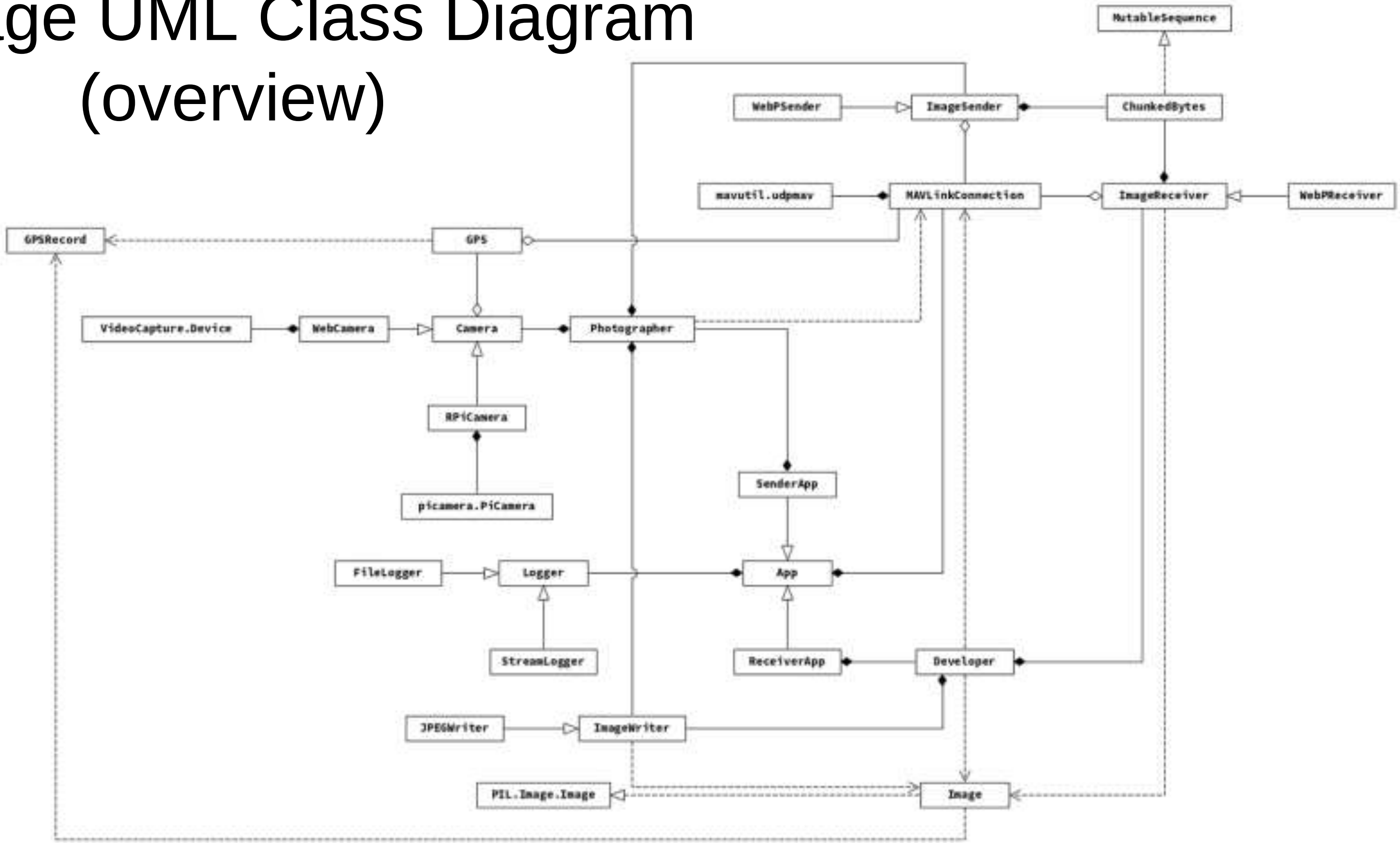
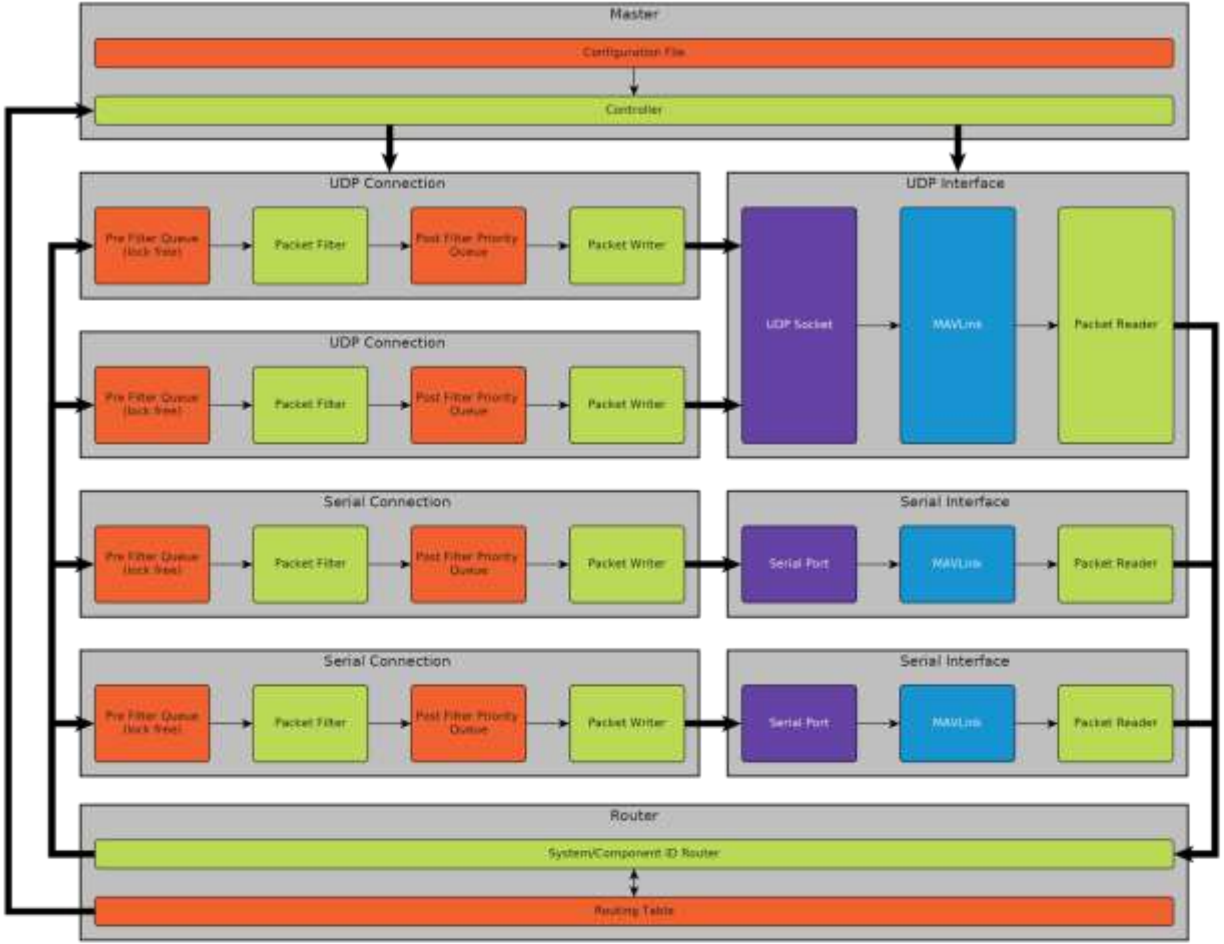
From UML class diagrams.

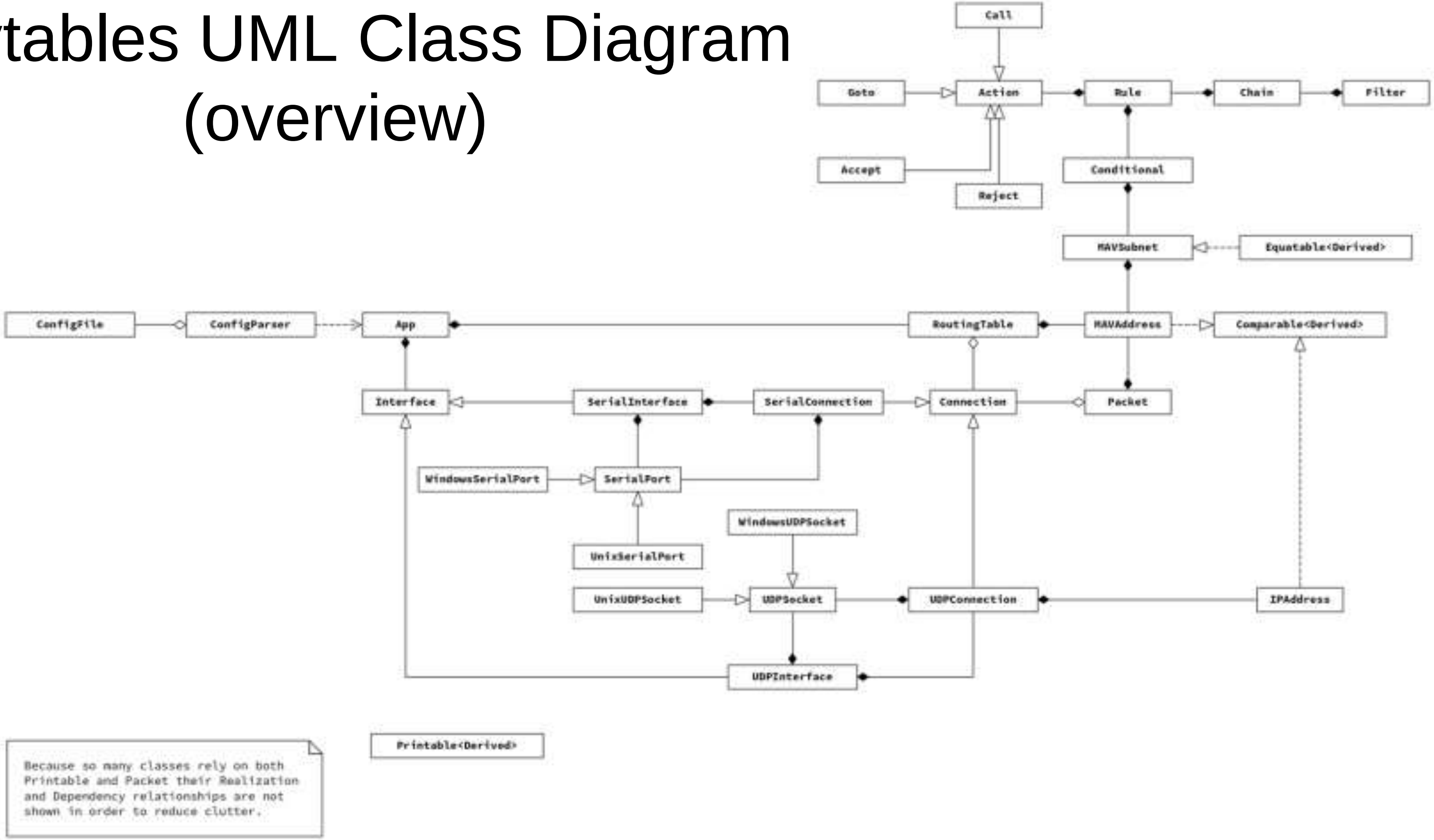
mavimage UML Class Diagram (overview)



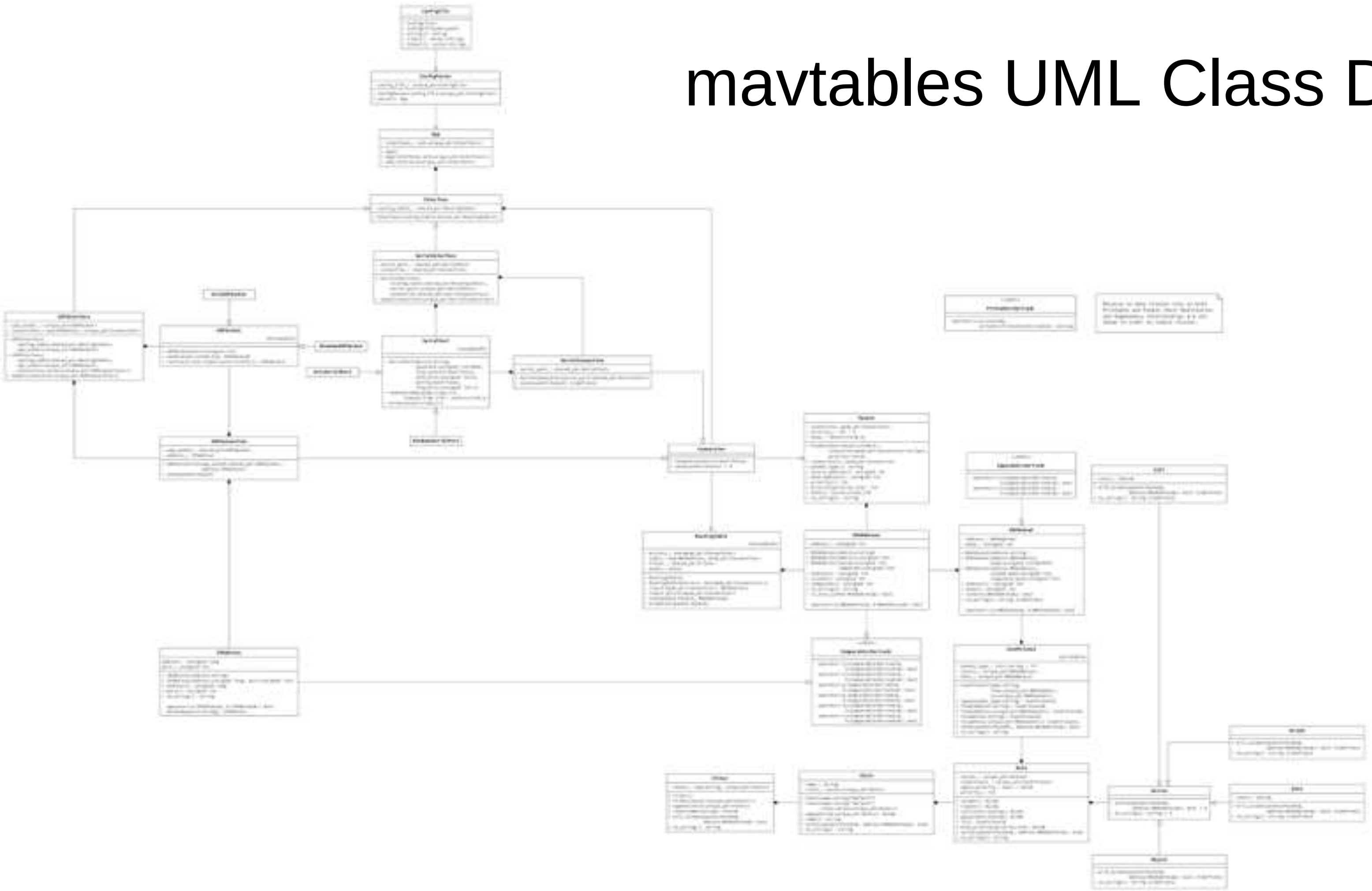
Mavtables Overview



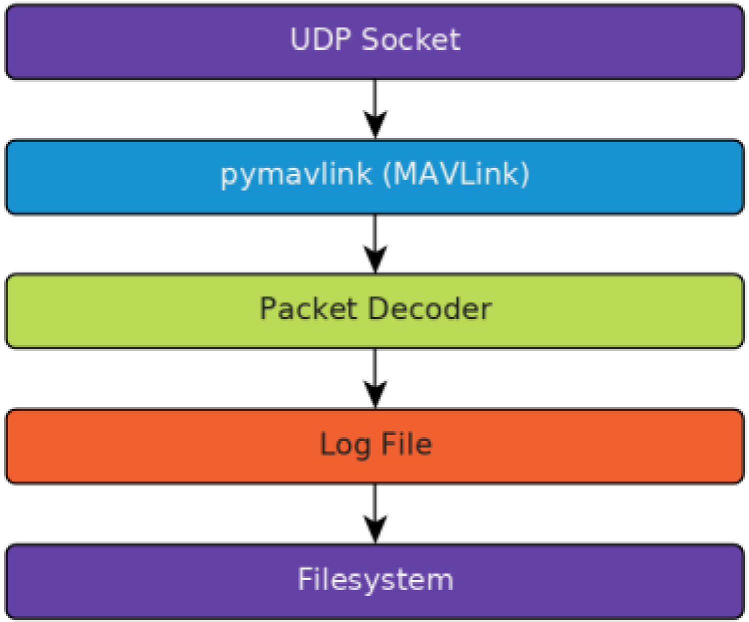
mavtables UML Class Diagram (overview)



mavtables UML Class Diagram



mavlogger Overview



mavlogger UML Class Diagram

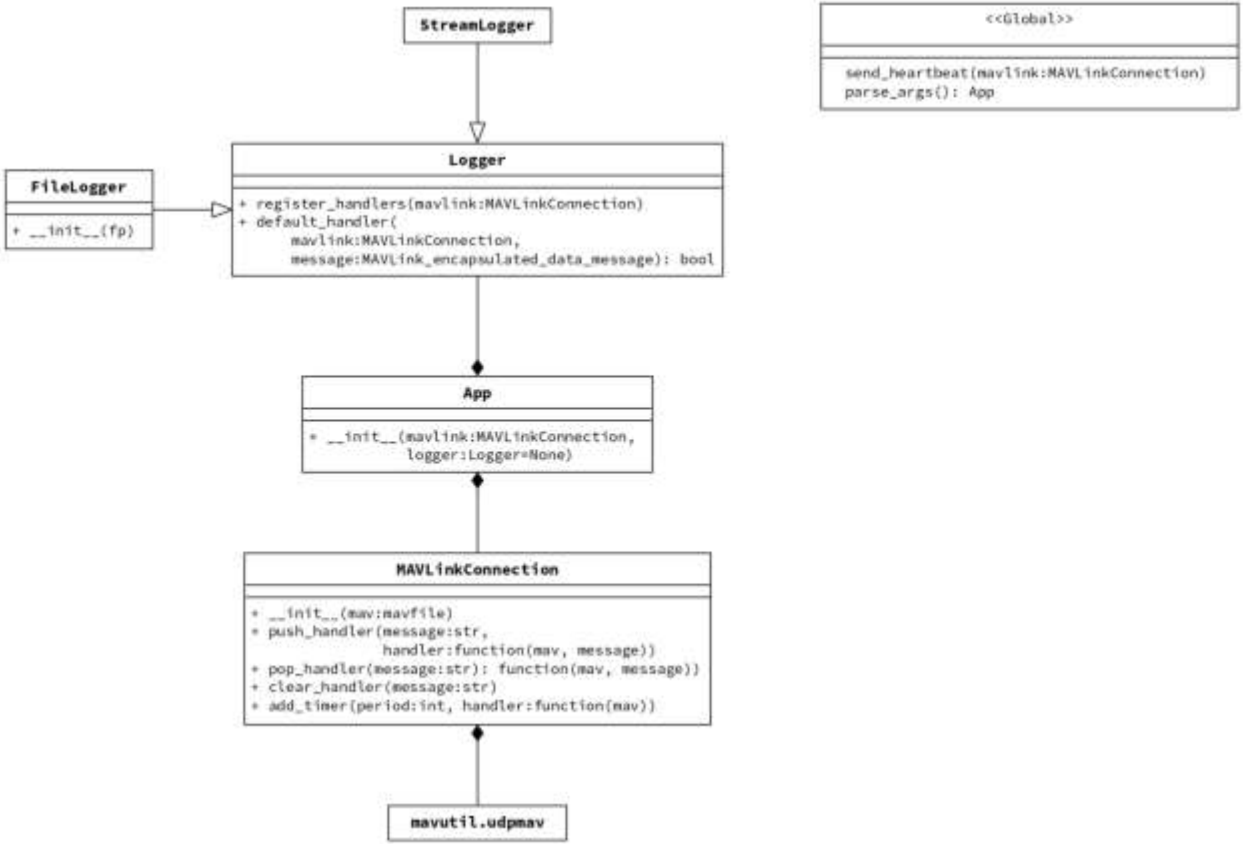
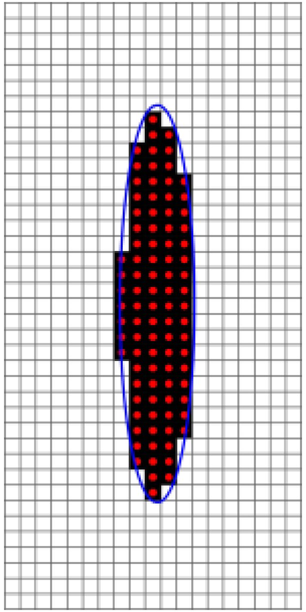


Image Resolution

- 1920x1080 (2MP) - downsampled
- 62^{O} 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.

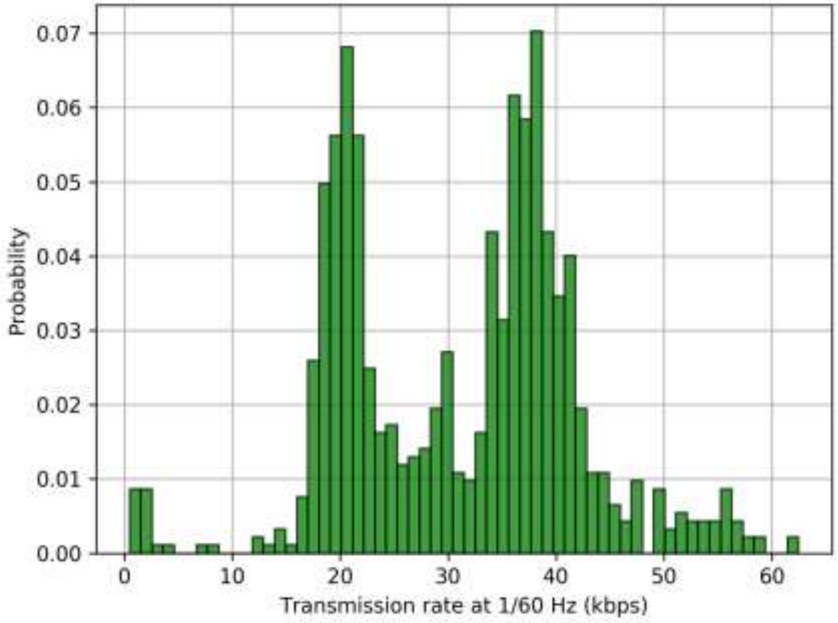


Modified from:
http://a.abcnews.com/images/US/ap_ca_whales_3_141007_4x3_992.jpg

Image Transfer Rate

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

Required Transmission Rate Statistics



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

Datalink Budget

Group	Up (kbps)	Down (kbps)
Virtual Cockpit (telemetry)	0	10.5
Status Information	0	6.9
Image Transfer	0	70.0
Waypoints/Mission Editing	infrequent	0
Needed	**N/A**	**87.2**
Available	**12.5**	**112.5**
Remaining	**N/A**	**25.3**

Can upload ~330 mission items (waypoints) per second with 12.5 kbps.

Testing Backup

Aircraft Tests

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

Launch Tests

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

Recovery Tests

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

Communication Tests

Test	Test set-up	Facilities/ equipment	Off ramps	So What?	Safety	Date
Data-Link Range Test	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	Laptop, 2 rfd900+ 900 Mhz 10 element yagi antenna 2 900Mhz 1/4 wave monopole antennas 5V power supply FTDI cable	If the required data rates fail to function at 12 km, the range of the mission shall be decreased to achievable levels	By successfully transferring an image at the required data rates qualifies the comm system for being able to operate successfully abiding by mission requirements.	Travel locations could be hazardous	Week of 2/1/18

Electronics Tests

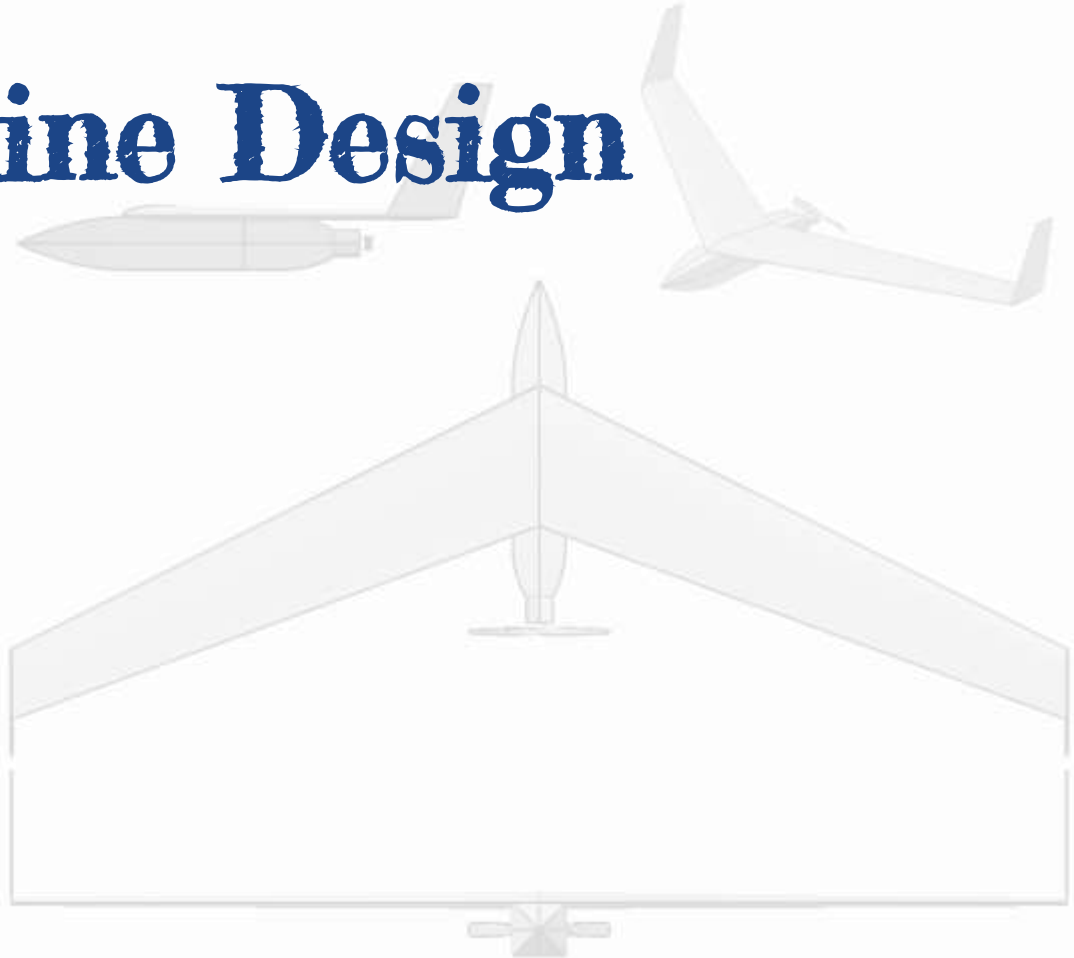
Test	Test set-up	Facilities/ equipment	Off ramps	So What?	Safety	Date
Component Testing	Circuit board laid out	Multimeter Banana clips Oscilloscope Power supply	Power budget can adjust	Must confirm power budget, range of aircraft could be reduced	Can fry a component, blow up	Post TRR
Motor Test	Motor hooked up to power source	Oscilloscope Multimeter Power supply	Change motor, decrease range	Need to validate the thrust output	Can blow up	Pre TRR
Battery Endurance Test	Battery hooked up to resistor load and voltmeter	Oscilloscope Multimeter Power Supply Resistors	Decrease range	Need to validate battery endurance	Can blow up	Pre TRR

Software Tests

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

OLD SLIDES

Baseline Design

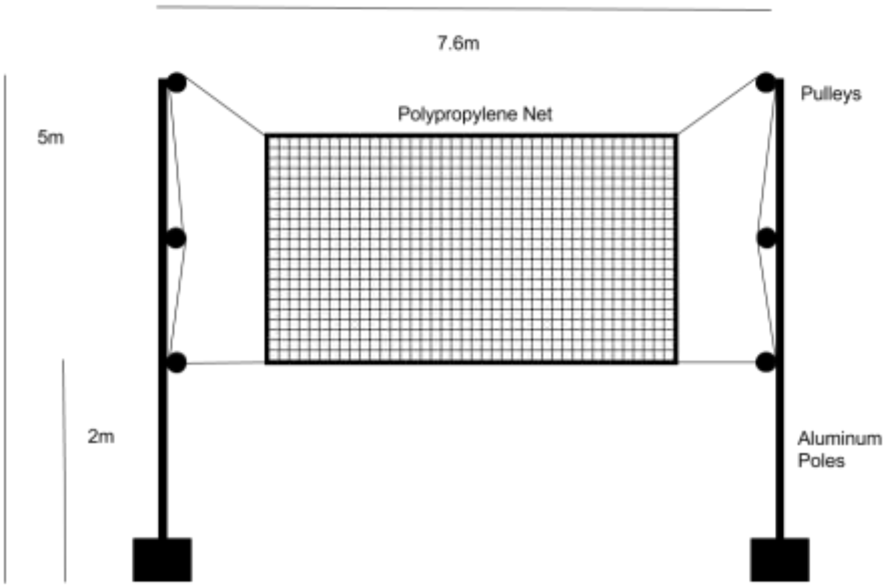


Baseline Design Selection

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

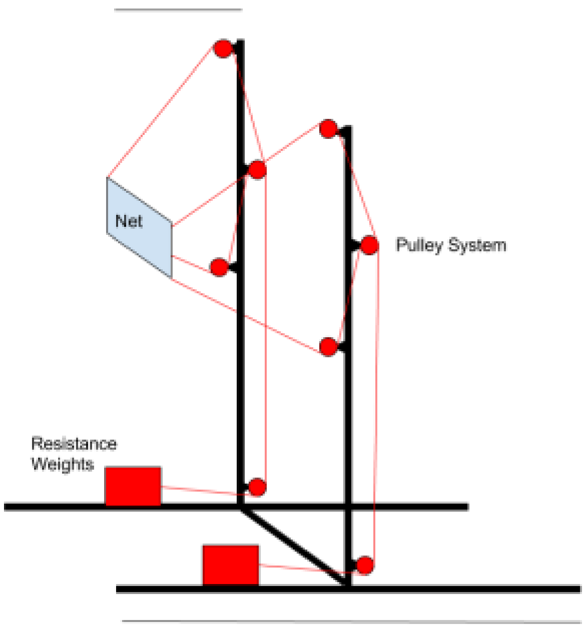
Landing System

- **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**



Landing System - Continued

- **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

Yagi

Omnidirectional

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

Subsystem	Mass Fraction	Mass (kg)
Structure	.35	
Electric Motor	.05	
Autopilot, Flight Computer, RC electronics, Communication System	.05	
Batteries		2.65 kg
Payload		2.00 kg

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.

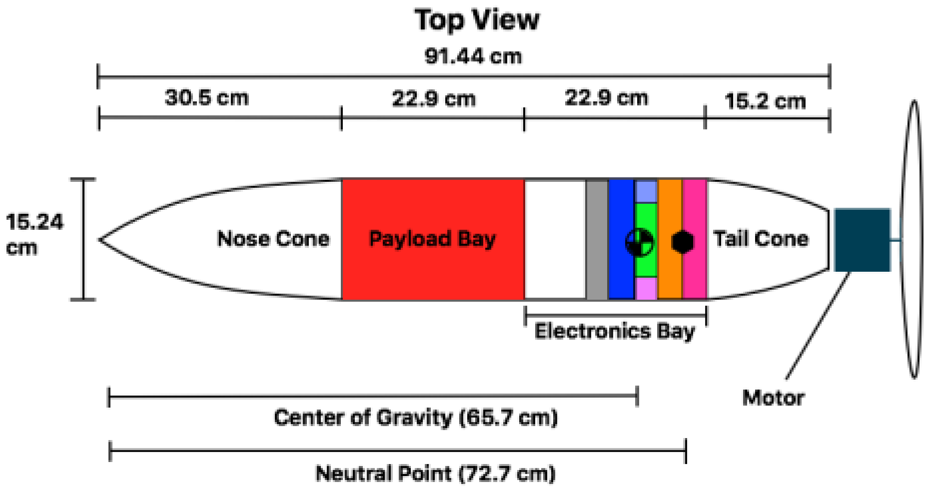
Subsystem	Mass Fraction	Mass (kg)
Structure	0.35	2.96 kg
Electric Motor	0.05	0.42 kg
Autopilot, Flight Computer, RC electronics, Communication System	0.05	0.42 kg
Batteries	0.31	2.65 kg
Payload	0.24	2.00 kg

$$mass = \frac{4.65kg}{.55} = 8.45kg$$

The aircraft mass 8.45 kg < 22.7 kg maximum ∴ Feasible

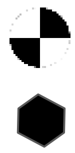
Center of Gravity & Fuselage Layout

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.

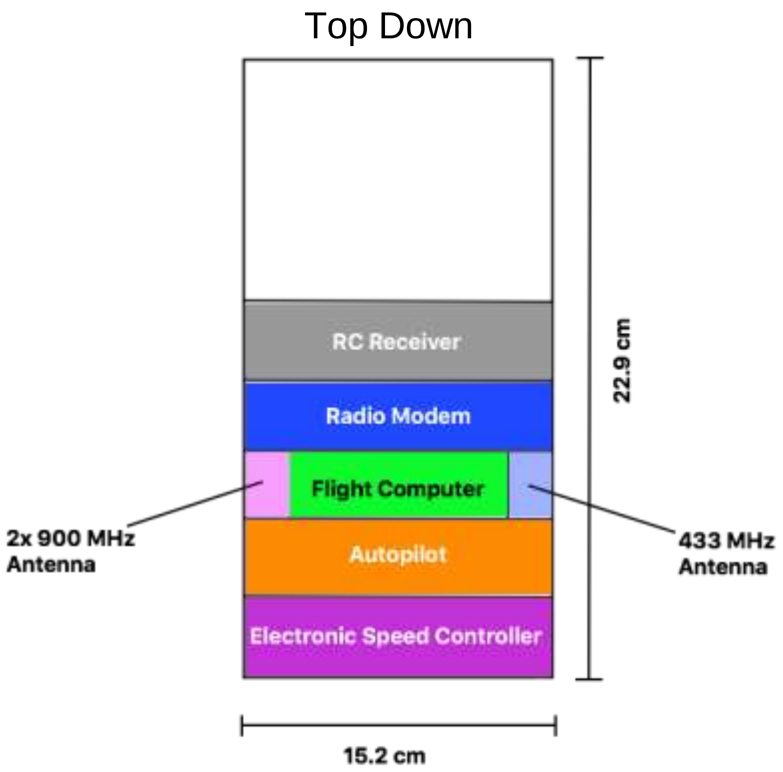
∴ Feasible



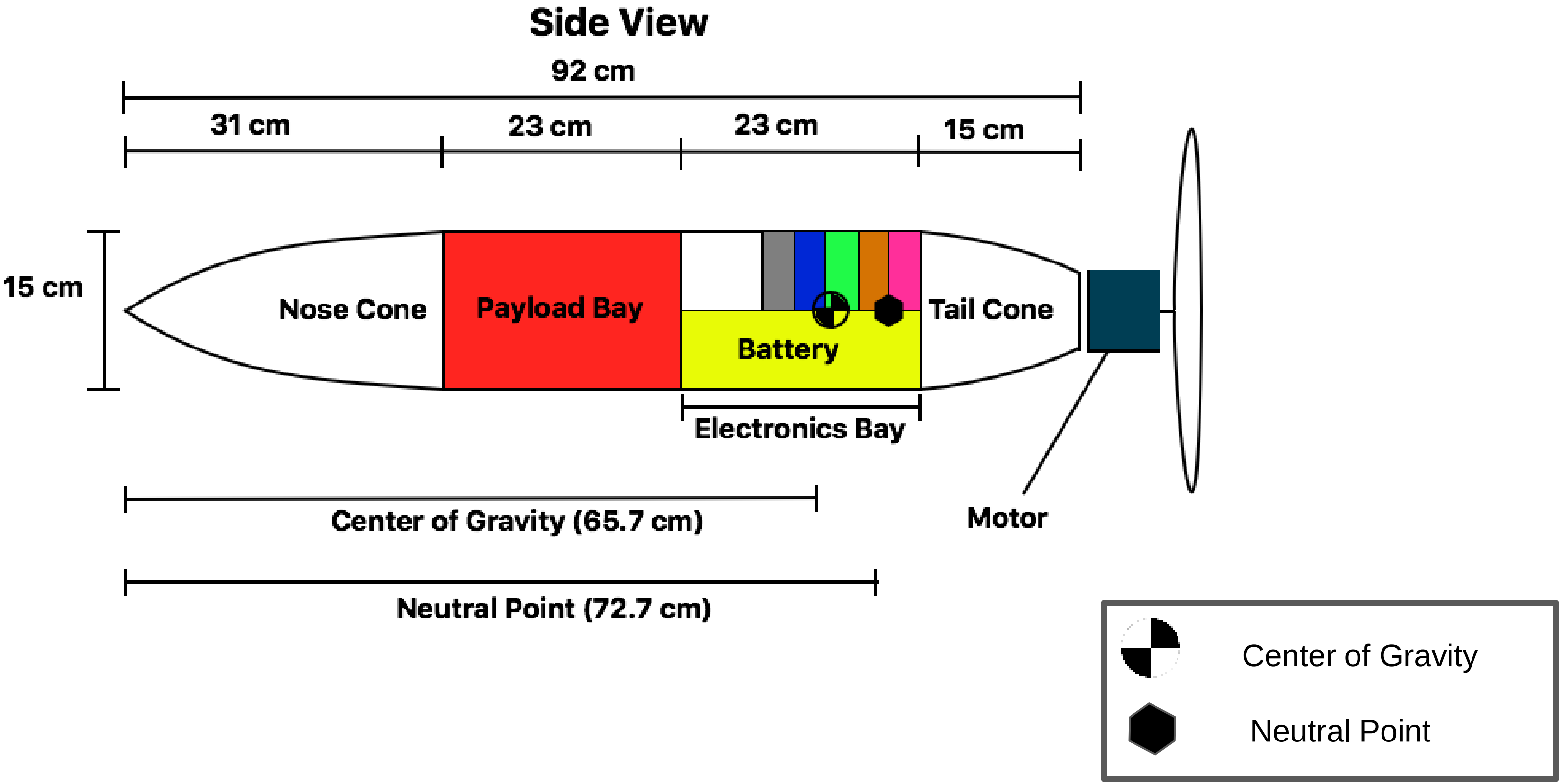
Center of Gravity & Fuselage Layout

- 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)

$$CG = \frac{\Sigma(weight_{component} * distance_{fromnose})}{weight_{total}}$$



Center of Gravity & Fuselage Layout



Wing Area and Aspect Ratio

- **Wing area S = 0.93 m²**
  - W = 84.9 N (Total aircraft mass = 8.45 kg)
  - Stall speed V_s = 11.0 m/s
  - $(C_L)_{max} \cong 1.2$
    - Reynolds number

$$L = \frac{1}{2}\rho V^2 C_L S$$

$$S = \frac{W}{\frac{1}{2}\rho V_S^2 C_{Lmax}}$$

- Aspect ratio based on span limit of 3 m → AR = 10.0

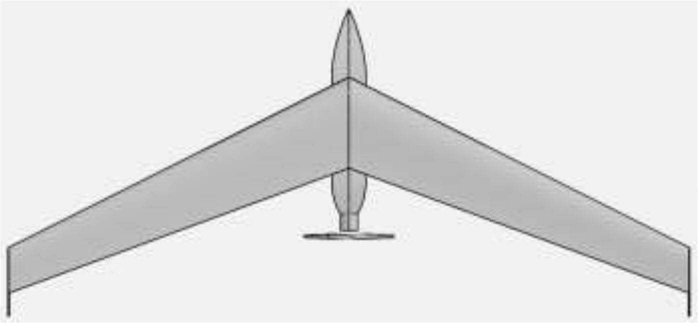
$$AR = \frac{b^2}{S}$$

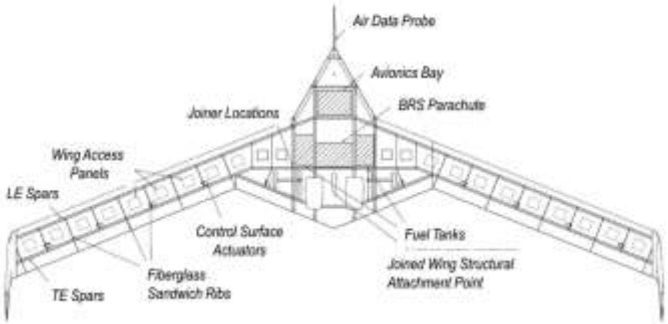
Wing area and coefficient of lift satisfy stall requirement of 11 m/s

Wing Sweep

- Helps satisfy stability and controllability requirements

- Similar aircraft with similar flight missions





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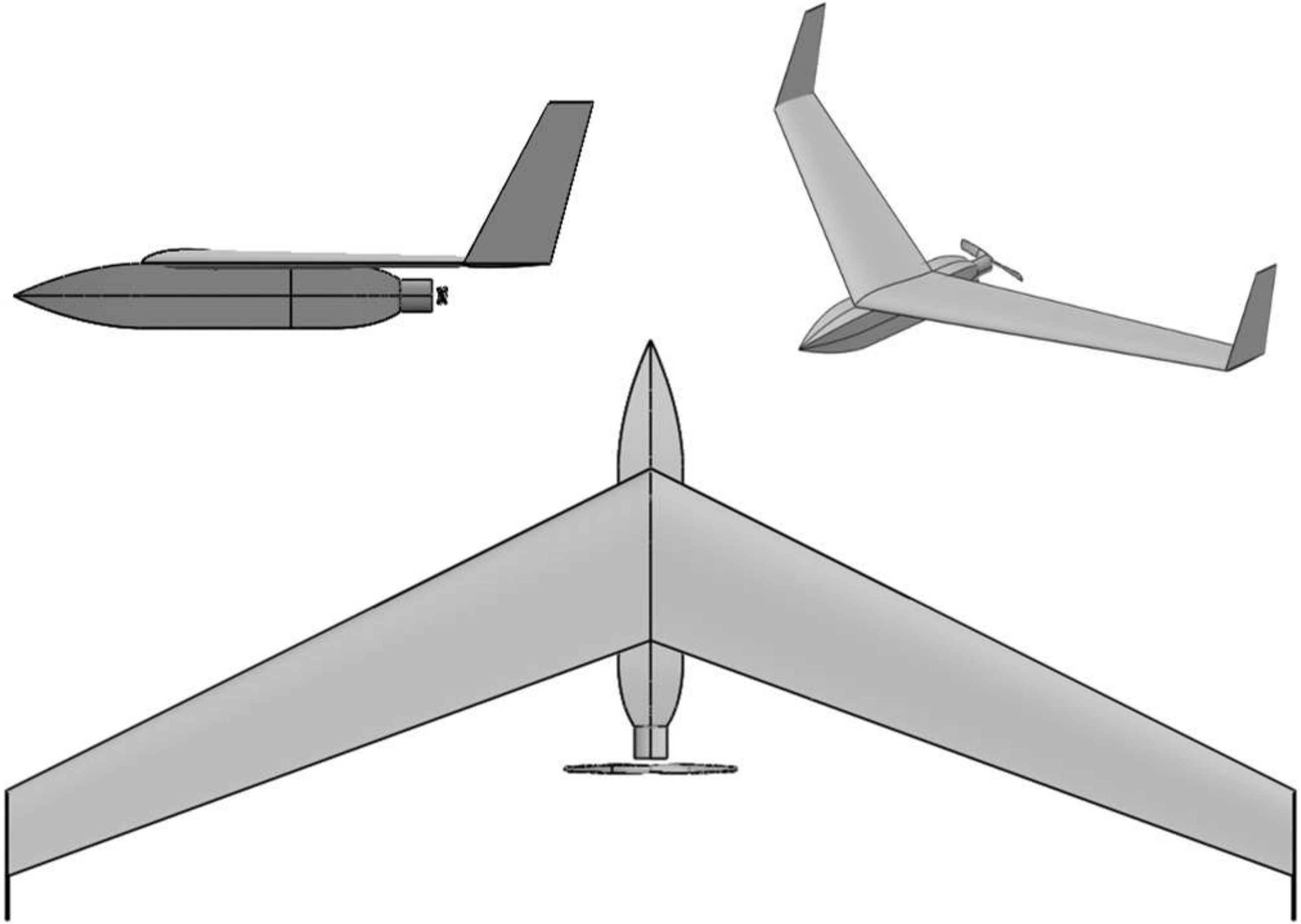
http://nick-stevens.com/wp-content/uploads/2016/12/marswing_ortho_setx.jpg

https://img.newatlas.com/insitu-scaneagle2-1.png?auto=format%2Ccompress&fit=max&h=670&q=60&w=1000&s=19accc2dfdc8f20c1330a8264063b3e0

https://img.banggood.com/thumb/water/oaupload/banggood/images/FA/F6/22135daa-d191-6ecd-fa67-252ce7a3dd1b.jpg

Layout



L/D

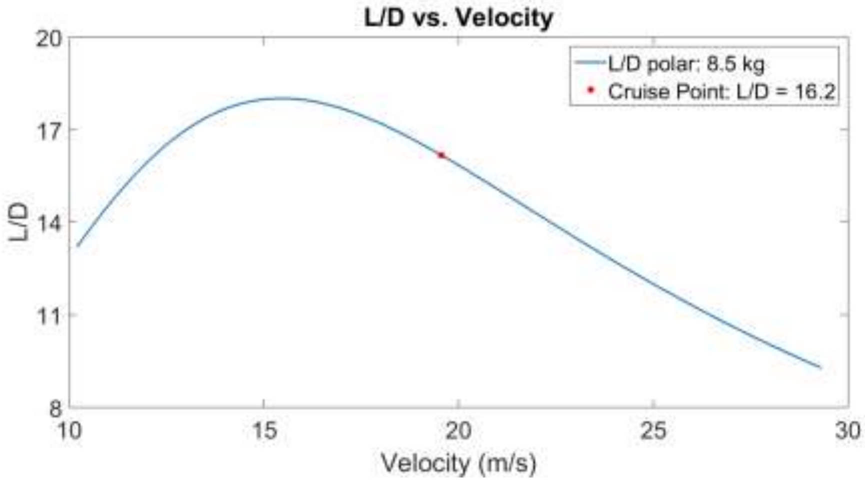
Requirement: The aircraft shall have an L/D of at least 12.

- Historical data (RECUV aircraft and AAA)
- OpenVSP model: L/D_{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:

$$L/D = \frac{C_L}{C_{D0} + \frac{C_L^2}{\pi e AR}} = 16.2$$



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.

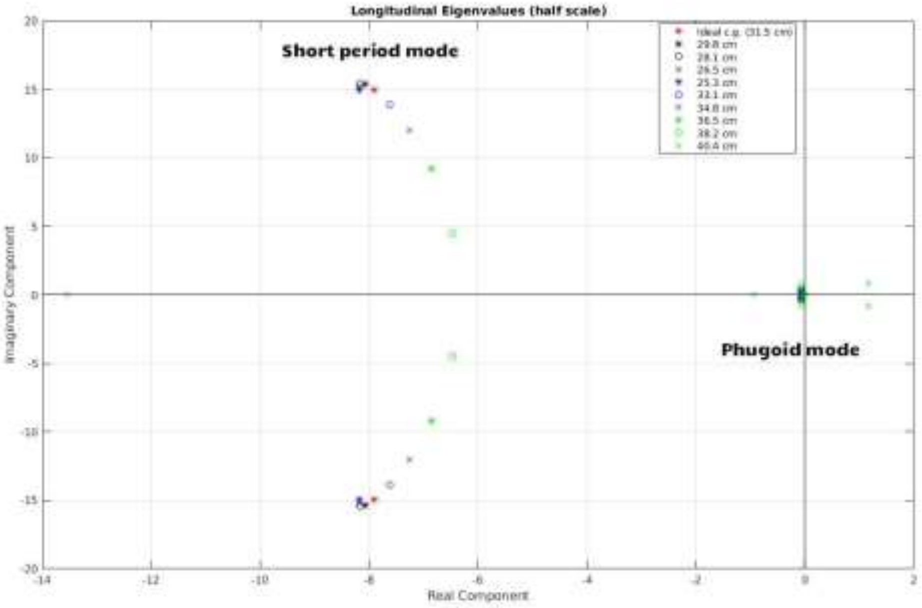
- Design will be transported in 5 pieces: Fuselage, 2 separate wings, 2 separate winglets.

Part	Dimensions
Fuselage	15 cm x 15 cm x 92 cm
Half-Wing	5 cm x 41 cm x 152 cm
Winglet	0.5 cm x 29 cm x 38 cm

Fit together, dimensions are 25.5 cm x 41 cm x 152 cm (less than 46 cm x 122 cm x 168 cm)
∴ 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

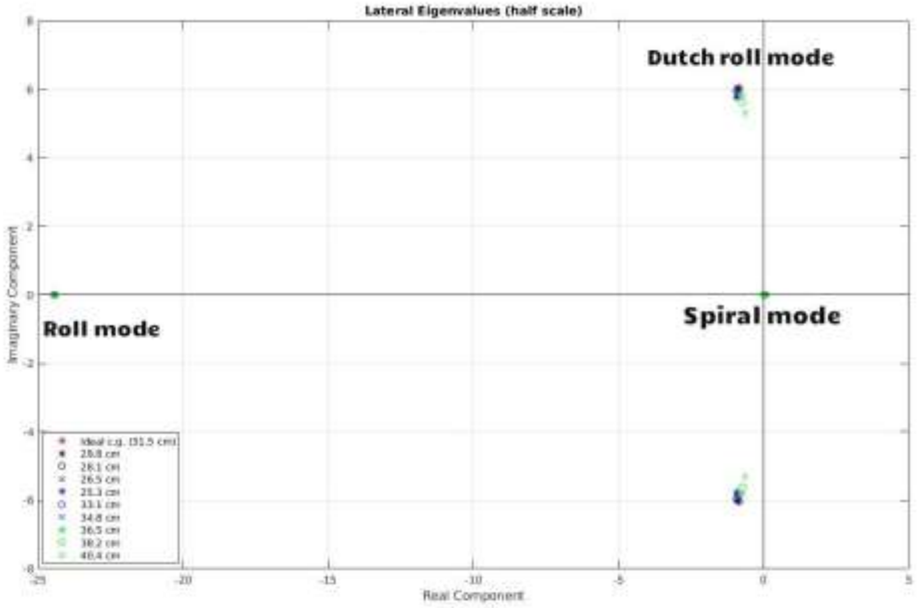
Aircraft Stability (half scale)- AVL/Matlab

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

Roll mode - very stable

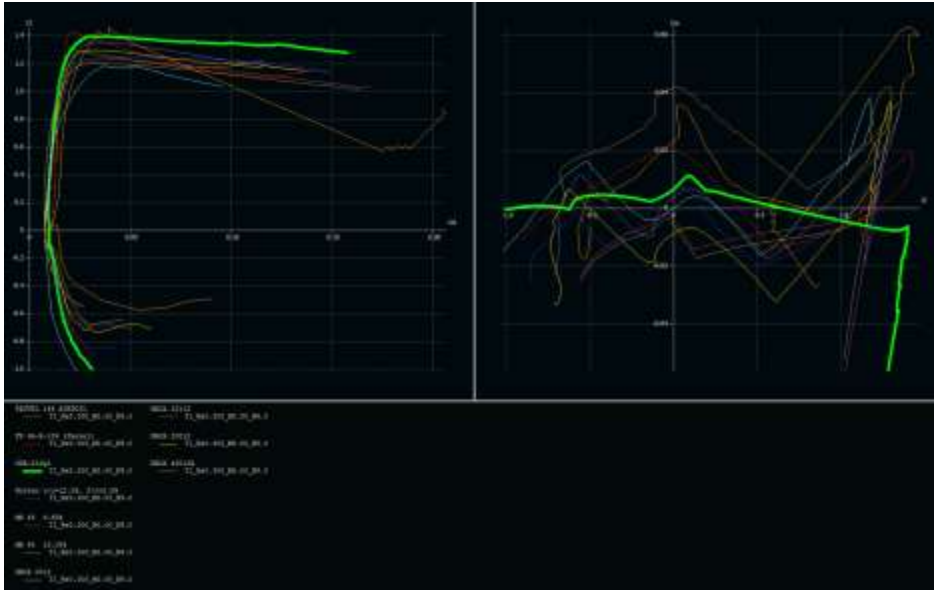
Dutch roll; Spiral modes - slightly stable for C.G. range of 25.3 cm - 38.2 cm.

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



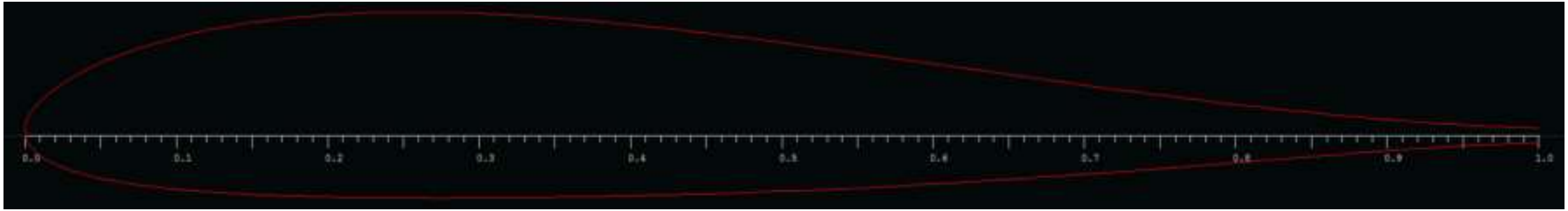
Airfoil

- Thickness
  - Need to get a spar through the wing
  - C_{Lmax} required
  - ⇒ ≥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?”



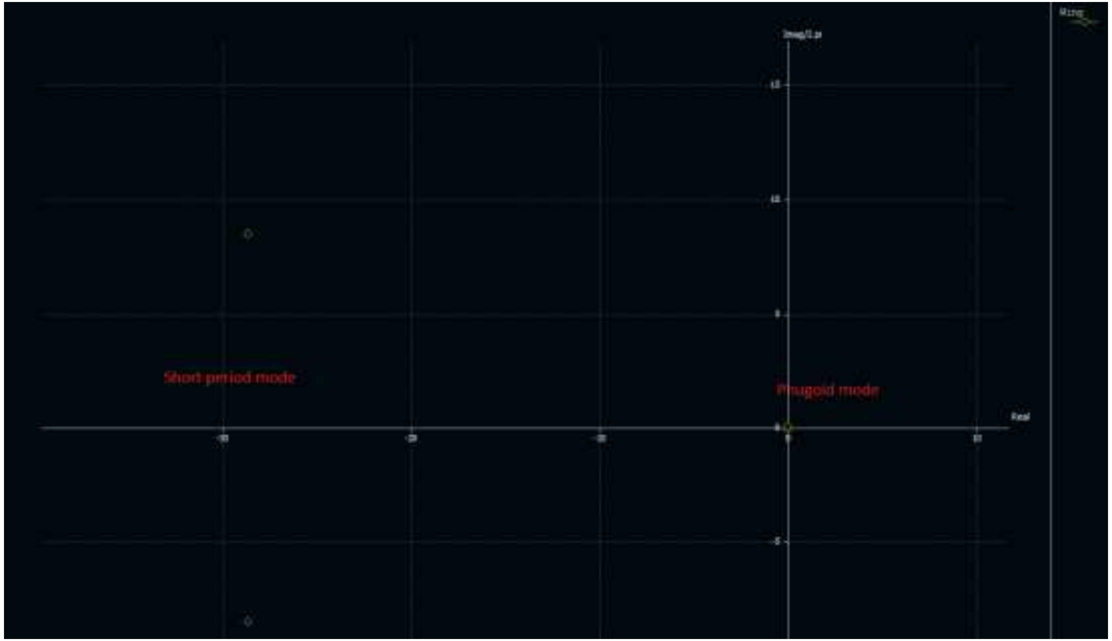
Airfoil

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



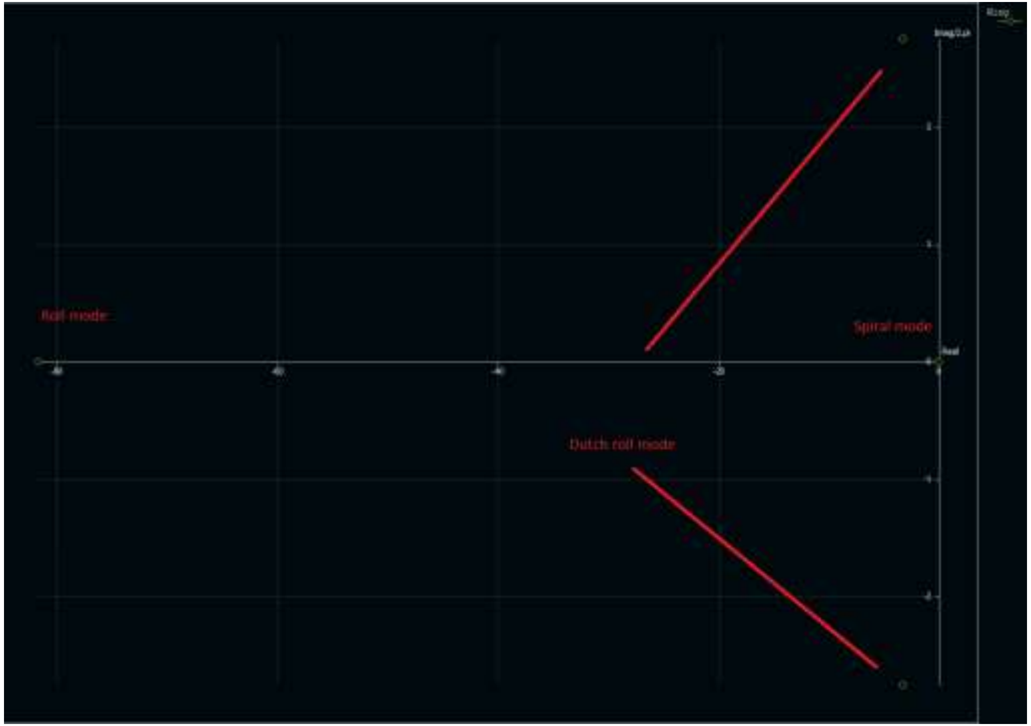
Aircraft Stability- XFLR5

- Longitudinal eigenvalue plot

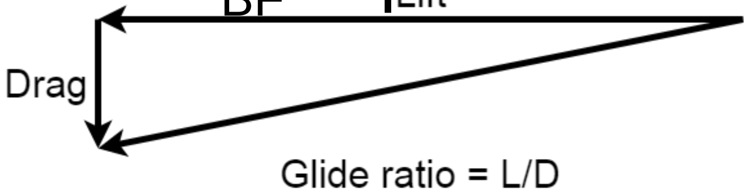


Aircraft Stability- XFLR5

- Lateral eigenvalue plot



M_{BF} Equation



$$E = mg\Delta h$$

$$\eta_p E = \frac{mgr}{L/D}$$

$$\eta_p d_{bat} m_{bat} = \frac{mgr}{L/D}$$

$$m_{bat} = \frac{mgr}{\eta_p d_{bat} L/D}$$

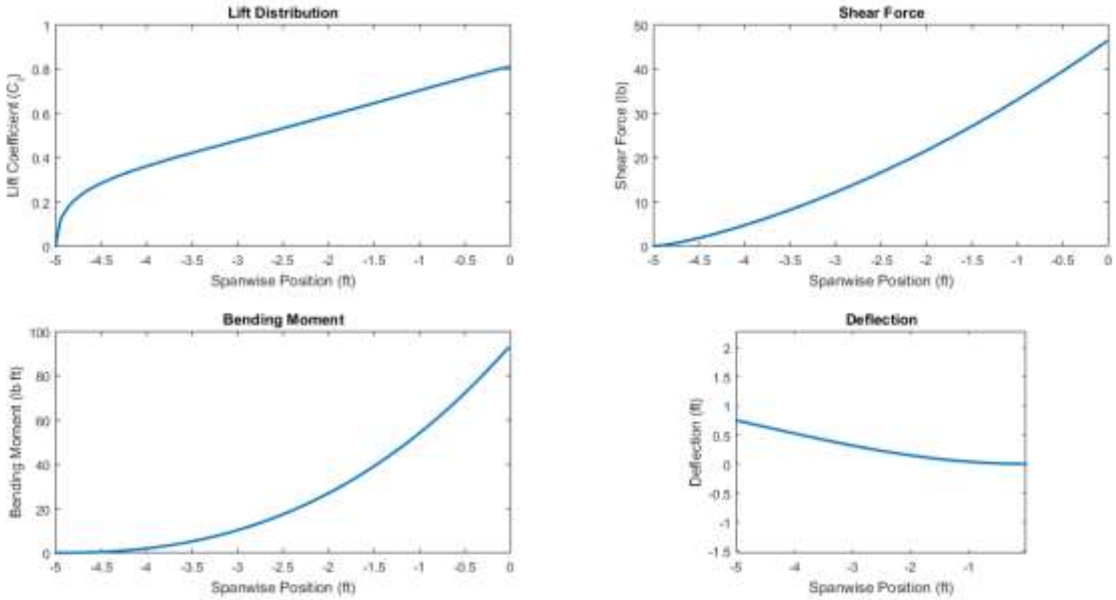
$$\frac{m_{bat}}{m} = \frac{rg}{\eta_p d_{bat} L/D}$$

$$M_{BF} = \frac{rg}{\eta_p d_{bat} L/D}$$

Wing Structure Modeling

Requirement: The aircraft shall have an operational *g* 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