CETI | SHAMU

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

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

Preliminary Design Review

Team

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Project Description

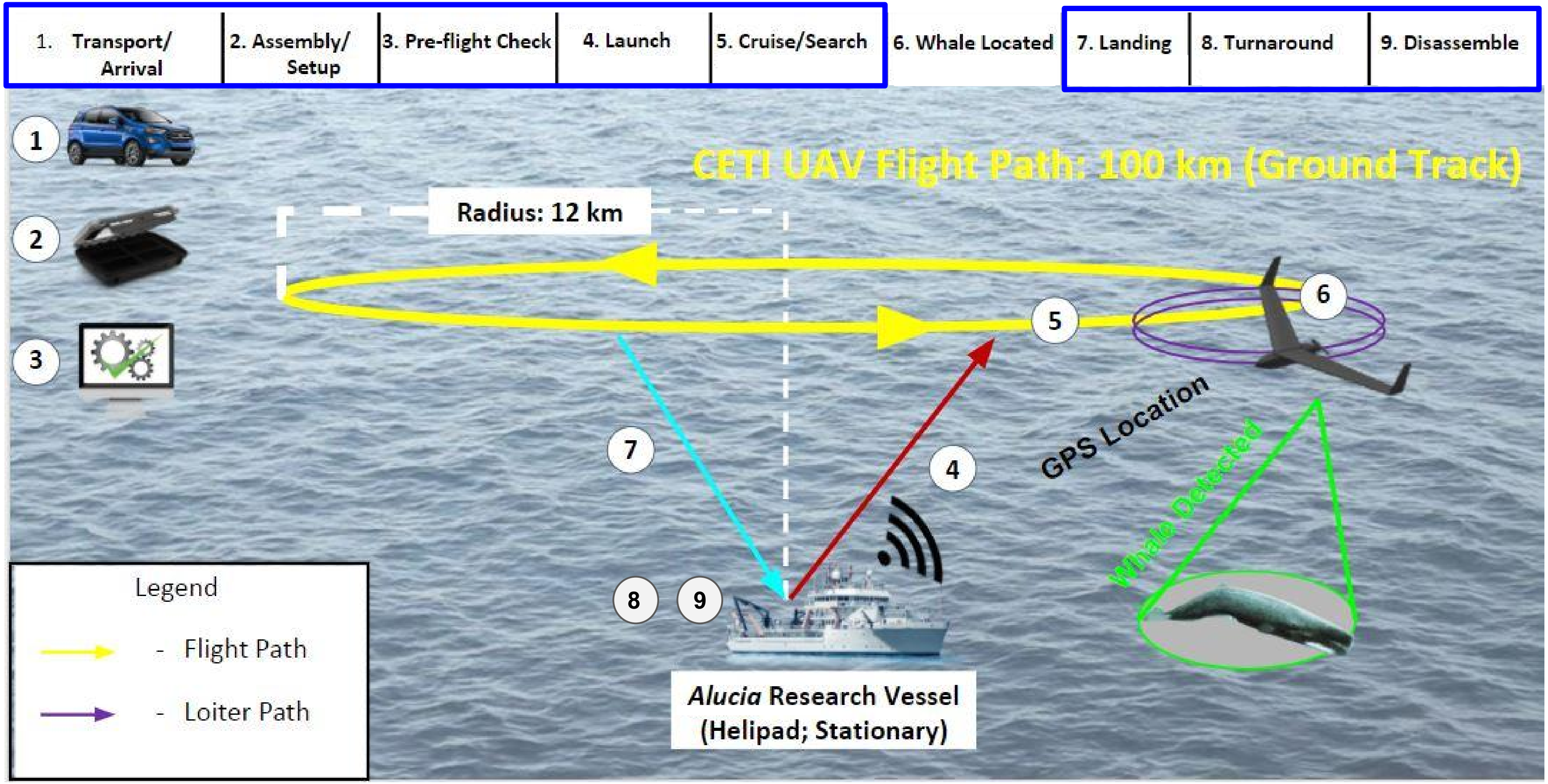
Search and **H**elp **A**quatic **M**ammals **UAS**

will design an **unmanned aerial system** to carry a **<u>future</u>** instrument payload capable of **locating sperm whales in the ocean.** The unmanned aerial vehicle will be **launched and recovered from a research vessel’s helipad.**

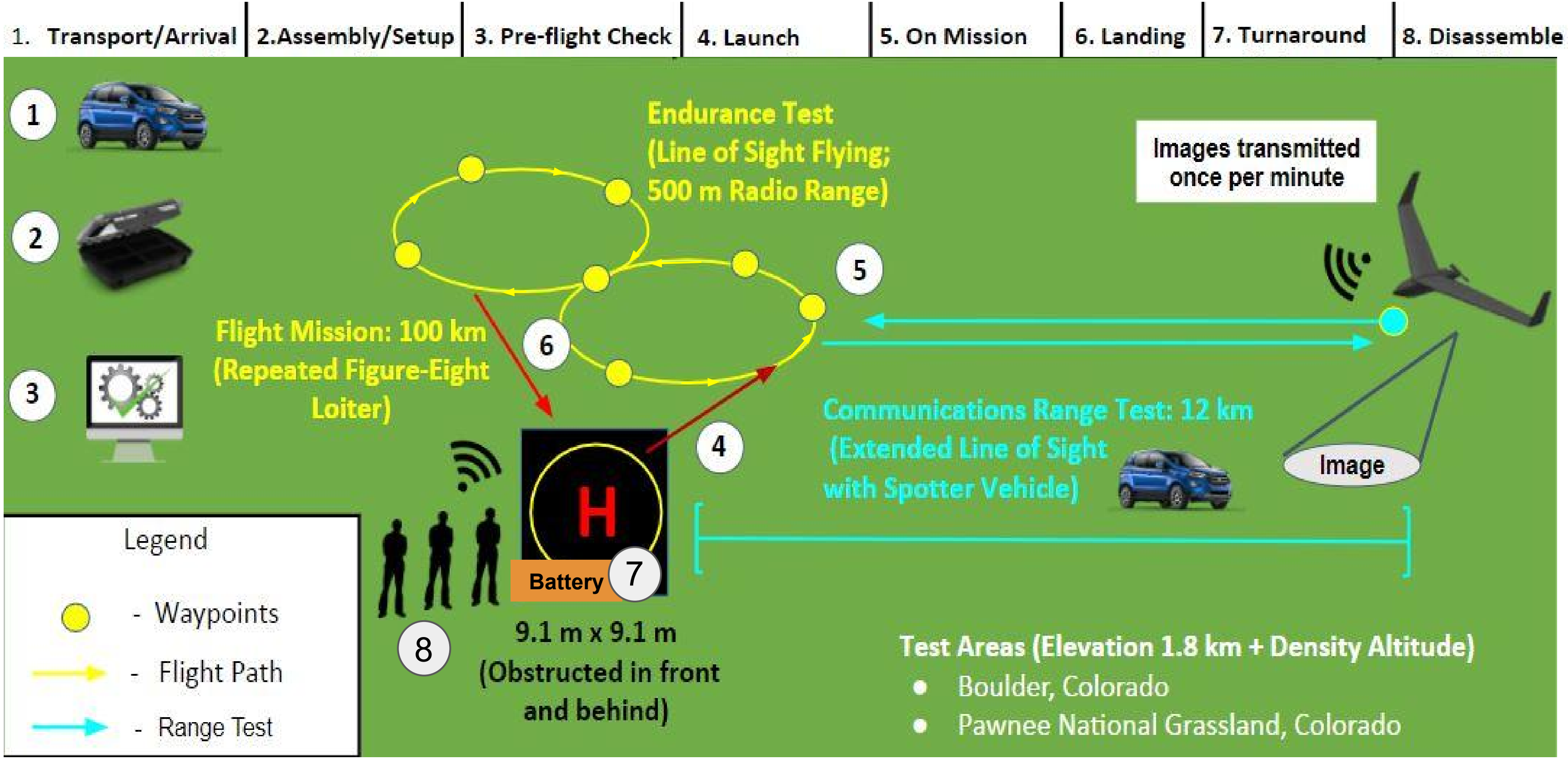
Scope Down Details

Previous Scope	**Current Scope**
Whale Detecting Sensor / Livefeed video	Camera captures and transmits 1 image / minute
Flight Mission Range: **400km**	Flight Mission Range: **100km**
Vertical Takeoff / Landing	Bungee Launch / Net Landing
Update Flight Waypoints: Capability while executing current flight mission	Update Flight Waypoints: Must enter autopilot loiter mode during transmission

Multi-Year User CONOPS



SHAMU Test CONOPS



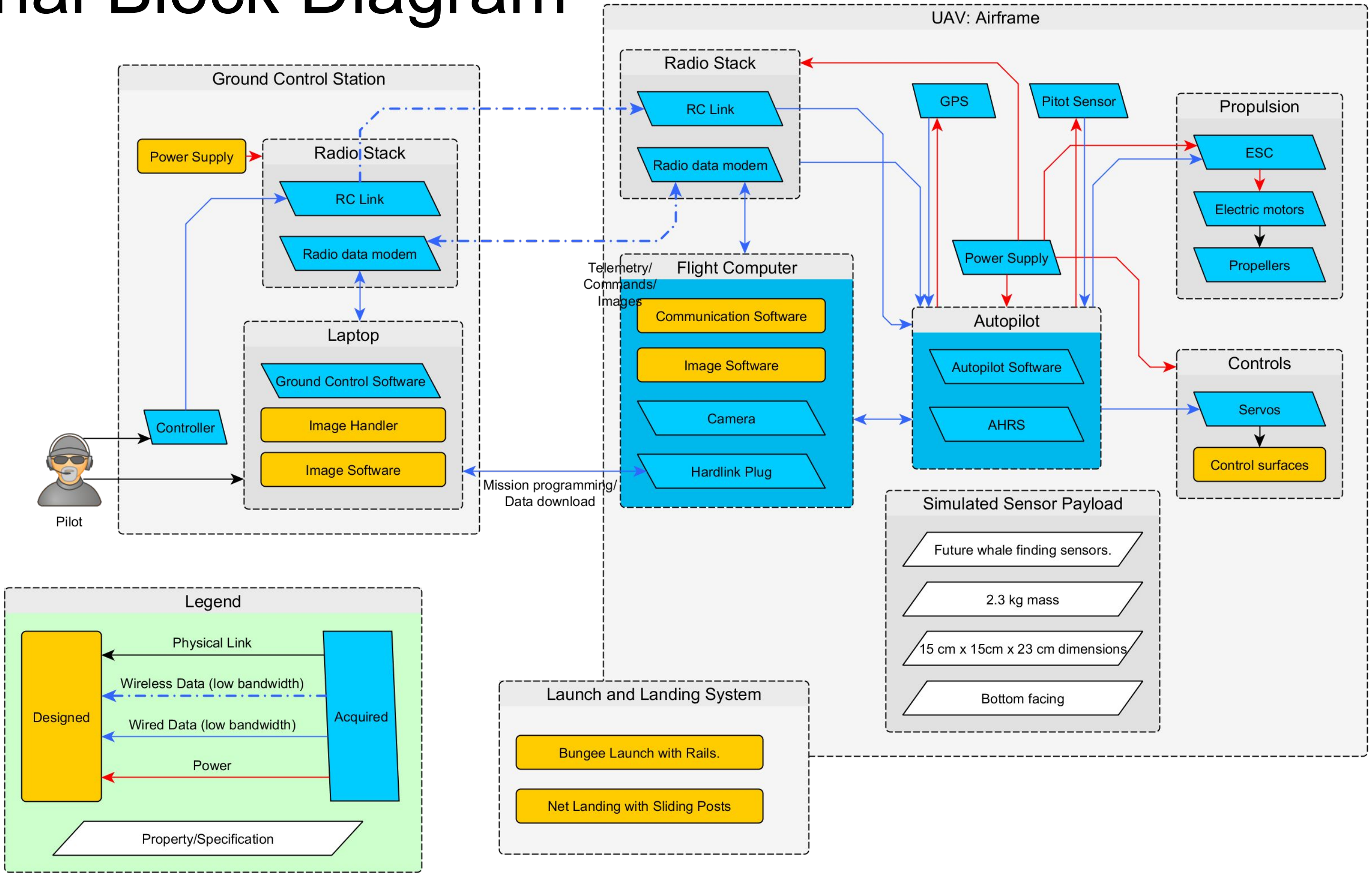
Functional Requirements

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 from ground control station.

Functional Requirements

4.	Aircraft supports **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.	**100 km ground track range endurance.**

Functional Block Diagram

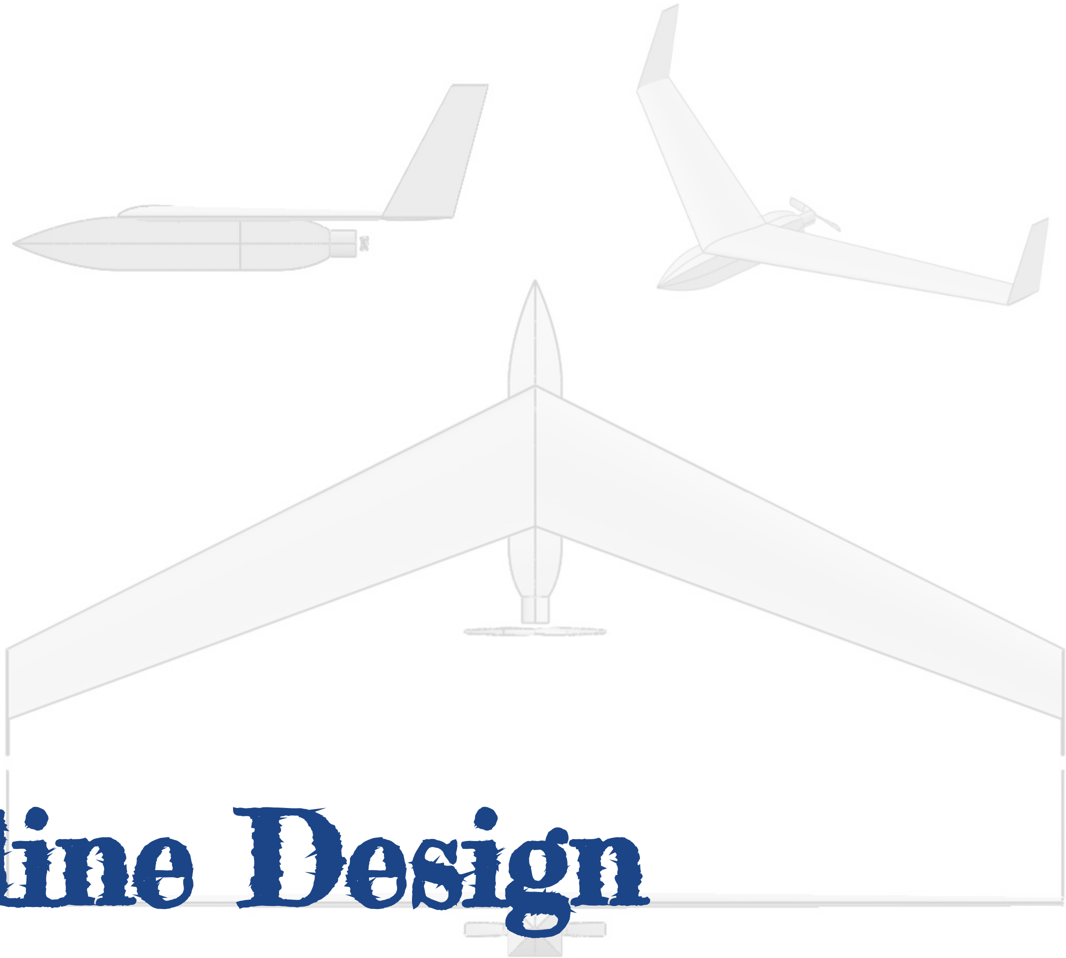


Critical Project Elements

CPE	Requirement Considerations
Aerial Vehicle Design	• **Stability and control** (ocean winds) • **Future sensor payload** • **Tradeoff** between **maximizing Lift-to-Drag** ratio and **structural/manufacturing complexity**
Takeoff and Landing	• 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**



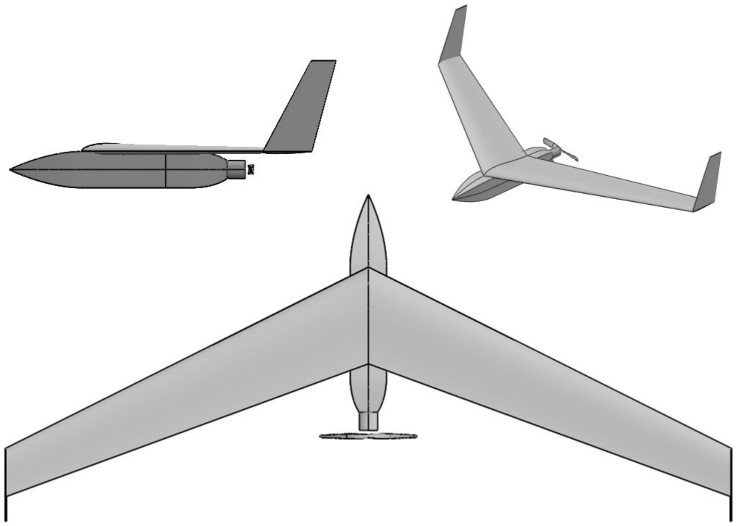
Baseline Design

Baseline Design Selection

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

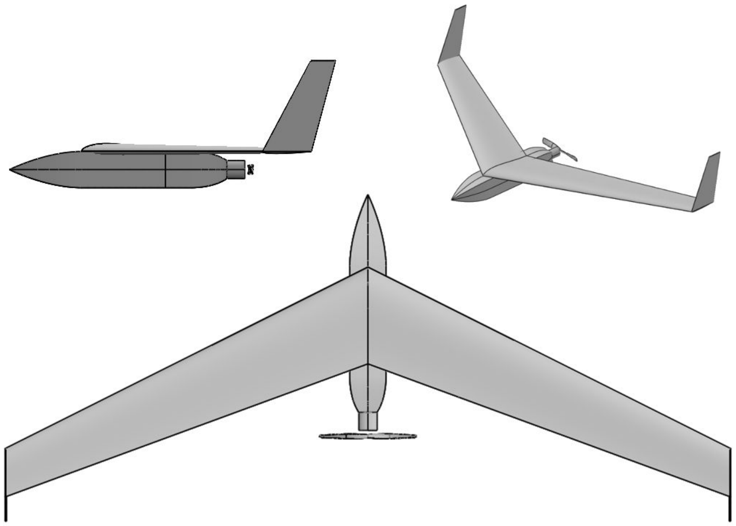
Aircraft Design: Specifications

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)



Aircraft Design: Performance

Cruise Speed	20 m/s (38 kt)
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)



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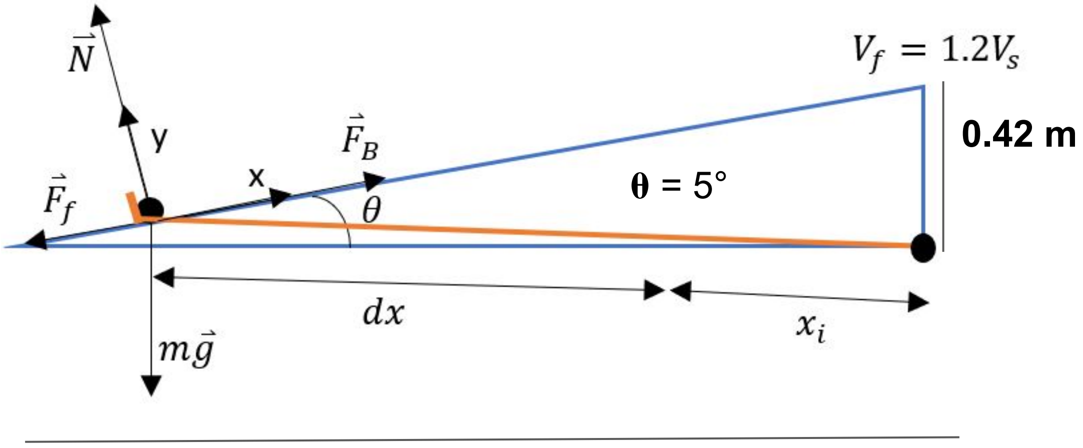
Takeoff Baseline

- 4 Bungee/ Dolley rail system
- Utilizes energy conversion: Potential energy to Kinetic energy
- Designed to give UAV sufficient speed beyond stall for independent lift production
- 5 degree takeoff angle - below stall angle; provides increased lift



Base length: **4.8 m**

Baseline Design Selection

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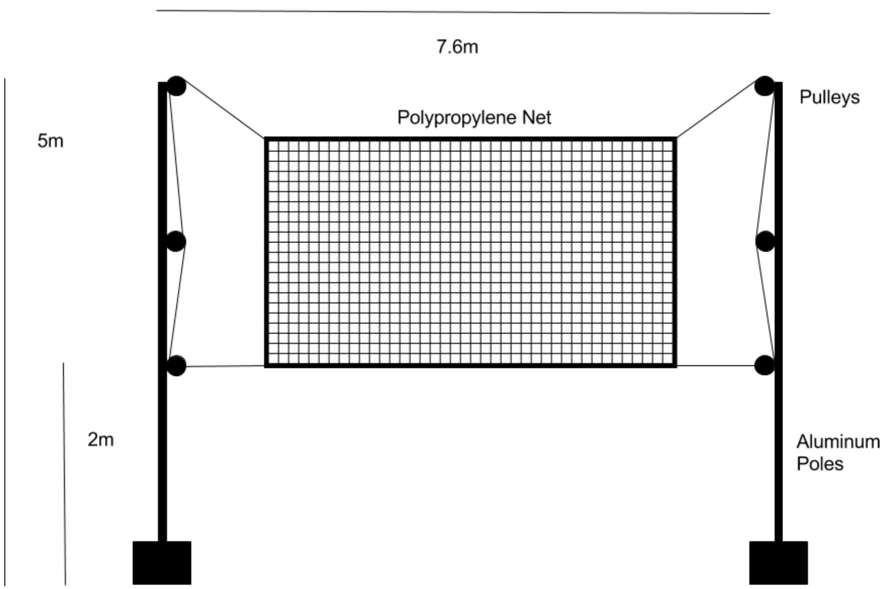
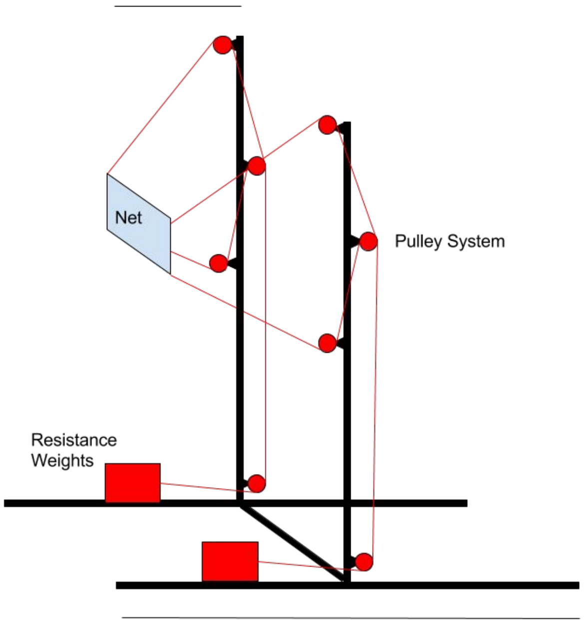
Landing System

- **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

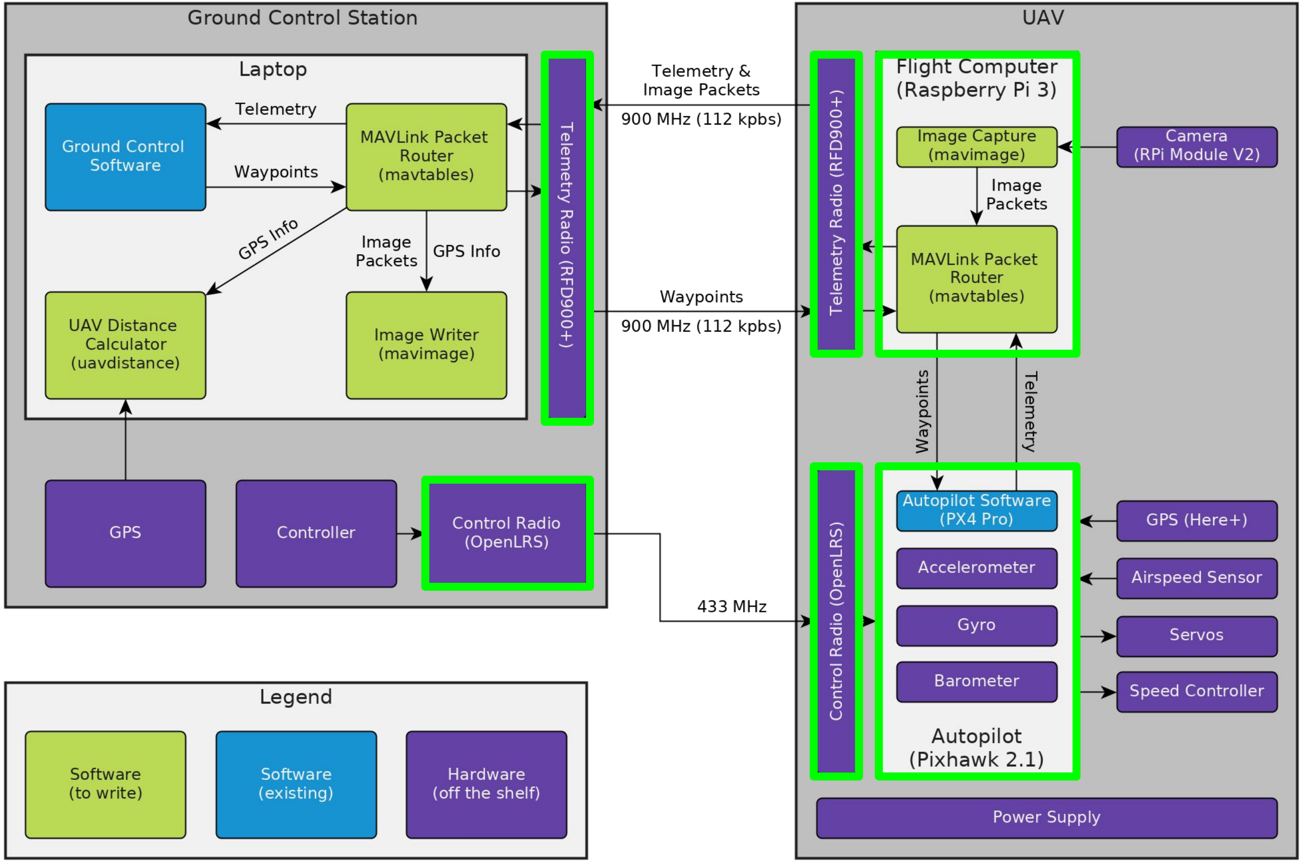
- **Tension** is required in net to **slow the aircraft** to a stop
- Tension is provided to lines by **friction** from a **weight** being **dragged along the deck**
- Weight will be **guided by rails** placed behind the net
- Weight will be **provided by seawater** to provide **easier transportation**



Baseline Design Selection

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

Navigation Hardware Design



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Power Supply

COTS

Capacity: 22000 mAh

Voltage: 22.2V

Weight: 2.65 kg

Dimensions: 20 x 9.1 x 6.4 cm

Volume = 1165 cm^3

Aircraft Design Feasibility

Why are we building our own UAV?

- Cost - how **expensive** is it?
- Complexity - **how long** will it take to **build/modify** the aircraft for **our mission**?
- Risk - how likely are we to **crash the airplane**?
- Suitability - does the aircraft set us up for a **high level of success**?
- COTS aircraft - two major categories
  - High suitability, but **high cost**
  - Low cost, but **low suitability**

Why are we building our own UAV? (Cont.)

- UASUSA Tempest
  - 1.5 hr flight time
  - 80 km/h cruise speed
  - 3.18 kg payload
  - **$26,995 ready to fly**

http://www.uasusa.com/media/widgetkit/home-tempest-dfc380ab4ec73a35e4a8bb13906bad7e.jpg

- Skywalker X-8
  - **1.0 hr flight time**
  - **30 km/h cruise speed**
  - 2 kg payload
  - $300 - $2,000 ready to fly (depending on options)

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Why are we building our own UAV? (Cont.)

- X-UAV Talon
  - **40 min flight time** (up to 2 hrs no payload)
  - 50 km/h cruise speed
  - **0.6 kg payload**
  - $250+ ready to fly (depending on options)
  - RAMROD's aircraft

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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.

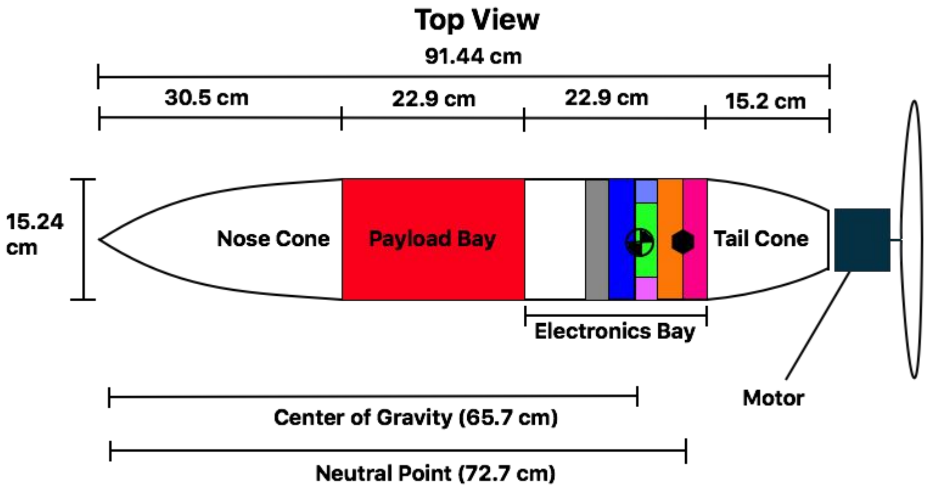
Subsystem	Mass Fraction	Mass (kg)
Structure	0.35	2.96 kg
Electric Motor	0.05	0.42 kg
Autopilot, Flight Computer, RC electronics, Communication System	0.05	0.42 kg
Batteries	0.31	2.65 kg
Payload	0.24	2.00 kg

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

The aircraft mass 8.45 kg < 22.7 kg maximum ∴ Feasible

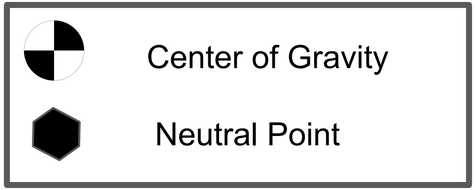
Center of Gravity & Fuselage Layout

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.

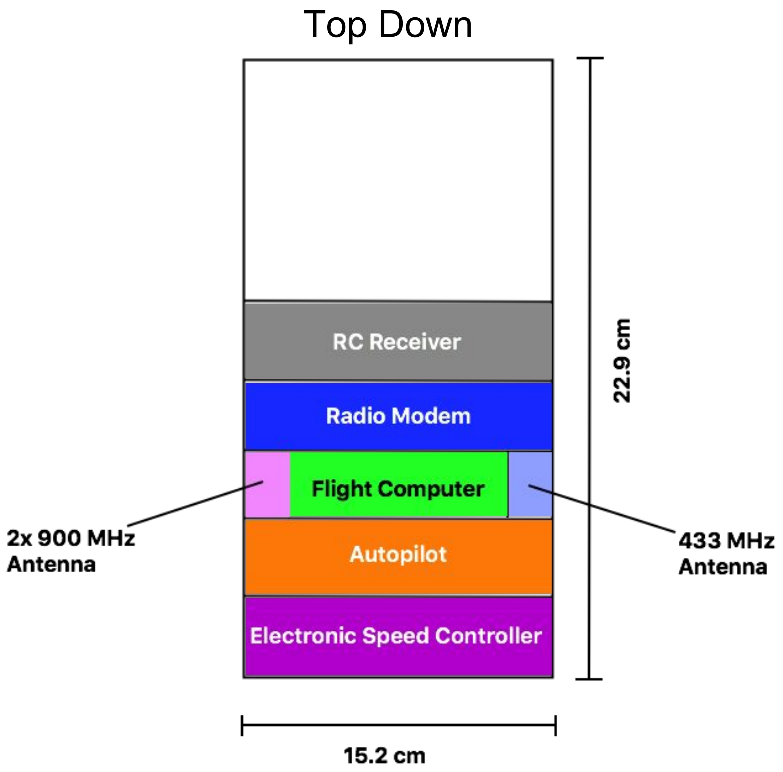
∴ Feasible



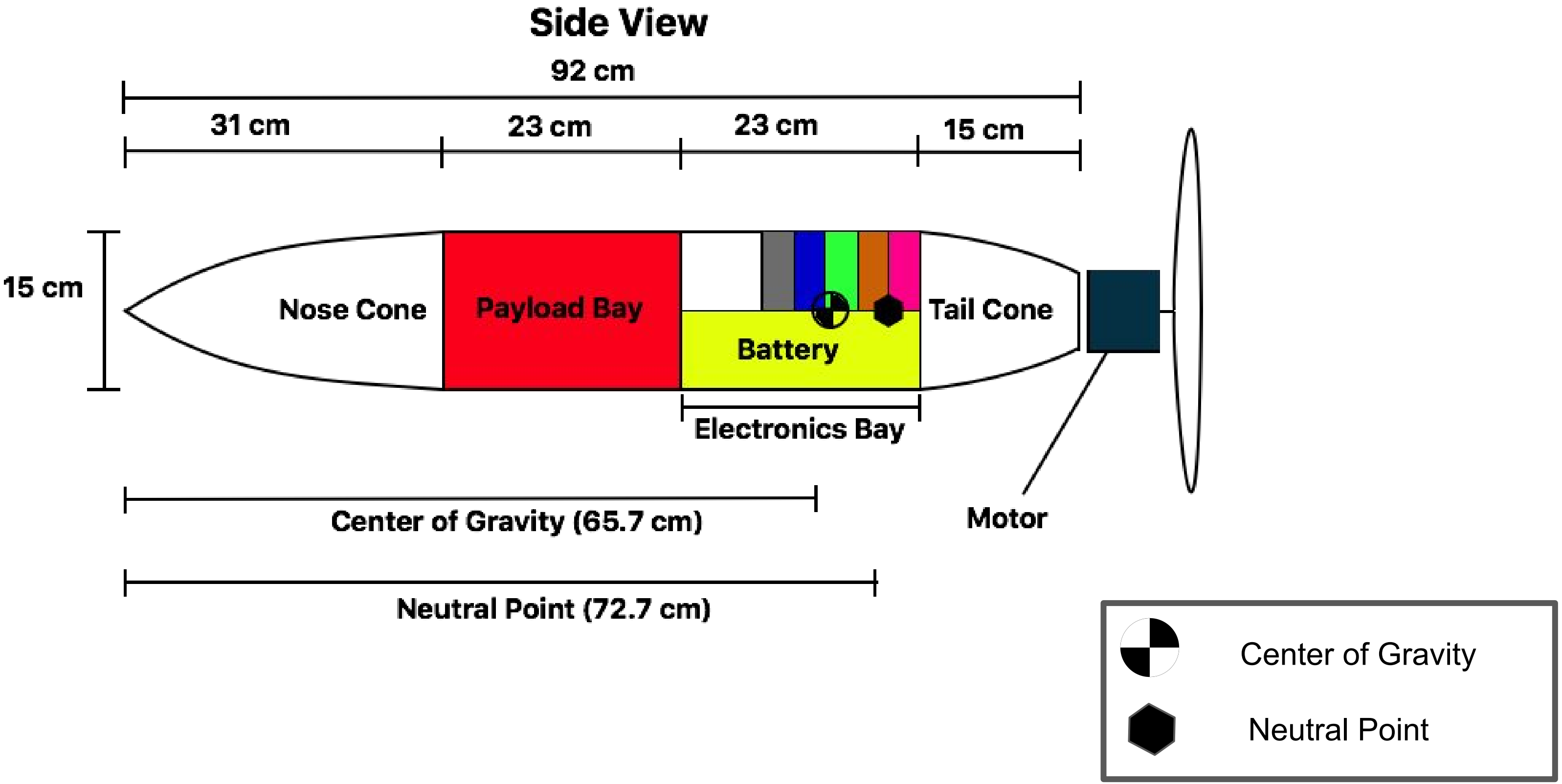
Center of Gravity & Fuselage Layout

- <u>Neutral Point</u>: 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

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

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

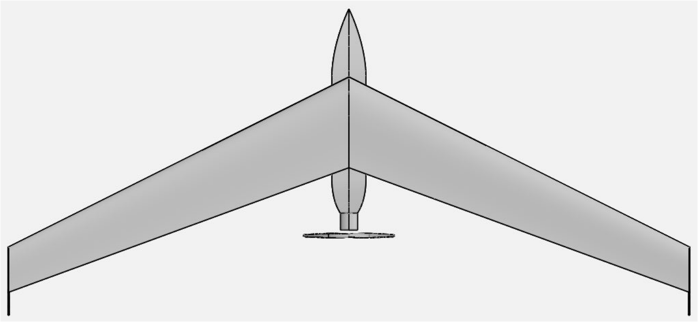
$$L = \frac{1}{2}\rho V^2 C_L S$$

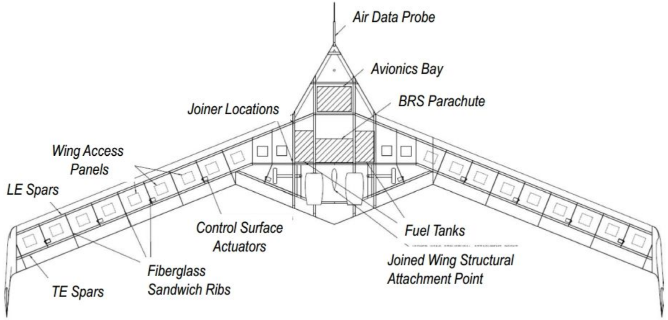
$$S = \frac{W}{\frac{1}{2}\rho V_S^2 C_{Lmax}}$$

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

Wing Sweep

- Helps satisfy stability and controllability requirements
- Similar aircraft with similar flight missions





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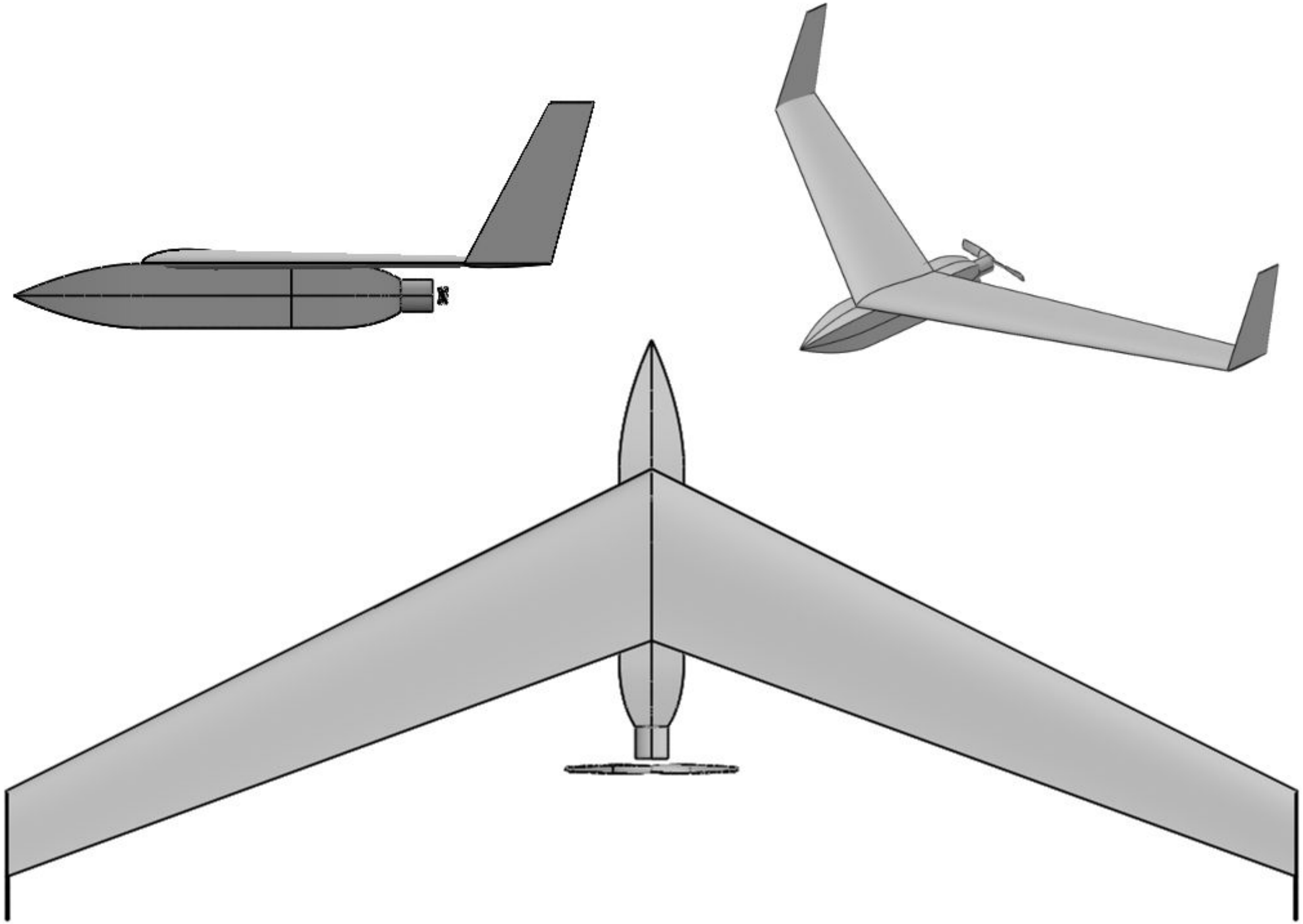
Layout



L/D

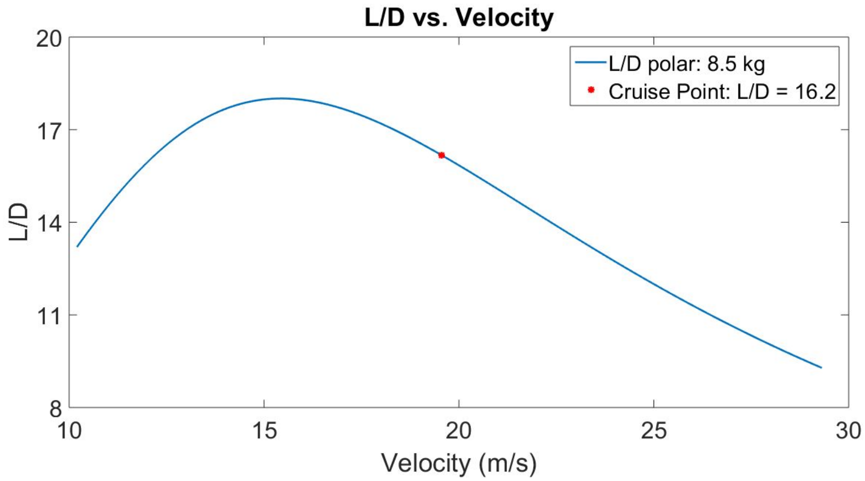
Requirement: The aircraft shall have an L/D of at least 12.

- 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

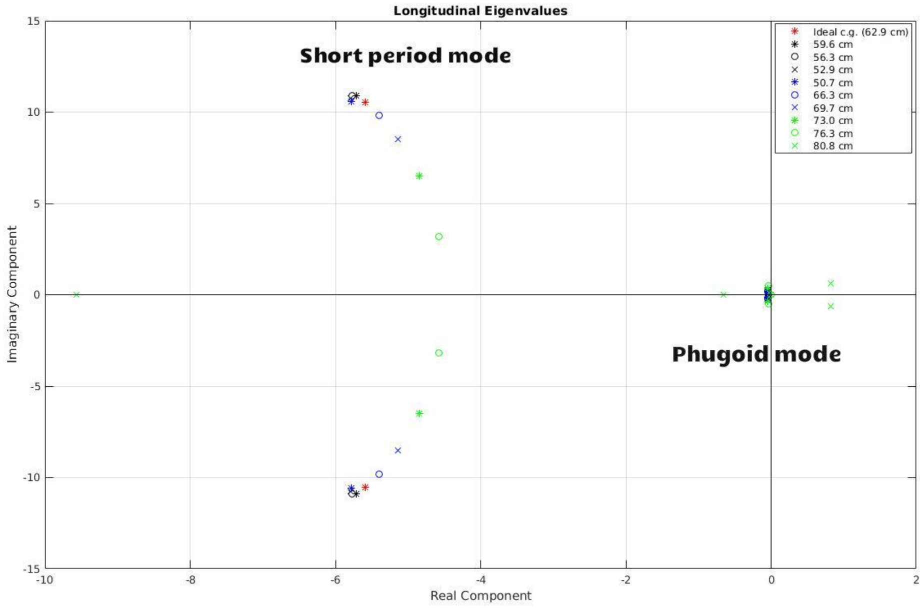
Aircraft Stability- AVL/Matlab

- 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



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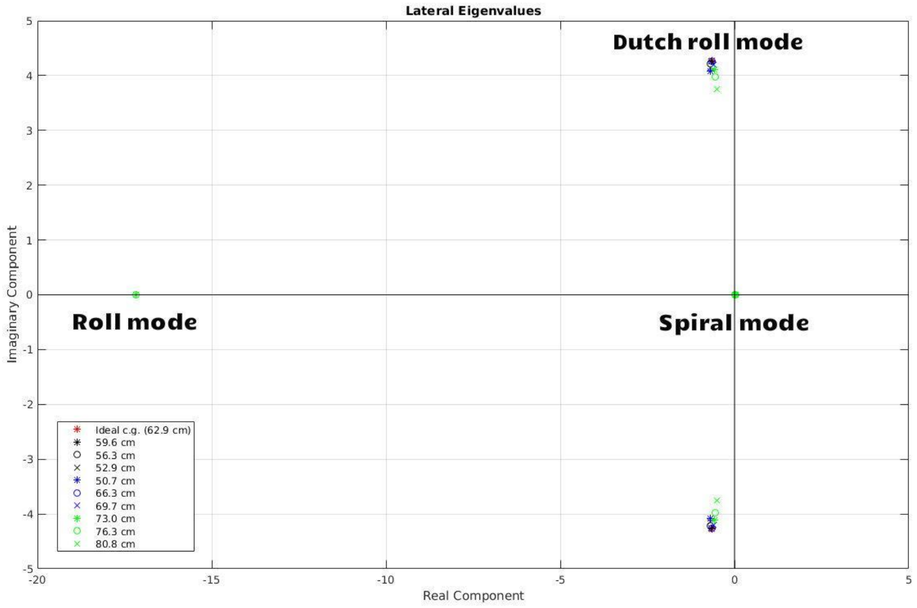


Roll mode - very stable

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

∴ Feasible

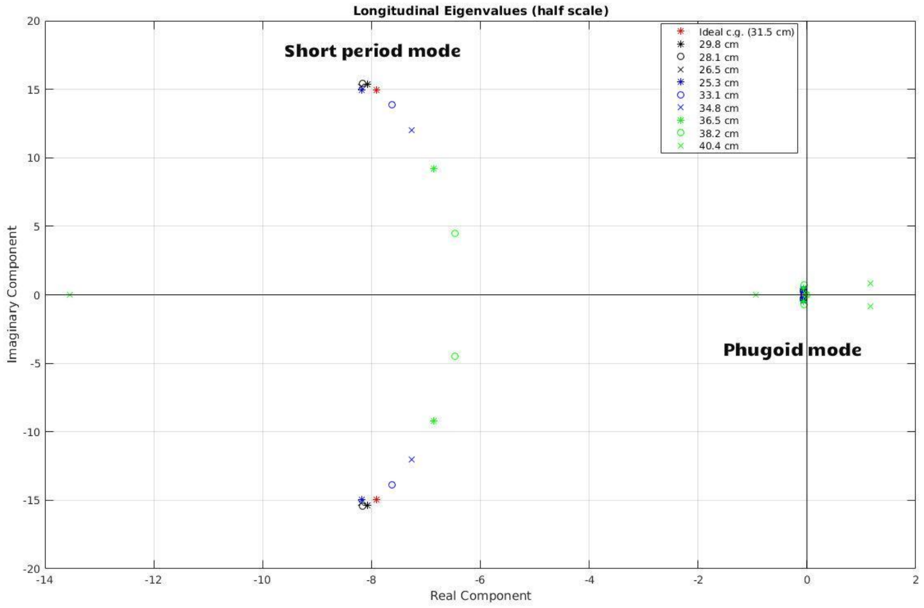
Aircraft Stability (half scale)- AVL/Matlab

- 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



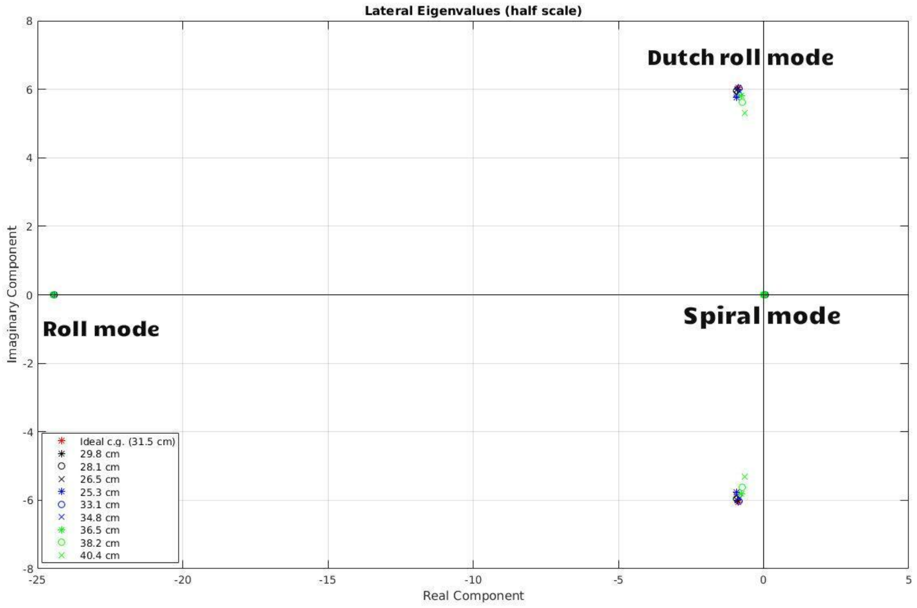
Aircraft Stability (half scale)- AVL/Matlab

- 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



Half-Scale Flight Tests

What do they tell us?

- Confirm **center of gravity** and **static margin** calculations
- No wing twist on model, but wing twist required
  - Model spins
  - Model pitches up at stall

Half-Scale Flight Tests

- **Future flight tests → video capture to quantify L/D**
    - Full-scale will have **better L/D** in comparison to half-scale
        - **Increased Reynold's number**

Half-Scale Flight Tests

- First estimate at control surface sizing was realistic
  - 25% chord, outer 50% of wingspan
  - Demonstrated controllability

Off-ramp

Computer models show an L/D up to 16.2;

Conservatively considered L/D minimum of 12;

<u>If final aircraft L/D < 12:</u>

- Range reduction to 80 km

Takeoff and Landing Feasibility

Worst Case Scenario

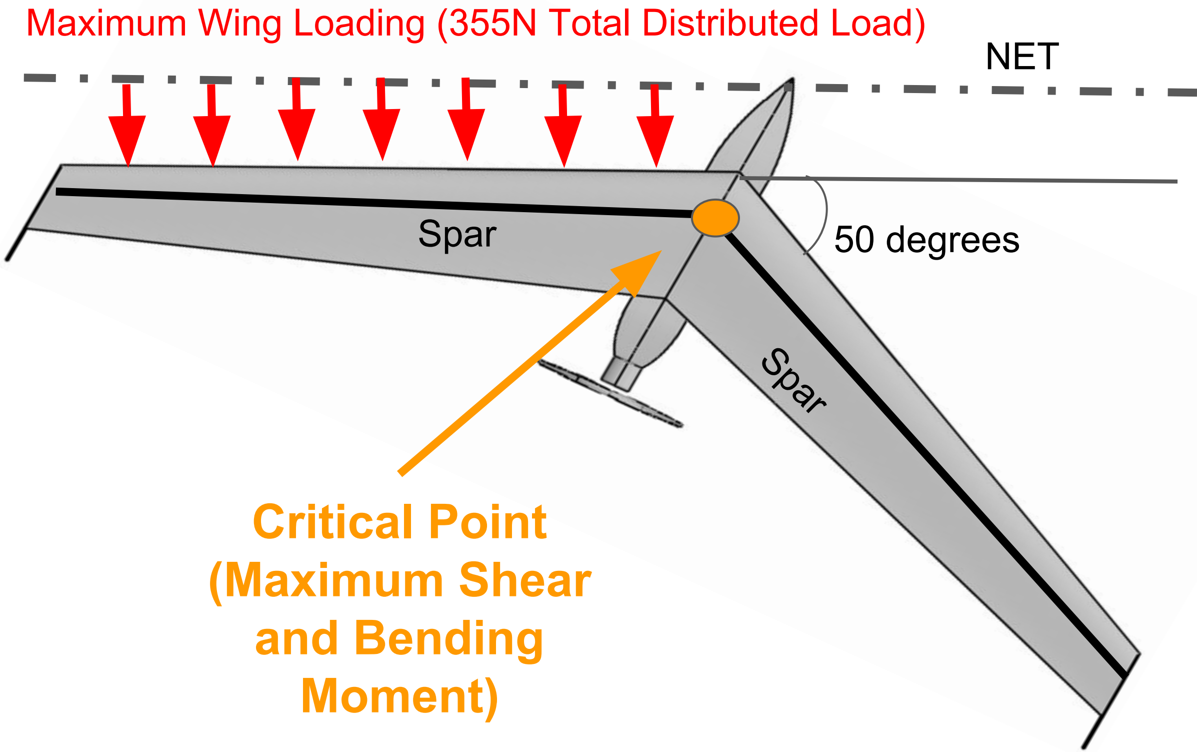
Landing/Takeoff Considerations:

Maximum takeoff forces on wing: 196N

Maximum landing forces on wing: 355N

WORST CASE SCENARIO

Must select material based on maximum landing load on wing



Major Structural Members

Wing spar material:

Epoxy/Carbon Fiber Rods
(20mm x 18mm x 1700mm)

Tensile Strength: 1.5 GPa
Shear Strength: 210 MPa

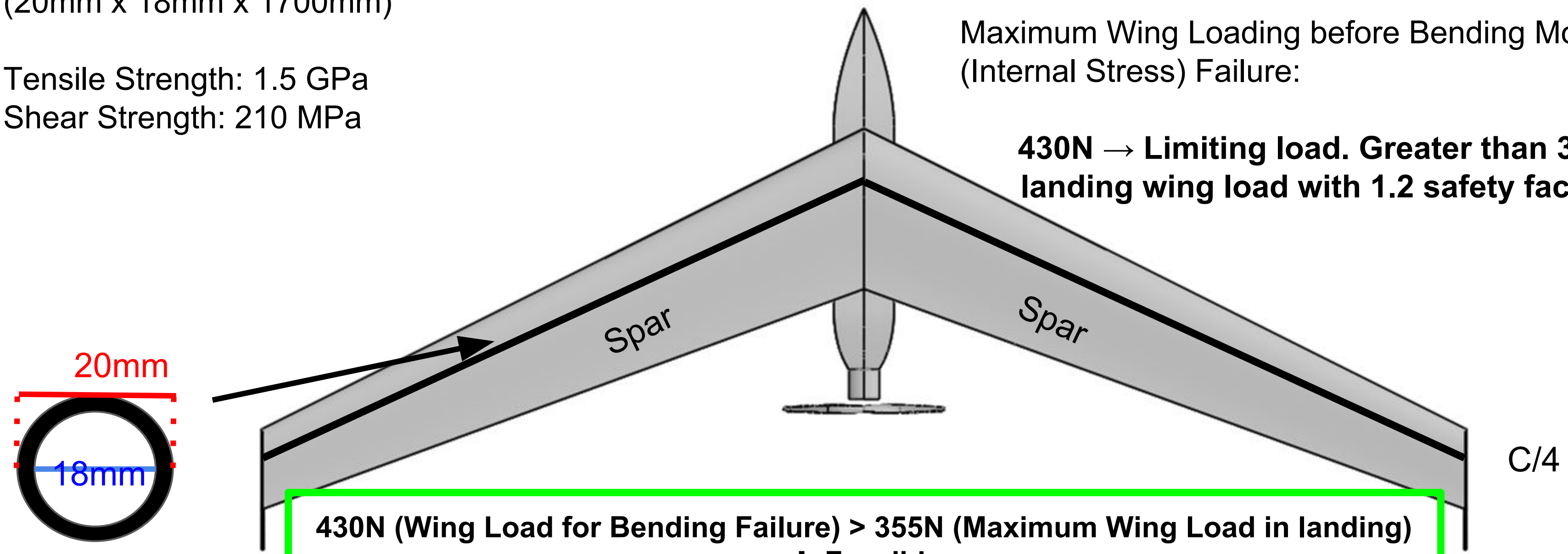
Must withstand 355N from Landing:

Maximum Wing Loading before Shear Failure:

3,990N

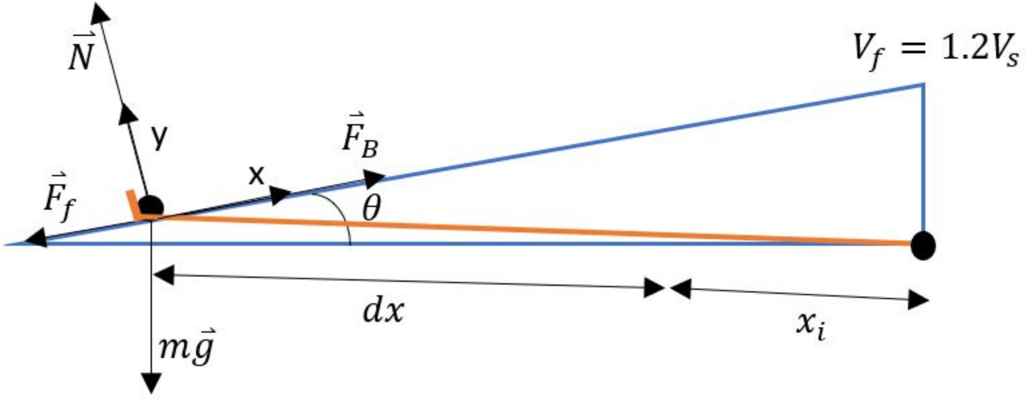
Maximum Wing Loading before Bending Moment (Internal Stress) Failure:

430N → Limiting load. Greater than 355N landing wing load with 1.2 safety factor.



430N (Wing Load for Bending Failure) > 355N (Maximum Wing Load in landing)
∴ Feasible

Takeoff Bungee System



$\vec{F}_B$- Tension force from bungee

$\vec{N}$- Normal force

$\vec{F}_f$- Friction force from rails

$m\vec{g}$- Weight

θ- Launch angle

V_f- Final velocity of UAV at end of ramp

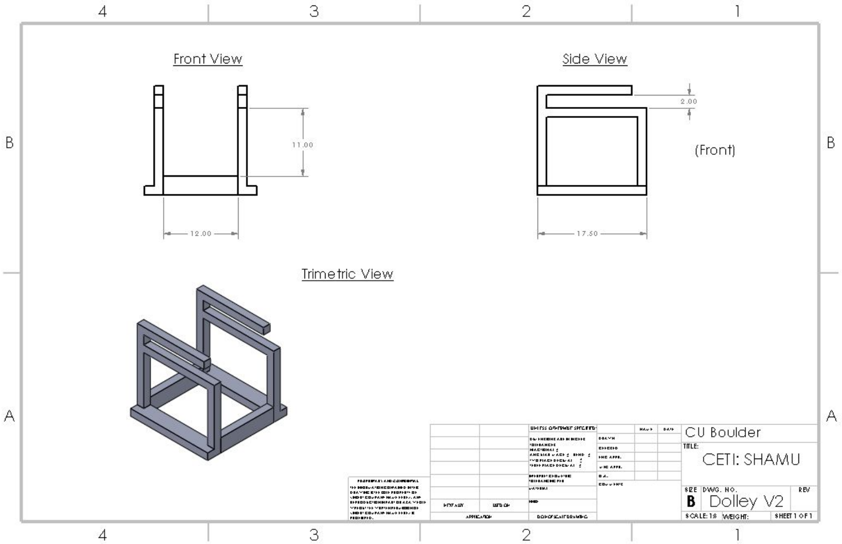
V_s- Stall velocity

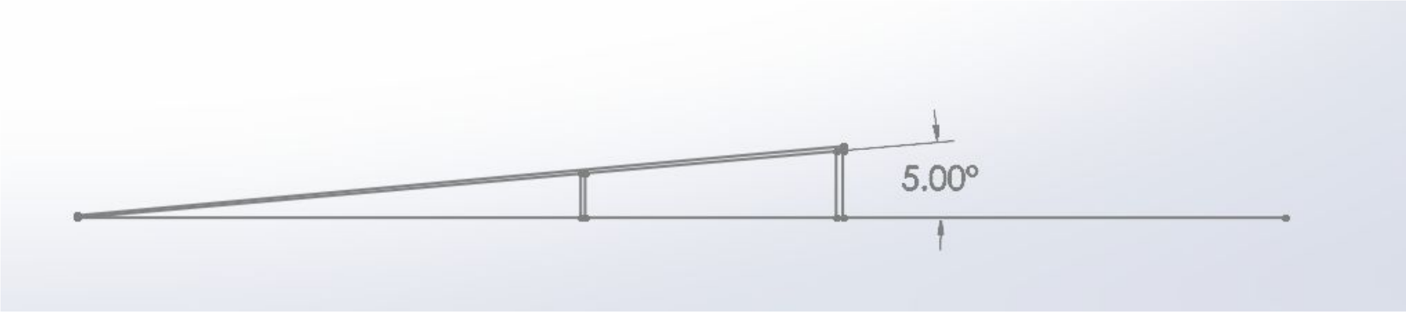
x_i- Initial bungee length

dx- Change in bungee length

Cradle and Rail System

Two-rail track with dolly





Rail Force Analysis

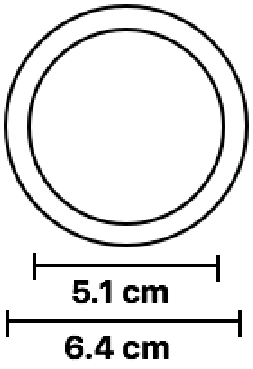
- Analyze forces on rail due to weight of UAV and the dolley, as well as the perpendicular component of the bungee force.

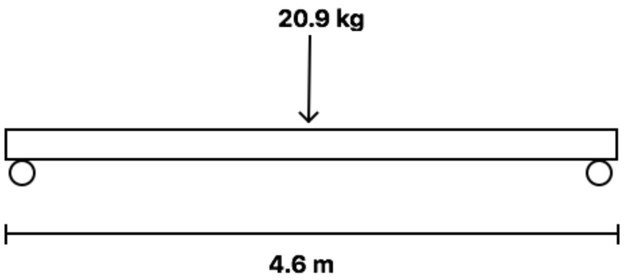
$$\sigma = \frac{M\,y}{I_x}$$

$$\delta_{max} = \frac{P\,L^3}{48\,E\,I}$$

$$I_x = \frac{\pi\,(d_o^4 - d_i^4)}{64}$$

Cross section



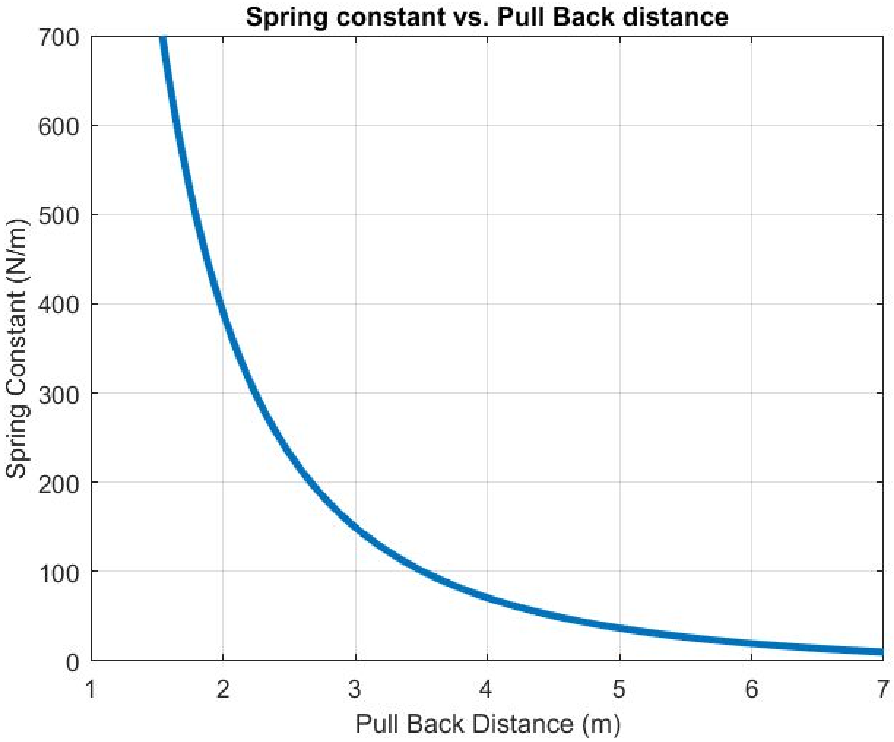


Force Analysis

Bending Stress (σ)	8.05 MPa

- Desire a lightweight, inexpensive material with tensile strength greater than 8.05 MPa.
- **Minimal deflection is desireable**
- ABS plastic is lighter than PVC, with a higher modulus of elasticity
- Tensile strength of 43.43 MPa, will be sufficient for use in this project with safety factor of 5.4

Bungee Spring Constant



Assumptions

- Energy is conserved
- Bungee coplanar with ramp
- Mass of cradle: 5 kg

$$\frac{1}{2}k(dx)^2 = \frac{1}{2}m(V_f)^2 + E_{Losses}$$

Any point on this line will get the UAV to the final velocity needed.

Bungee Selection

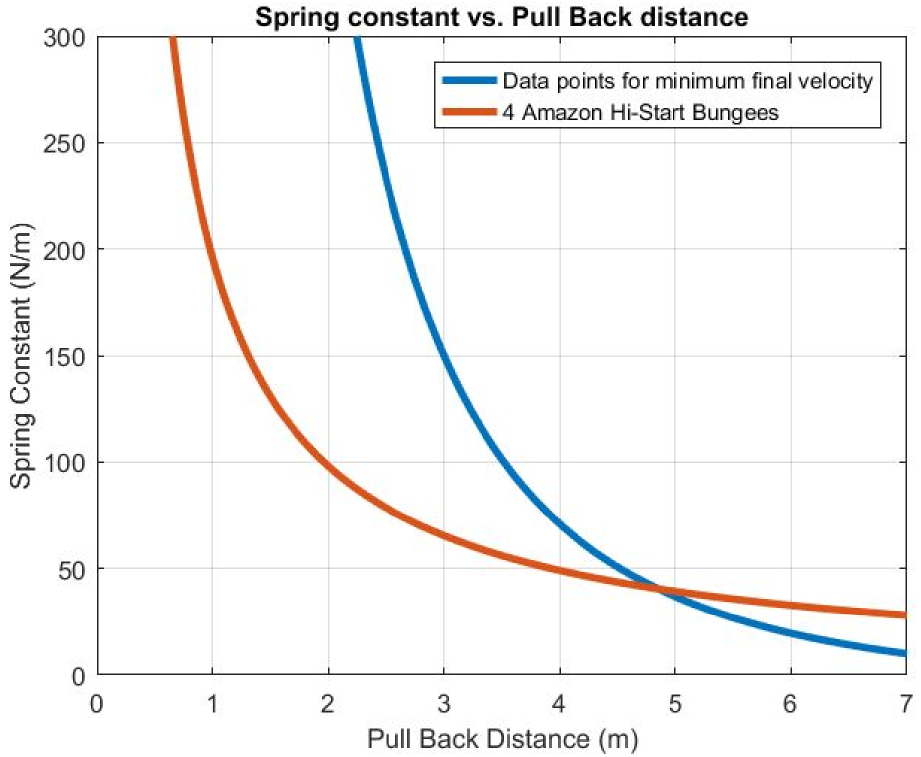
Bungee Material	Tensile Strength (σ)	Yield Strength(σ_y)	Max Elongation
Silicon Rubber	5.5 MPa	5.5 MPa	6x original length
Nylon Rope	82.7 MPa	45 MPa	2.4x original length

We determine the bungee spring constant by:

- Assuming bungee hangs vertically.
- Maximum elongation occurs with the specified max weight.

$$W_{maximum} = K_{bungee} * \Delta L_{maximum}$$

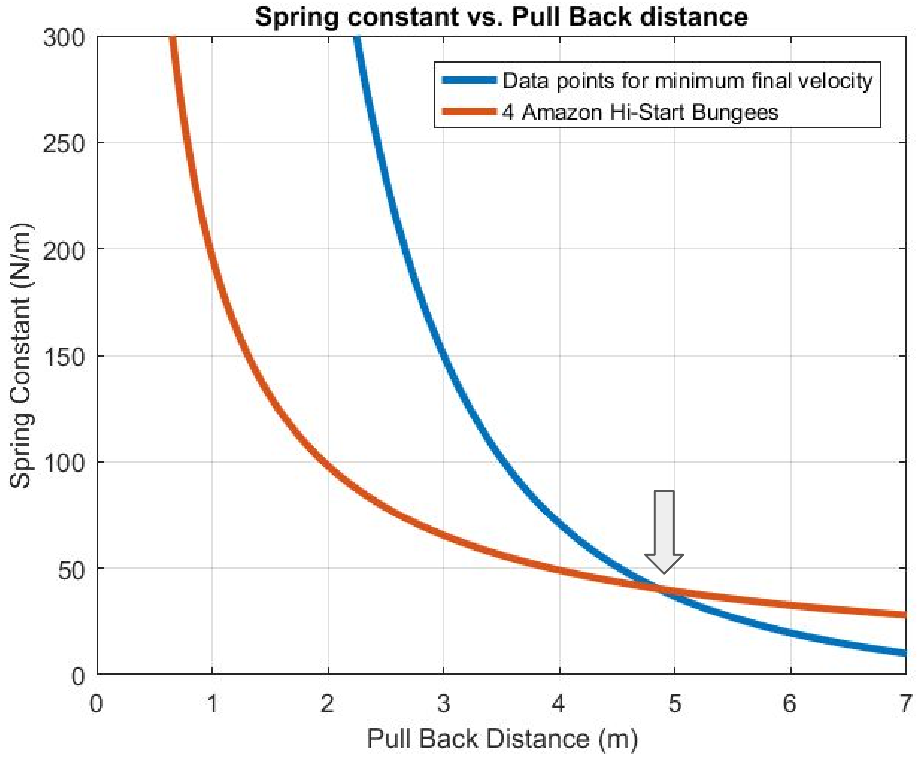
Bungee Selection: Hi-Start Bungee



Concerns and Requirements:

- Force < 430 N (For g)
- Final Length < 9.1 m
- Tensile Strength < 5.5 MPa

Bungee Selection: Hi-Start Bungee



Concerns and Requirements:

- Force < 430 N (For g)
- Final Length < 9.1 m
- Tensile Strength < 5.5 MPa

$x_i = 0.97\ m$

$\Delta x = 4.84\ m$

$x_f = 5.82\ m < 9.10\ m$

$k = 40.47\ N/m$

$F = 196.20\ N < 430\ N$

$\sigma_{req} = 1.60\ MPa < 5.50\ MPa$

∴ Takeoff is Feasible

Launching - Off Ramp

Decision Date:

17th Nov

What needs to be done by then:

1. Material Selection
2. Bungee testing
3. How everything will fit together (Solidworks models)
4. Full force analysis

Plan:

1. Self powered launch from a wheeled dolly
2. Remove the 9m by 9m launch requirement

Landing Forces: Ideal conditions

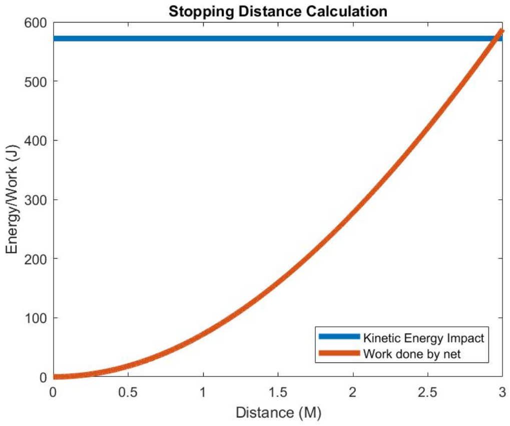
Requirement: Aircraft structure must be able survive the forces endured during landing into net capture system at a speed of 11.5 m/s

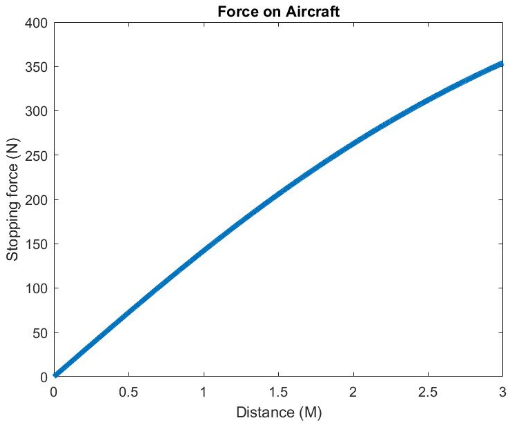
Relevant Measurements and Assumptions:

- 3 meter net height
- 7.6 meter net width
- Net modeled as 4 lines connected to point of impact
    - Force on aircraft will be force perpendicular to initial plane of net
- 150 N tension in each line
- Center impact

Landing Forces, Ideal Conditions

- Aircraft at 11.5 m/s strikes net with 571 J of KE
- Force directed on aircraft increases as net deflects more
- Center strike gives stopping distance of 2.9 m
- Tension in each line 150 N
- Maximum force on aircraft 355 N





Landing Forces - Exceptions and Allowances

- If **fuselage strikes first**, force distributes between **both wings**

- Approach angle assumed to be less than wing sweep
  - Allowable landing angle 25 degrees from the perpendicular

- 430 N maximum allowable wing load force, starting tension of 195 N in each line
  - 150 N tension selected to provide safety factor of 1.2

- Required sliding distance for center strike 0.87 m at 150 N tension
  - Allowable sliding distance will be 1.2 m

(Design force) 355 N < 430N (Maximum structural wing load)
∴ Feasible

Landing System - Friction Damping

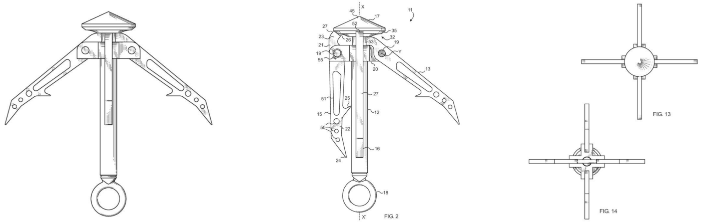
Requirement: Frictional force in landing system shall provide 150N of tension in each line to the net.

- With one weight on each side of the net, 300N frictional force is required (2 lines attached)
- Dry aluminum on aluminum $\mu k = 1.4$, requires 22kg mass
- 22kg mass corresponds to 22 liters of water

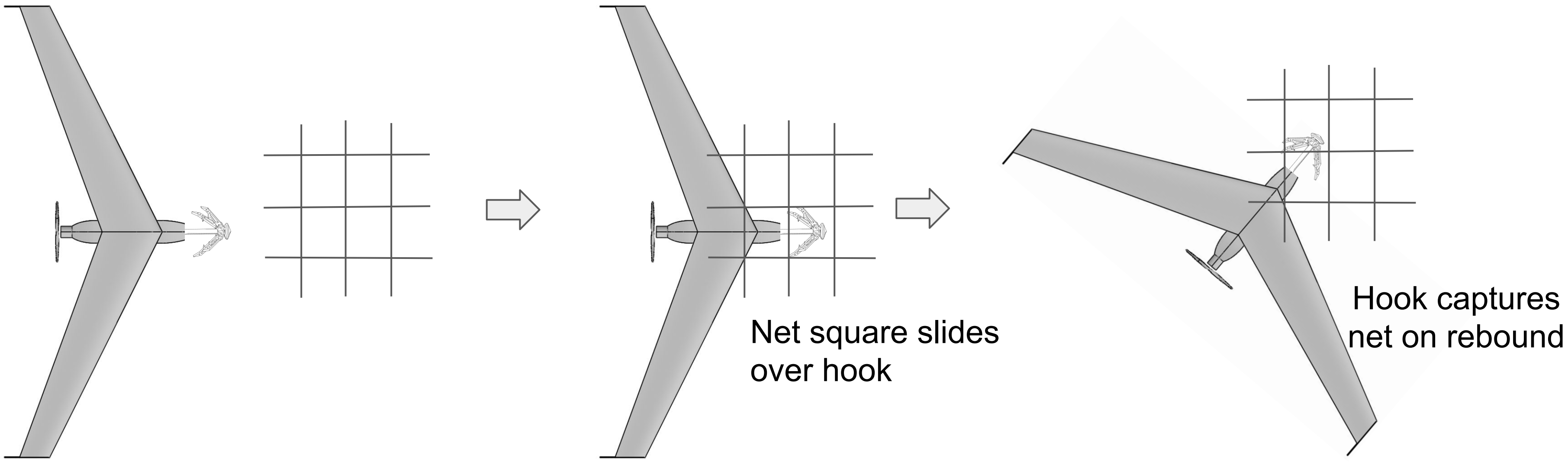
22 liter containers readily available. 22 liters of water available in the expected operating area (ocean). Design of the landing system will be made to accommodate container size

∴ feasible

Hook Capture



- Grapple system must be fixed to airframe such that recovery loads do not exceed tolerance
- Protruding aircraft features (winglets) will likely get tangled (favorable)
- Very high chance of successful capture based on videos (to be tested quantitatively)
- If hook width is less than / equal to the gauge of the net, hook will pass through net

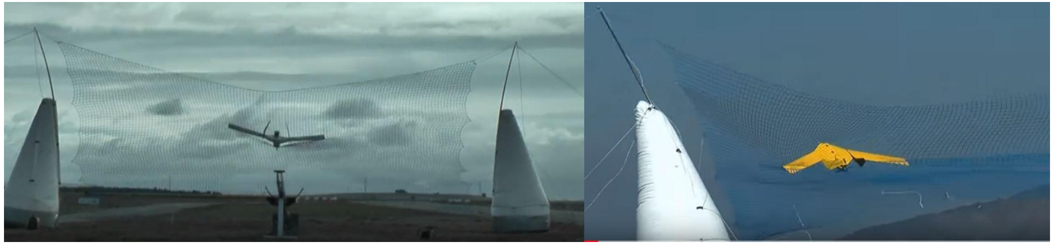


Net Recovery Feasibility

- Multiple successful tests of similar UAV’s provide strong extension basis.
- No hook system used in previous tests
  - entanglement reliant
  - Increases capture feasibility

Sea Bat Recovery

X8 Recovery



Fulmar Aerovision Recoveries

Landing - Off Ramp

Decision Date:

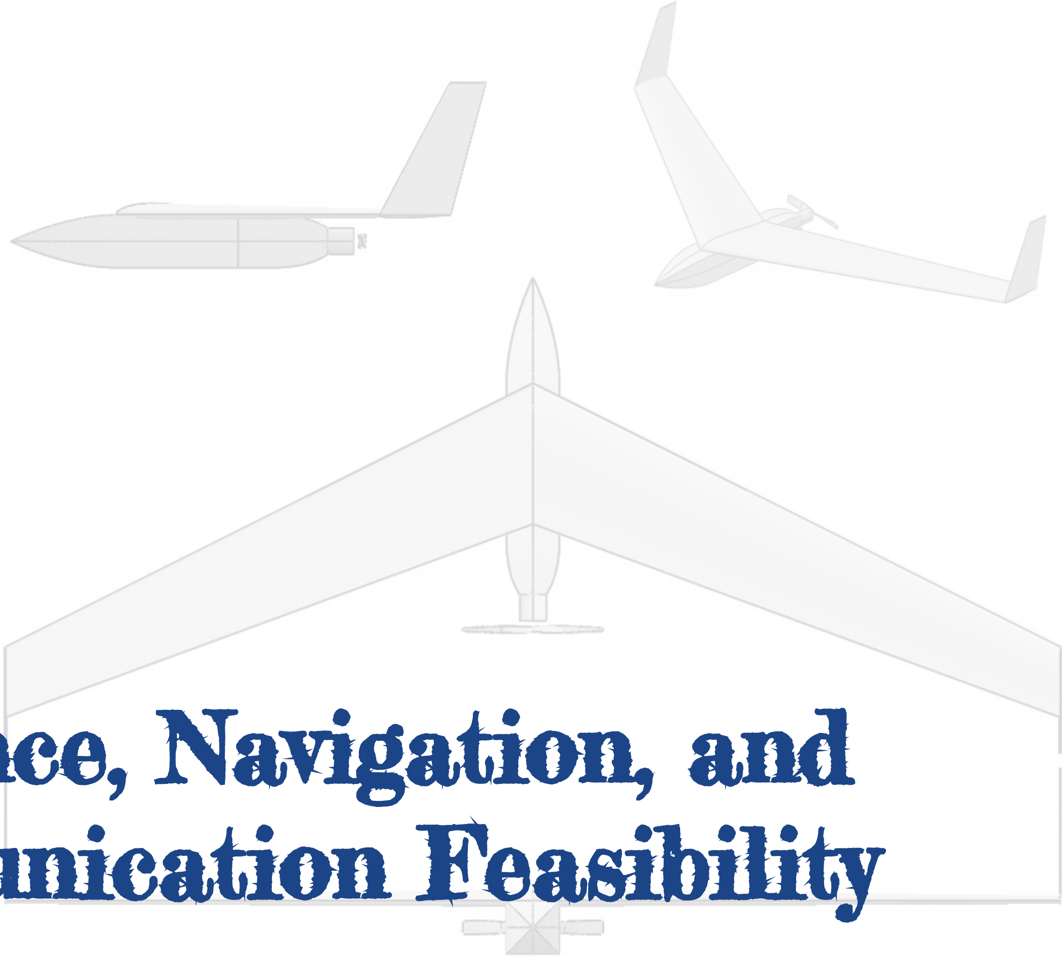
17th Nov

What needs to be done by then:

1. Material Selection
2. How everything will fit together (Solidworks model)
3. Full force analysis

Plan:

1. Add landing gear
2. Remove the 9m by 9m landing requirement



Guidance, Navigation, and Communication Feasibility

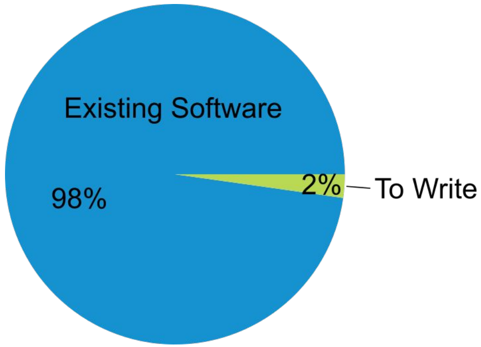
Nav/Comm Requirements

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).

Nav/Comm Diagram



Requirement NCR.1:
Autonomous mission (follow waypoints).

PX4 Pro supports programmed waypoints.

∴ NCR.1 is Feasible

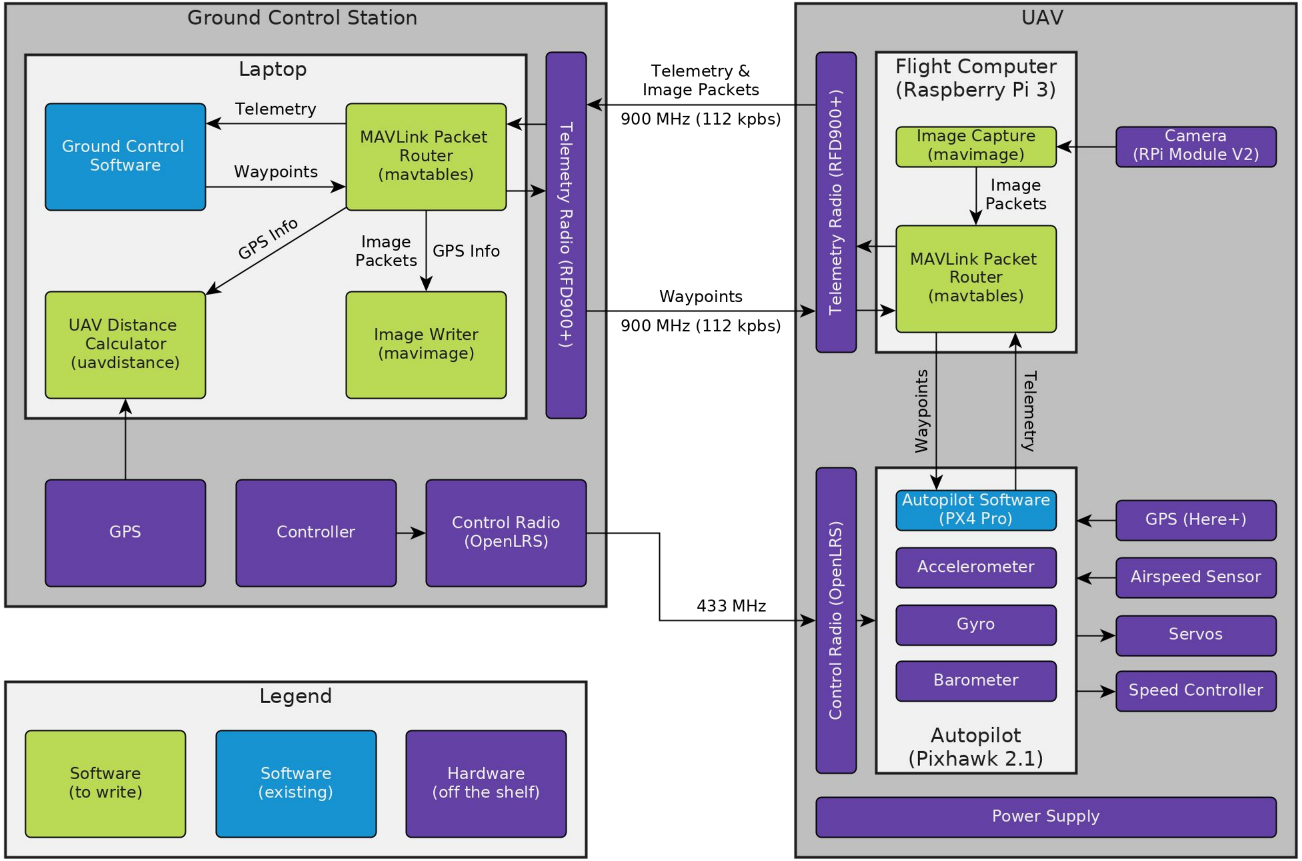
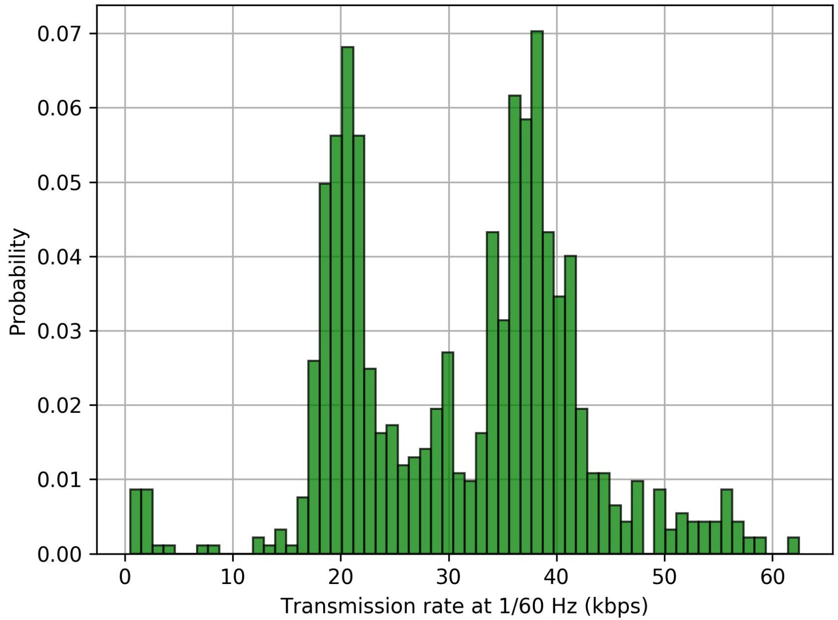


Image Transfer Rate

- 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.

Communication Feasibility

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

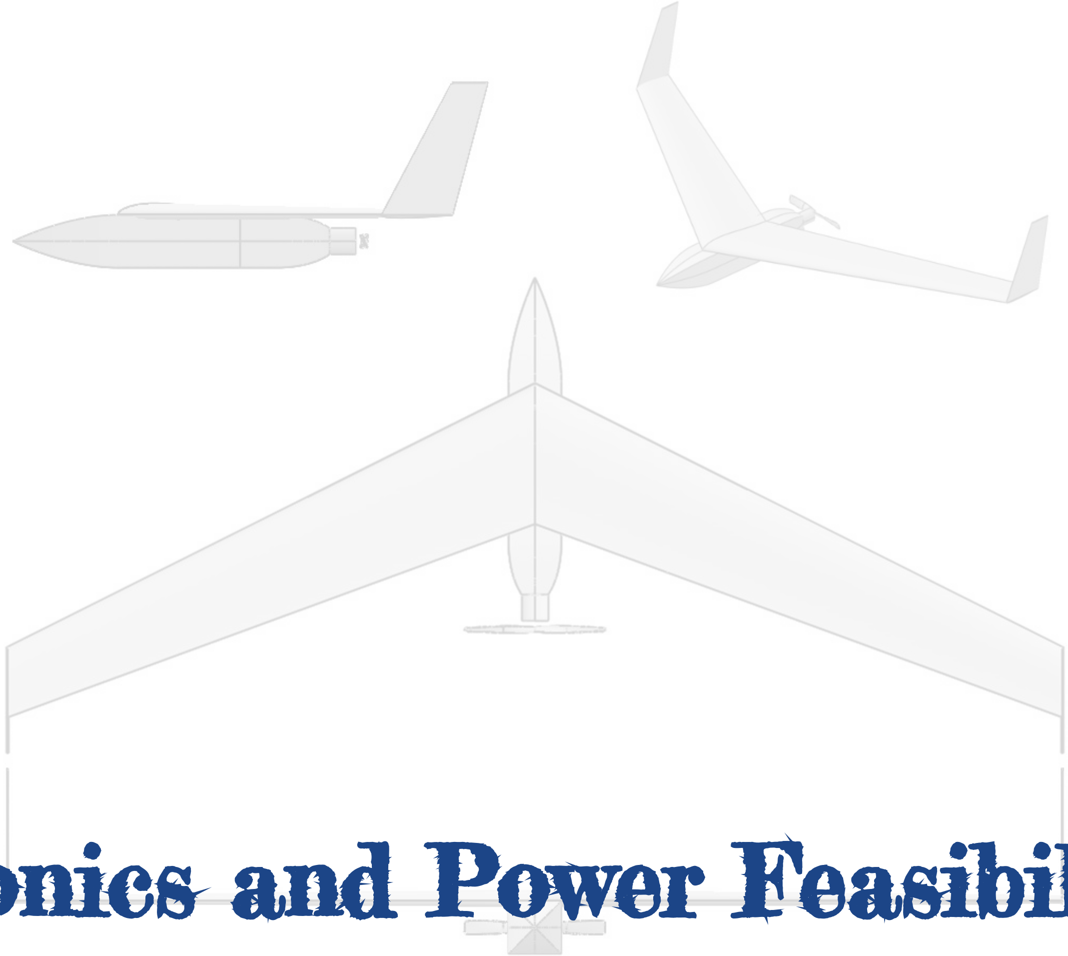
Requirement NCR.3:
Virtual cockpit (for beyond line of sight operations).

25.3 kbps remaining

∴ NCR.2 and NCR.3 Feasible

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.



Electronics and Power Feasibility

Power Requirements

- Power for the following: (via LiPo batteries)
  - 100 km range at 20 m/s cruise speed
  - 5 m/s rate of climb
  - Onboard components powered (autopilot, flight computer, servos, etc.)
- Allotted weight: 2.8 kg
- Allotted volume: 2744 cm^3

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

M_{BF}: Mass battery fraction
r: range [km]
g: gravity parameter 9.8 m/s^2
η_p: propulsion efficiency
d_{bat}: battery energy density [kJ/kg]
L/D: Lift over Drag

Power Budget

Wh_{req} At PDR
584 Wh

Changes:

Weight:
- 25 → 20 lbs

Efficiency:
- 70 → 75 %

Apply 80/20 rule

Component	Power Needed (L/D = 12)
Motor (Steady Flight)	277 Wh
Motor (Climb)	38.6 Wh
Pixhawk	1.155 Wh
RFD 900+	5.6 Wh
OrangeRX Open LRS	.14 Wh
Raspberry π	5.6 Wh
Servo	7 Wh
Total:	368 Wh

Required Energy Density

Allotted Mass: 2.8 kg

Given mass and watt-hours:

- L/D = 12 → 460 Wh → **592 kJ/kg**

Tattu 22000mAh 6S 25C 22.2V Lipo Battery Pack
Capacity: 22000 mAh
Voltage: 22.V
Watt-hours: 488 Wh
Available Watt-hours: 390 Wh
Weight: 2.65 kg
Energy Density: 664 kJ/kg

Power - Off Ramp

Decision Date:

31st Jan

What needs to be done by then:

1. Battery endurance tests

Plan:

1. Reduce range requirement

Budget Estimations

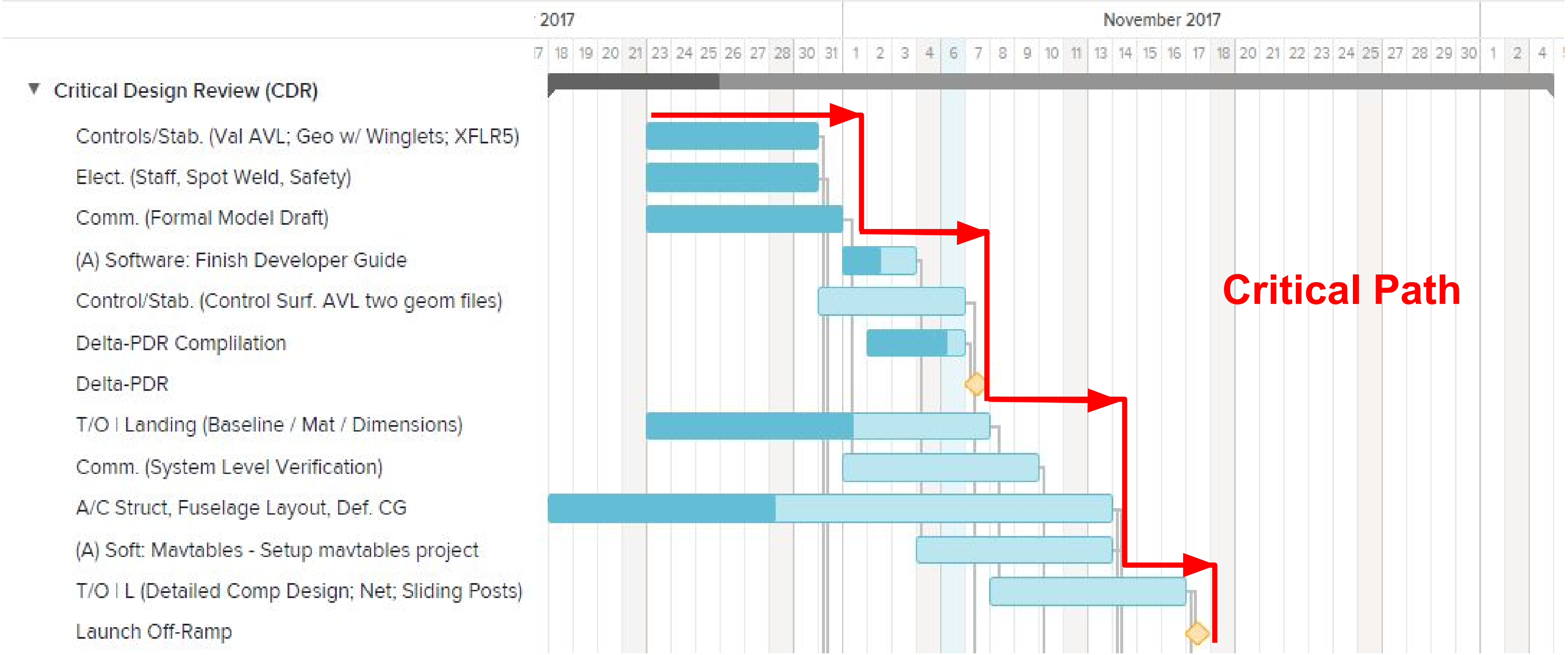
Airframe w/ motor:	$2000
Raspberry Pi 3:	$35
Pixhawk 2.1 Here+ GPS:	$275
2 x RFD900+:	$200
Pitot Tube:	$65
FTDI adapter:	$8
16 GB SD card:	$9
Antenna Tracker:	$250
Battery configuration:	$450
Launch system:	$500
Land system:	$430
R Pi camera module v2:	$23

Total: $4,245 < $5,000

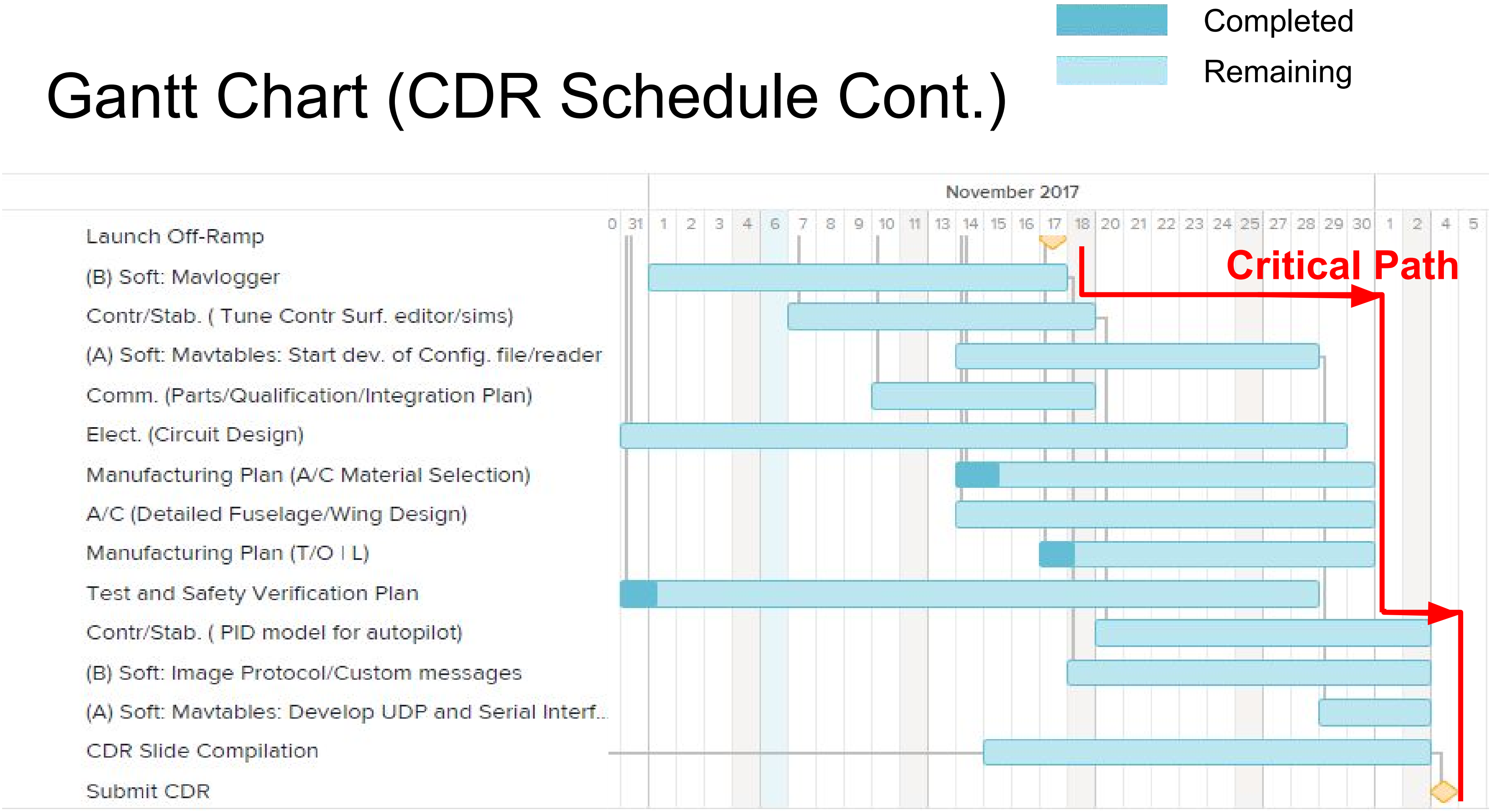
Leaves the SHAMU team with a 15.1% margin

Gantt Chart (CDR Schedule)

Completed
Remaining



Gantt Chart (CDR Schedule Cont.)



Summary of Feasibility

Aircraft Design:

- **Center of gravity, high L/D**, and **stability** validated by **half scale model test**.
- Will validate **Stability model** by comparing expected and actual stability of half scale model
- Know that variations in CG location still produce **stable, correctable** flight

Next Steps:

- Material selection based on structural analysis
- Manufacture plan

Aircraft Design	**Feasible**
Takeoff	
Landing	
Nav/Comm	
Electronics	
Logistics	

Summary of Feasibility

Takeoff:

- Materials available for **bungee** that provide **force** and **strength** needed for takeoff within **9.1 x 9.1 m platform**
- Design for **guide rail system** validated by **force analysis**

Next Steps:

- Solidworks model of rail system
- Manufacturing plan
- Force analysis of system
- Test of purchased bungee k values

Aircraft Design	**Feasible**
Takeoff	**Feasible**
Landing	
Nav/Comm	
Electronics	
Logistics	

Summary of Feasibility

Landing:

- **Force** from net less than **maximum force on wings**
- **Weight** required to provide friction for net is calculated and **available** from operating area (ocean)
- Stopping design **distance less** than helipad dimensions

Next Steps:

- Detailed design of system for connection of COTS components
- Manufacturing plan

Aircraft Design	**Feasible**
Takeoff	**Feasible**
Landing	**Feasible**
Nav/Comm	
Electronics	
Logistics	

Summary of Feasibility

Nav/Comm:

- Most of **software** capabilities will be **pre-existing** and **tested** software libraries
- Communication **downlink rate** much **less** than overall budget

Next Steps:

- Creation of developer guide
- Beginning of code development as outlined by software schedule

Aircraft Design	**Feasible**
Takeoff	**Feasible**
Landing	**Feasible**
Nav/Comm	**Feasible**
Electronics	
Logistics	

Summary of Feasibility

Electronics:

- **COTS** battery pack will provide **mission requirements** with an 10% **safety margin**
- If **L/D is less** than expected, can **manufacture** own battery pack
- **Safety plan** and **risk mitigation** designed for customized battery pack

Next Steps:

- Detailed circuit diagram

Aircraft Design	**Feasible**
Takeoff	**Feasible**
Landing	**Feasible**
Nav/Comm	**Feasible**
Electronics	**Feasible**
Logistics	

Summary of Feasibility

Logistics:

- Within **financial budget**
- Currently **on track** with Gantt chart, only behind a few days due to delta-PDR
- Have **"off-ramp"** plan to prevent falling further behind schedule for **level-one success**
- **Range and endurance** of project scope met with current baseline design

Aircraft Design	**Feasible**
Takeoff	**Feasible**
Landing	**Feasible**
Nav/Comm	**Feasible**
Electronics	**Feasible**
Logistics	**Feasible**

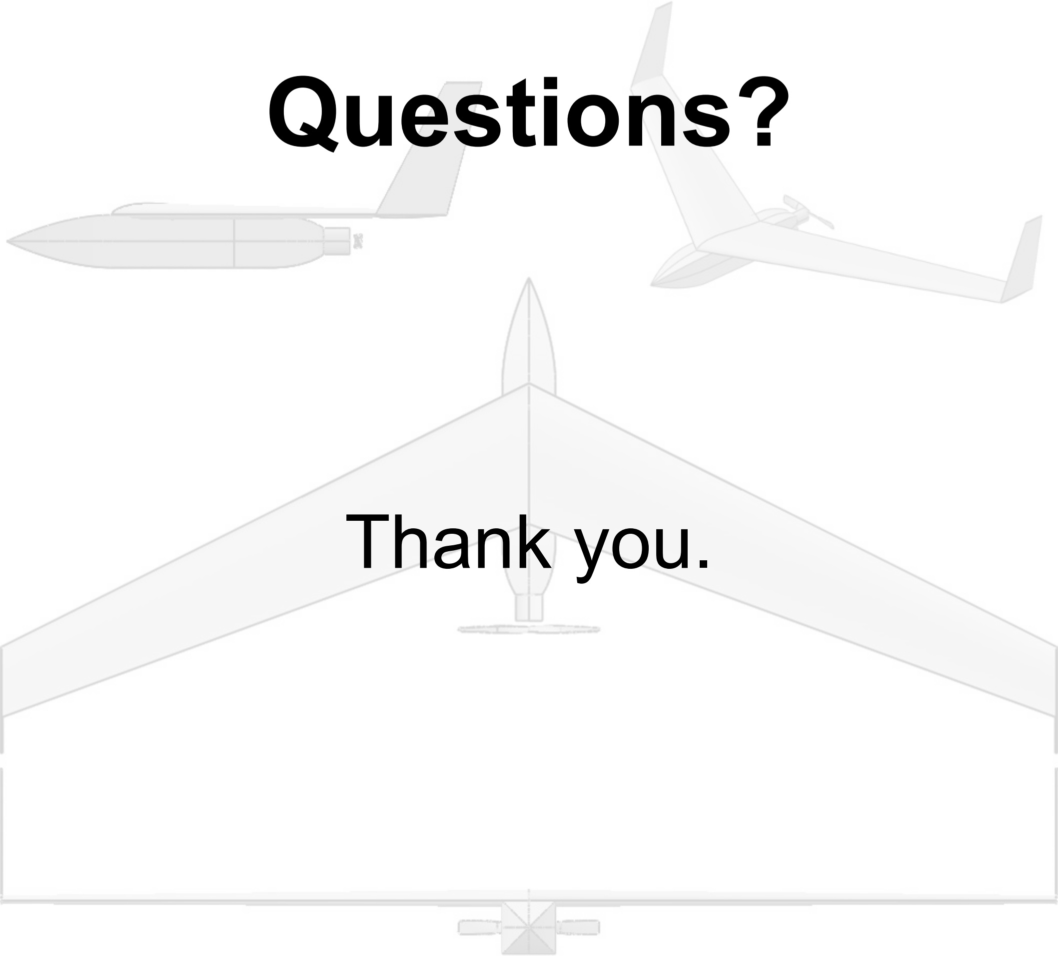
Acknowledgements

Special thanks to the PAB, Dr. Koster, James Nestor, David Gruber, Dr. Gerren, Matt Rhode, Dan Hesselius, Bobby Hodgkinson,

Tim Kiley, Matthew McKernan, USNA

Questions?

Questions?



Thank you.

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Willy's Widgets

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BACKUP SLIDES

Project Motivation

- **Marine researchers** want to study the sperm whale language by **deploying listening buoys** directly next to **located whales**.
- Currently, researchers **spend weeks** on board a research vessel locating whales with **only binoculars**.
- Locating whales with a **unmanned aerial vehicle will increase search efficiency resulting in saved time and cost.**

Taper Ratio and Twist

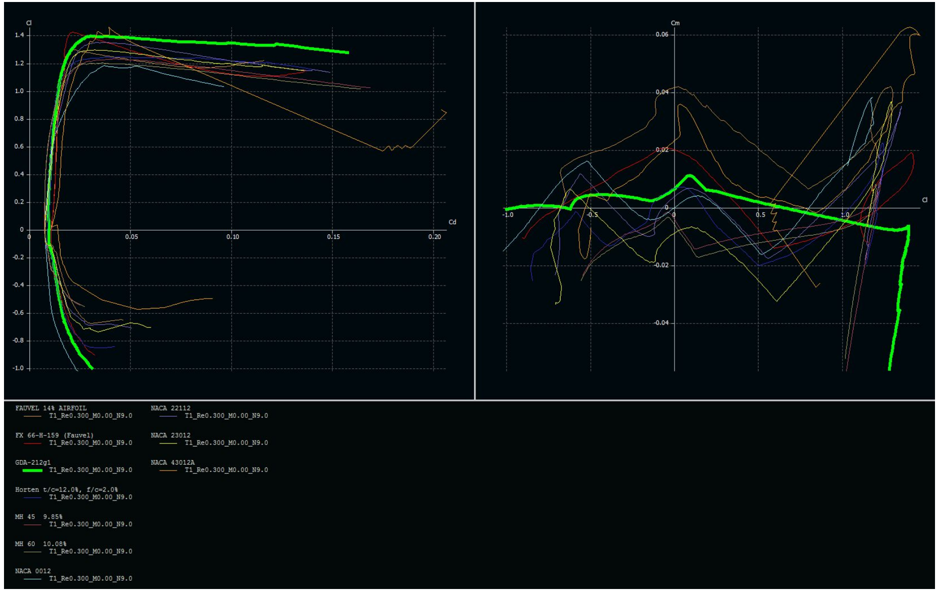
- Taper ratio set at 0.5
  - Most efficient at 25° sweep angle, including effects of required twist.
- Twist set at -3° (washout)
  - Required twist at this sweep angle to prevent tips from stalling first (based on AVL model)
  - Improves stall characteristics
    - Prevents pitch-up at stall
    - Improves spin resistance
    - Lowers flight risk
  - Requirement supported by half-scale model flight tests

Dihedral

- Set at 0°
  - High wing aircraft
  - Winglets
  - Easier geometry for wing-fuselage joint

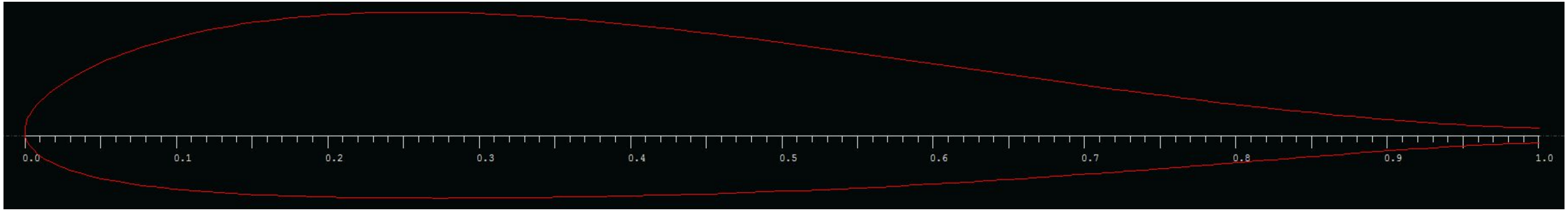
Airfoil

- 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?”



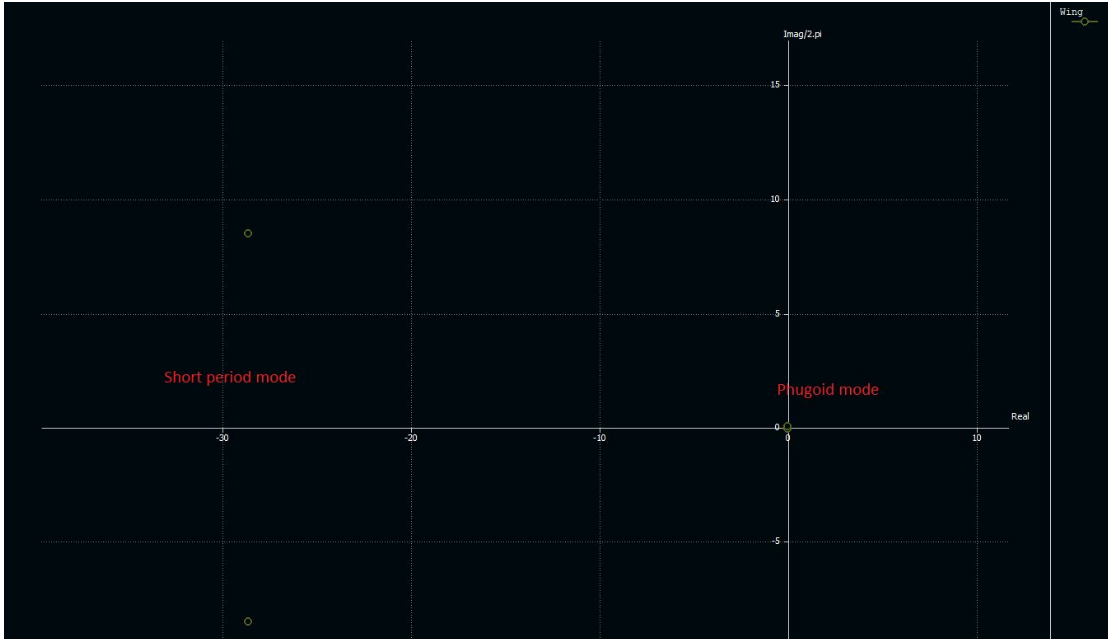
Airfoil

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



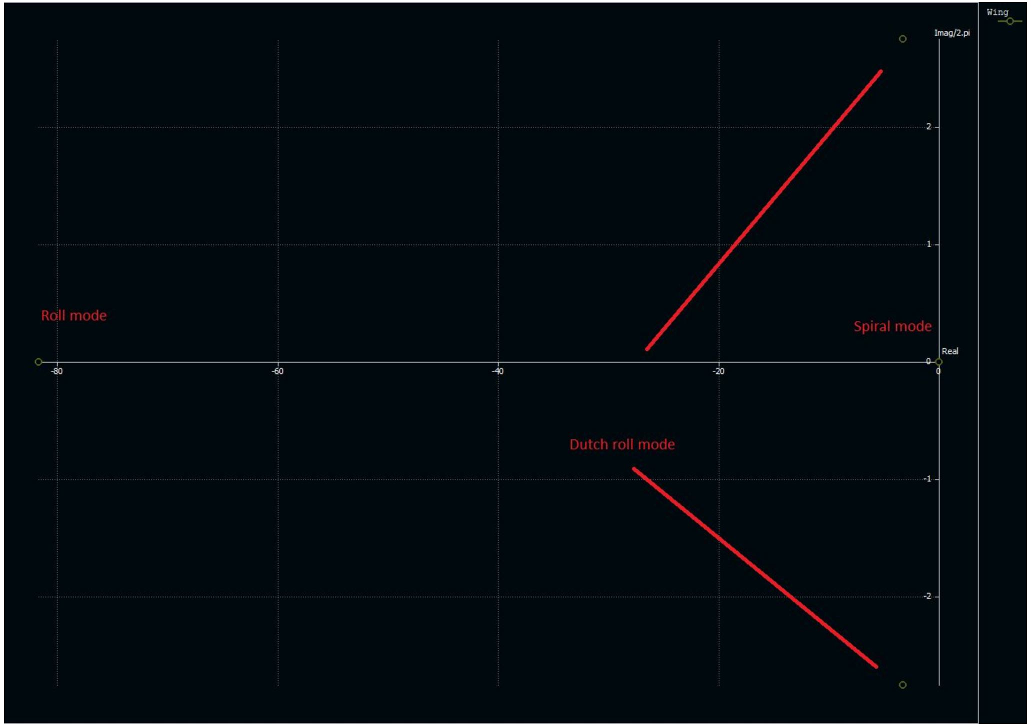
Aircraft Stability- XFLR5

- Longitudinal eigenvalue plot

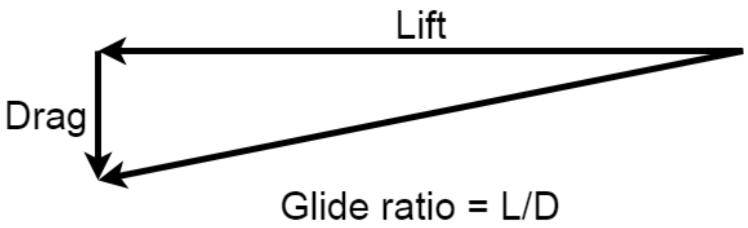


Aircraft Stability- XFLR5

- Lateral eigenvalue plot



M_{BF} Equation



$$E = mg\Delta h$$

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

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

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

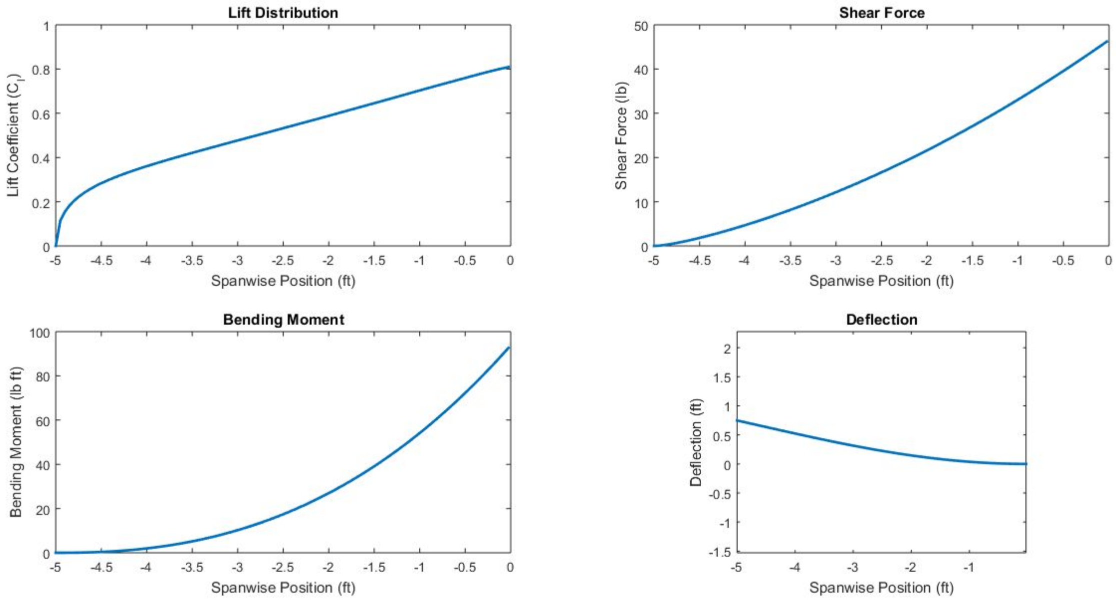
$$\frac{m_{bat}}{m} = \frac{rg}{\eta_p d_{bat} L/D}$$

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

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.



Structures

- Primary concern in-flight is ensuring wings do not shear off
- Maximum shear force is 213.5 N at wing root in 5g flight
- Wing cross-sectional area at root is 0.01198 square meters
- Primary aircraft material 0.03 g/cc expanded polypropylene, tensile strength 450 kPa
- Average shear strength for foams in MATWEB is 37% of tensile strength
- For expanded polypropylene, this gives a shear strength of 167.625 Kpa

Shear Stress = F/A = 213.5/0.01198 = 17.821 kPa < 167.625 kPa

Aircraft Will Survive Shear up to 5 g ∴ Feasible

Takeoff Conservation of Energy

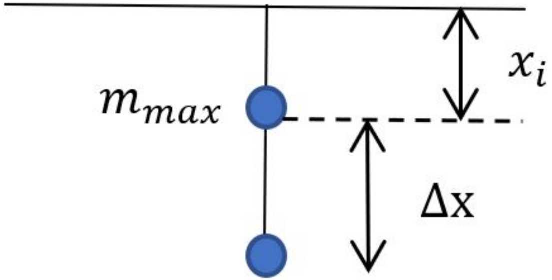
$$\sum E_i = \sum E_f$$

$$E_{Losses} = F_f(dx) = \mu mgcos(\theta)dx + mgsin(\theta)$$

$$\frac{1}{2}k(dx)^2 = \frac{1}{2}m(V_f)^2 + E_{Losses}$$

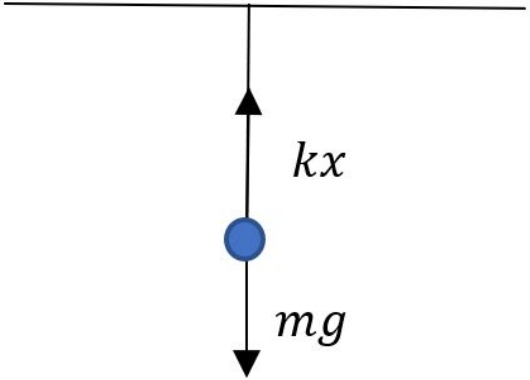
$$k = \frac{m(V_f)^2 + 2E_{Losses}}{(dx)^2}$$

Spring Constant Calculation model



$$k\Delta x = m_{max} g$$

$$k = m_{max} g / \Delta x$$

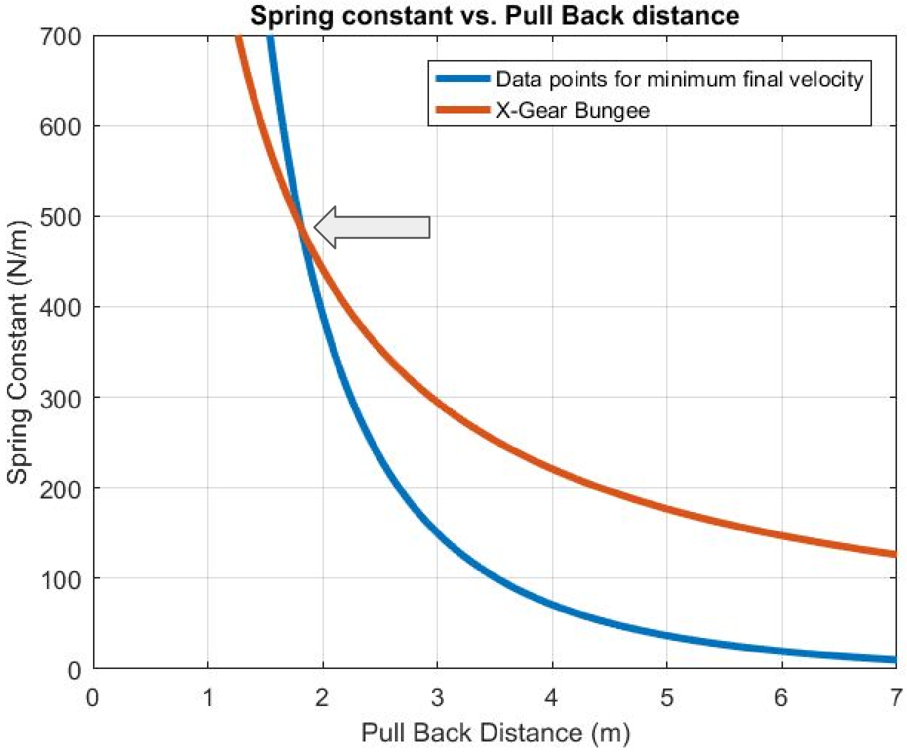


Tensile Strength Calculations

$$\sigma = \frac{F}{A} \quad A_{nylon} = \pi(d_{nylon}/2)^2 \quad or \quad A_{silicon} = \pi(d_{outer}/2)^2 - \pi(d_{inner}/2)^2$$

Bungee	Area	Force	Tensile strength	Max Tensile Strength of Material
Silicone Rubber	3.06e-5 m^2	196.2 N	1.6 MPa	5.5 MPa
Nylon Rope	1.13e-4 m^2	882.9 N	7.8 MPa	82.7 MPa

X-Gear Bungee



Concerns and Requirements:

- Force < 430 N (For g)
- Final Length < 9.1 m
- Tensile Strength < 82.7 MPa

$x_i = 1.2976\ m$

$\Delta x = 1.8166\ m$

$x_f = 3.1142\ m < 9.1\ m$

$k = 486\ N/m$

$F = 882.9\ N > 430\ N$

$\sigma_{req} = 7.8\ MPa < 82.7\ MPa$

∴ Takeoff is not Feasible

Landing Forces (Cont.)

Maximum allowable force during landing is found with the stress equation:

$$\sigma = \frac{F}{A}$$

- Using σ as the maximum allowable stress of 120 kPa and A as the cross sectional area of the fuselage at 0.0201 square meters, maximum allowable force is calculated to be 2412 Newtons
- 2412 Newtons corresponds to an acceleration of 278.81 m/s^2 or 28.45 g using F = M/A
- Time to stop using this maximum force is calculated using the velocity equation:

$$V = 0 = V_o - at$$

- Using our initial velocity of 10.3 m/s and calculated acceleration, stopping time is found to be 0.0369 seconds
- Calculated values were then plugged into the distance equation to determine stopping distance:

$$X = V_0 t - 0.5at^2$$

Using calculated values, minimum stopping distance found to be:
0.1898 m < design stopping distance of 1.3198 m
Feasible by analysis

Landing Forces

- Primary Concern Is acceleration sustained upon impact with net
- With net dimensions at 2.44m x 3.96m
- Calculation assumes 60 degree deflection of 2.44m vertical section of net, allowing for a stopping distance of 1.06 m
- Using stall speed of 20 kts = 10.3 m/s and a 5g acceleration during landing, landing time is calculated to be 0.177 seconds using $X = V_0 t - 1/2 a t^2$
- Based on video of net landing on similar systems, this stopping time is reasonable
- Most force compressive, focused on fuselage during landing
- Compressive strength of EPP is 120 kPa
- Under this limit, assuming all force is focused on fuselage and minimum fuselage cross section is more than or equal to maximum wing cross section (worst case), maximum allowable landing force is 16.96 g
- Redoing stopping time calculation with 16.96 g force gives a stopping time of 0.062 seconds, even easier to achieve based on video evidence

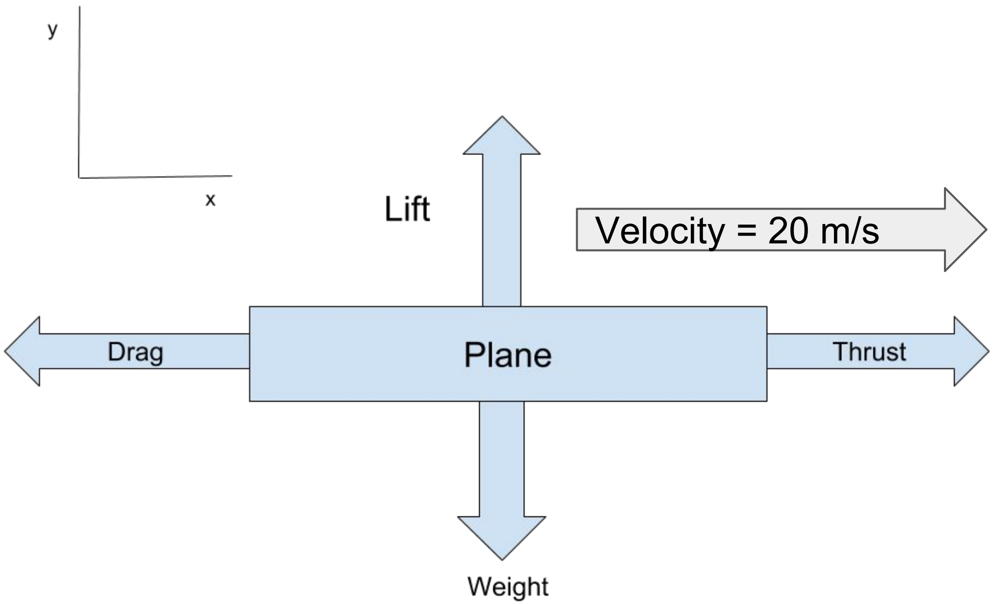
Feasible From Video Evidence

Landing Forces (Cont.)

- Primary concern is acceleration sustained upon impact with net.
- Stopping distance of 1.06 m.
- Impact time is calculated to be 0.177 seconds.
- Based on videos of net landings for similar sized systems, this stopping time is reasonable.
- The maximum allowable landing force is 16.96 g. (worst case scenario)

Impact time with 16.96 g: .062 seconds
∴ Feasible

Cruise Power



Power in Flight:

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

Given L/D = 10

Assuming Steady Level Flight

Lift = Weight = 89 N

⇒Thrust = 8.9 N

Using Computed Thrust and Velocity

Power = 8.9 * 20 m/s = 178 W

Assuming propulsion efficiency of 0.75

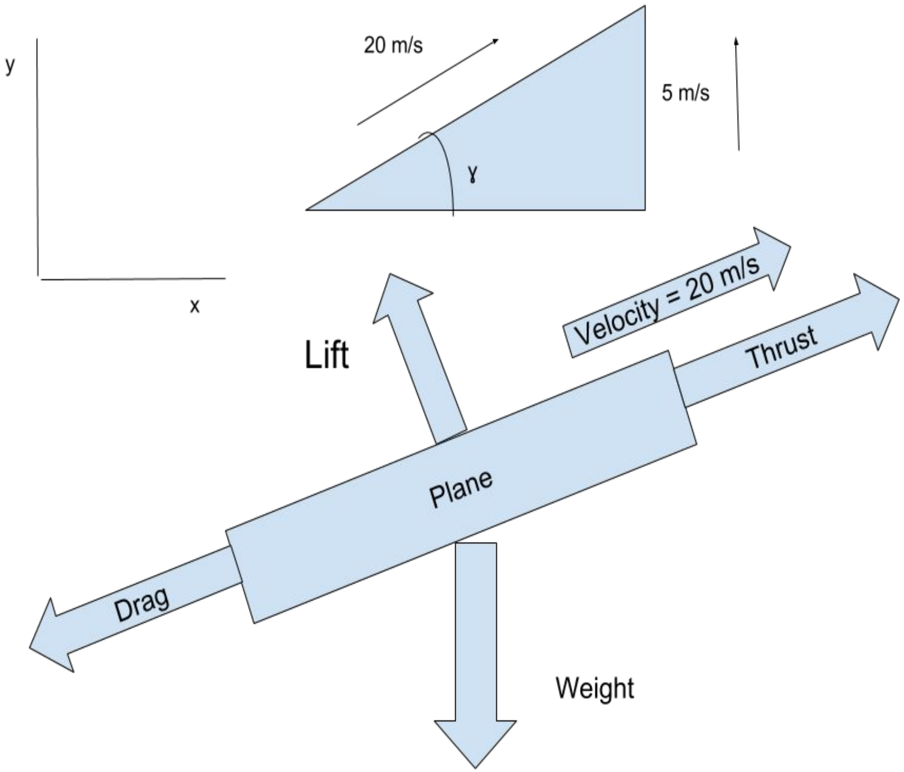
Power = 238 W

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

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

= 238 * 1.4 = 332 Wh

Climb Power



Given: Velocity = 20 m/s, Climb Rate = 5 m/s
Weight = 111.12 N, L/D = 10, t = 0.05 hr
Need: Power [W] = Thrust [N] * Velocity [m/s]
Thrust

Climb Angle Equation:
$\sin(\gamma) = (\text{Thrust} - \text{Drag}) / (\text{Weight})$

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

Solve Climb Angle Equation for Thrust
$\text{Thrust} = \text{Weight} \cdot \sin(\gamma) + D$
$= 30.43\text{N}$
Power = 30.43 N * 20 m/s = 608.62 W
Assuming 0.75 efficiency
Power = 811.50 W

Energy Required = 811.5 * 0.05 = 40.57 Whr

Alternative

Samsung 48G 21700 4800mAh Battery

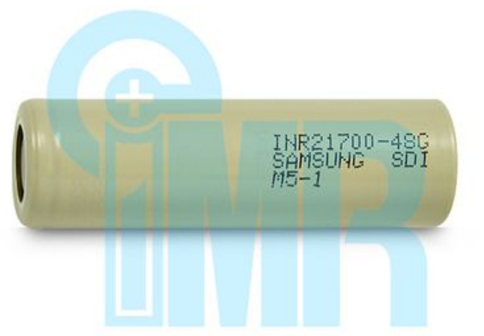
1 battery specifications:

- 4800 mAh
- 3.70 V
- 0.067 kg
- 4.8A Max discharge for optimum life cycle
- 9.6A Max discharge
- 17.76 Wh
- Rechargeable

584 Wh Achievable with 33 batteries

Battery Energy:
$Wh_{AV} = V*Ah$ [Wh]

Number of Batteries:
$Num = Wh_{Req}/Wh_{Av}$



Samsung Battery Cell

Required Energy Density

Allotted Mass: 2.8 kg

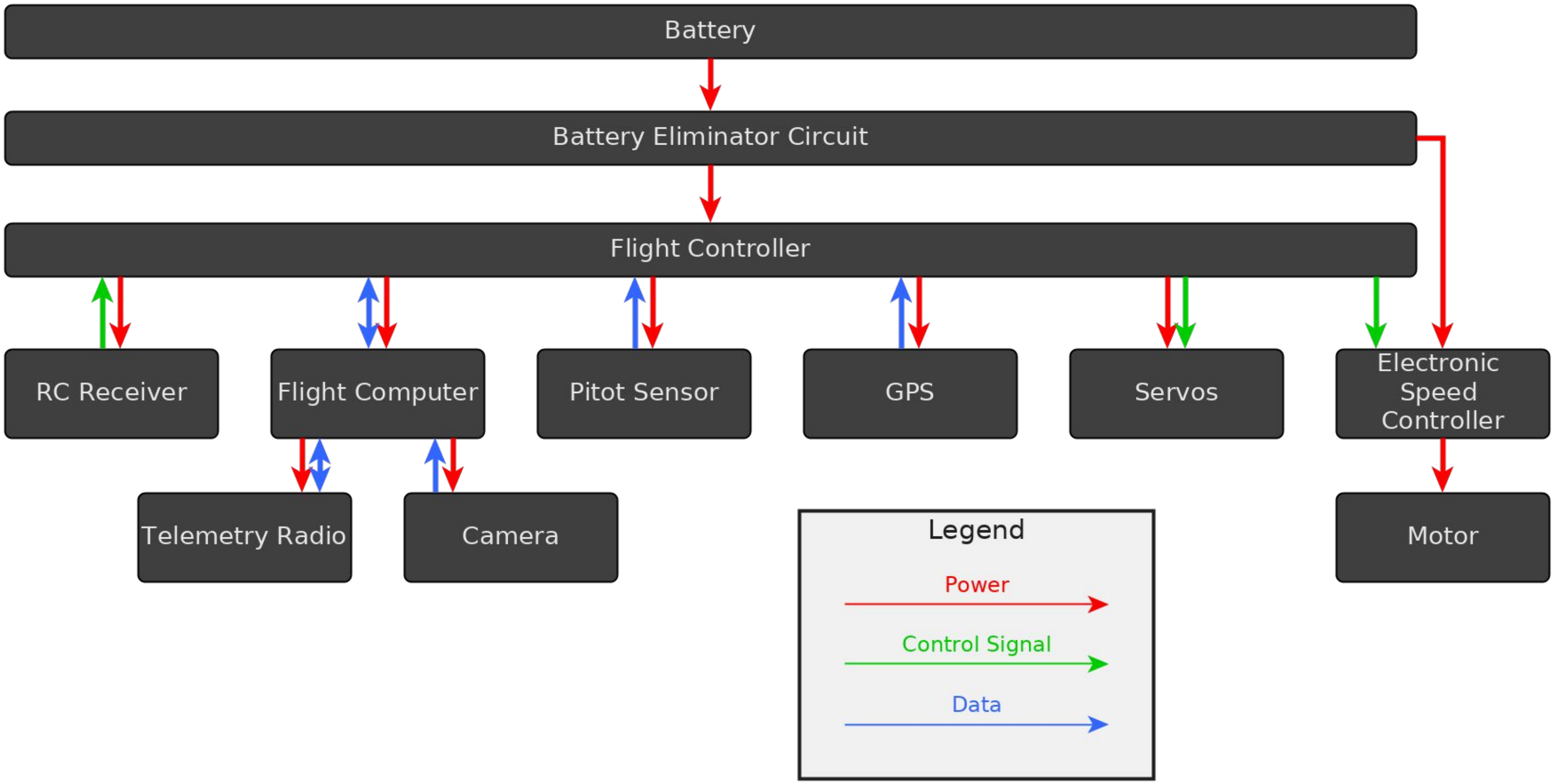
Given mass and watt-hours:

- L/D = 10 → 540 Wh → **694 kJ/kg**
- L/D = 12 → 460 Wh → **592 kJ/kg**

Samsung 48G 21700
Energy Density: 955 kJ/kg

Tattu 22000mAh 6S 25C 22.2V Lipo Battery Pack
Capacity: 22000 mAh
Voltage: 22.V
Watt-hours: 488 Wh
Available Watt-hours: 390 Wh
Weight: 2.65 kg
Energy Density: 664 kJ/kg

Electronics Layout



Alternative Configurations

Pack Configurations: (36 batteries required for complete cells)

6x6 Pack:
- 6 batteries per cell
- 22.2 V
- 28800 mAh

9x4 Pack:
- 9 batteries per cell
- 14.8 V
- 43200 mAh

4x9 Pack:
- 4 batteries per cell
- 33.3 V
- 19200 mAh

Total Energy: 639 Wh > 584 Wh
Total Weight: 2.43 kg < 2.49 kg
Total Volume: 1120 cm^3 < 2744 cm^3

∴ Feasible

Check: average draw per battery is 0.71 C < 1C

Check

Can the batteries sustain the power draw? Must be less than 1.00 C

- (@ 22.2 V) 28.8 Ah / 1.40 hrs
  - 20.6 Amps average drawn in flight
- 20.6 Amps / 6.00 cells
  - 3.43 Amps per battery
- The average draw is 0.71 C per battery

Navigation

Requirement Section	Requirement	Motivation
COM 1.2	The UAV shall transmit RC and datalink at 20kbit transmission rates	Derived requirement to have the UAV controlled by RC and transmit data back to the GCS
SW 4.3	The flight computer shall receive commands, waypoints, and GPS coordinates from the GSC and broadcast telemetry(including location, altitude, attitude, airspeed, groundspeed, vertical speed) and health/status.	Derived requirement to have the UAV search an area for whales and return to home
SW 7.1	The flight computer shall run the programmed software, control aircraft position without manual input, and decide a flight path when given a search area or on return to land.	Derived requirement based on specifications for autonomous flight

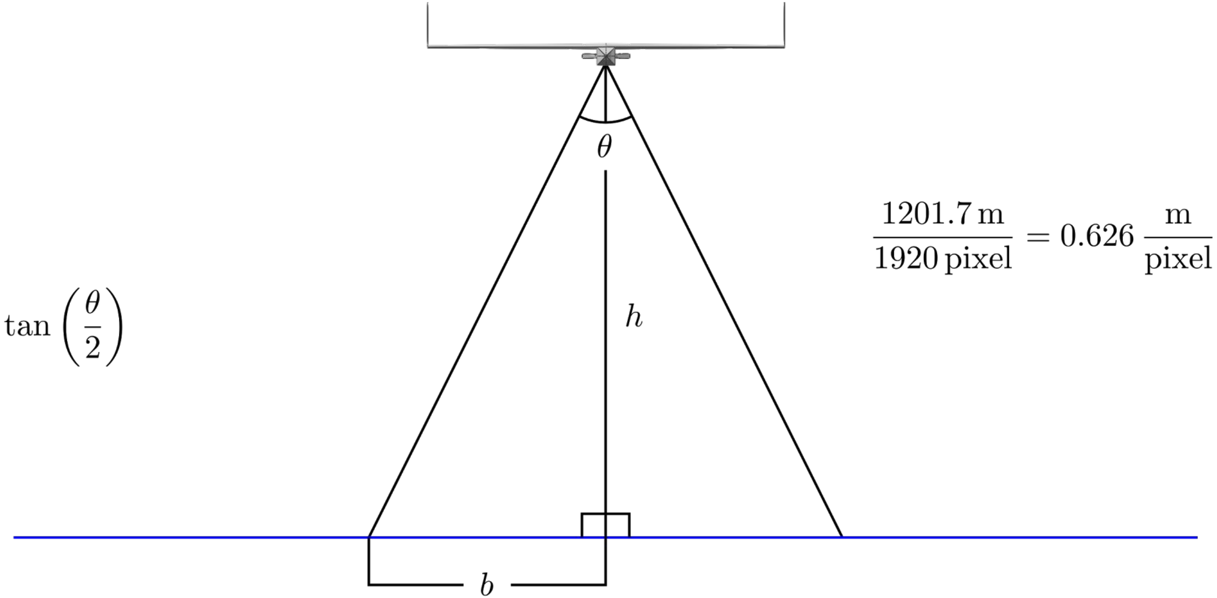
FOV Calculations

$h = \text{cruise altitude}$

$b = \text{FOV (in meters)}$

$\theta = \text{FOV (in degrees)}$

$$\frac{b/2}{h} = \tan\left(\frac{\theta}{2}\right) \quad \rightarrow \quad b = 2\,h\,\tan\left(\frac{\theta}{2}\right)$$



$$\frac{1201.7\,\text{m}}{1920\,\text{pixel}} = 0.626\,\frac{\text{m}}{\text{pixel}}$$

Width

$h = 1000\,\text{m}$

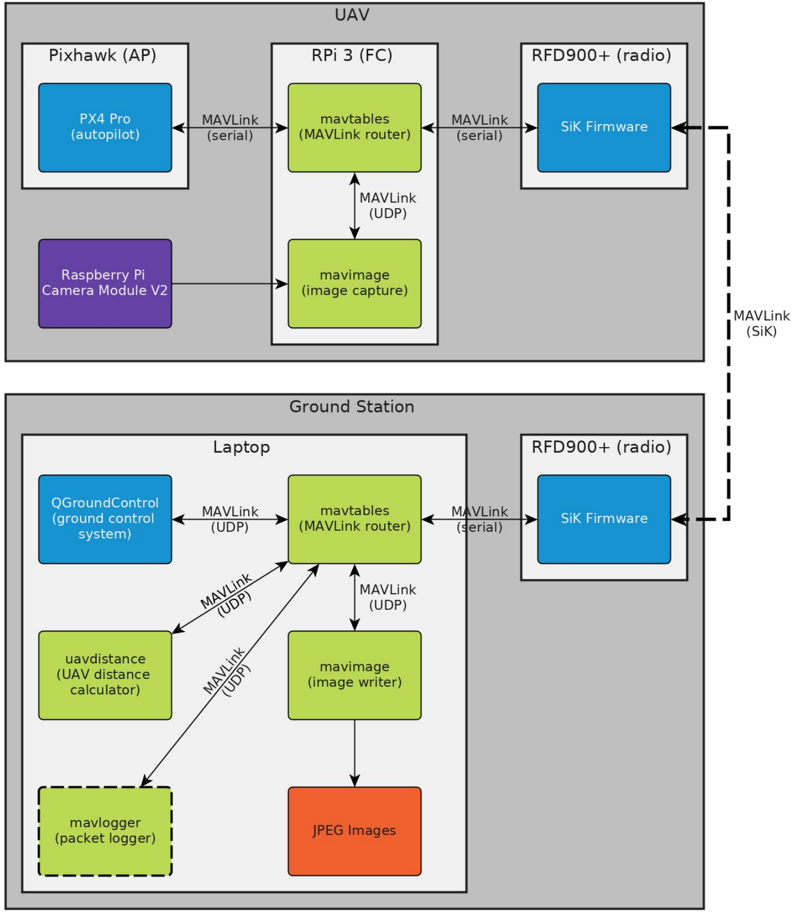
$\theta = 62°$

$$b = 2\,h\,\tan\left(\frac{\theta}{2}\right) = 2 \cdot 1000\,\text{m} \cdot \tan\left(\frac{62°}{2}\right) = 1201.7\,\text{m}$$

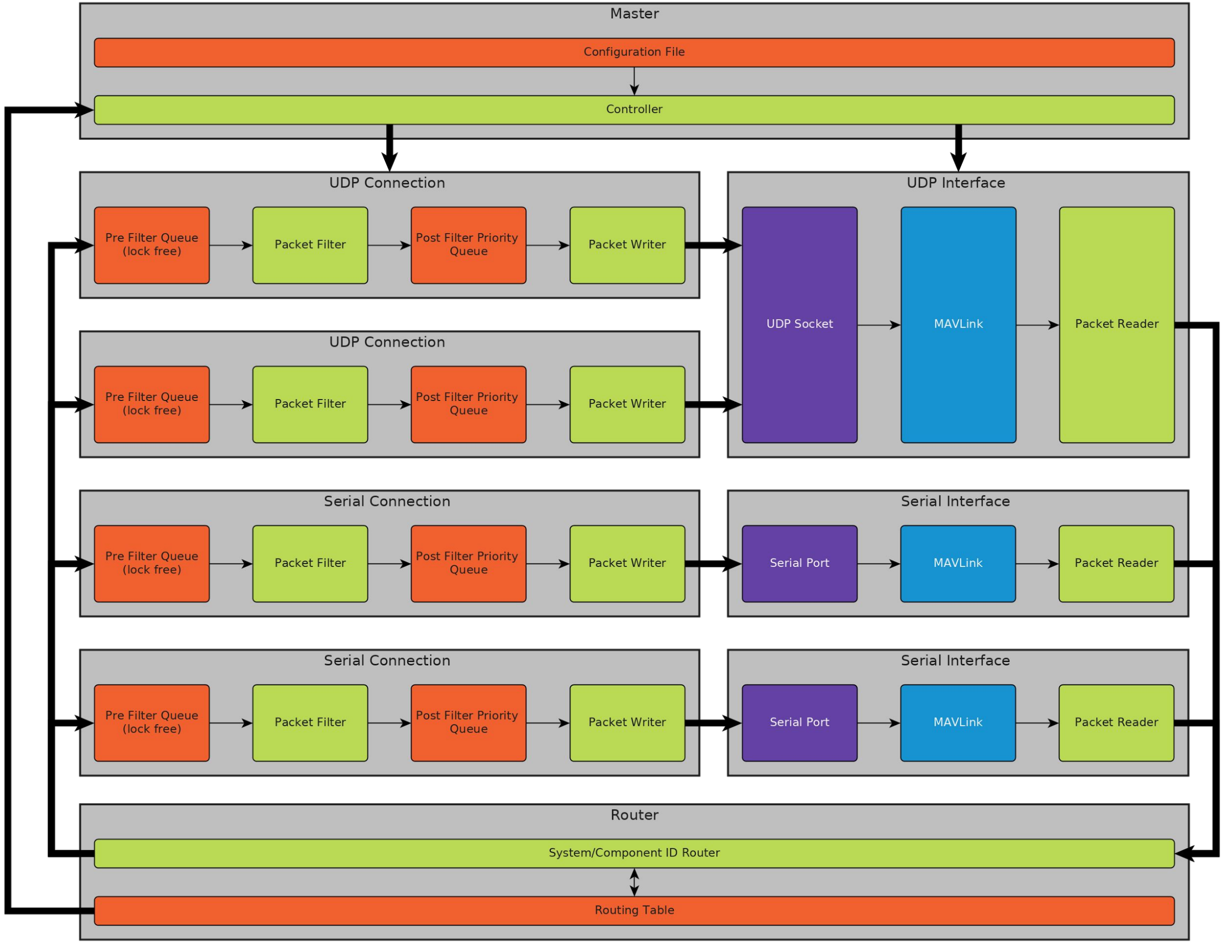
Height

$$b = 2\,h\,\tan\left(\frac{\theta}{2}\right) = 2 \cdot 1000\,\text{m} \cdot \tan\left(\frac{49°}{2}\right) = 911.5\,\text{m}$$

Software Overview

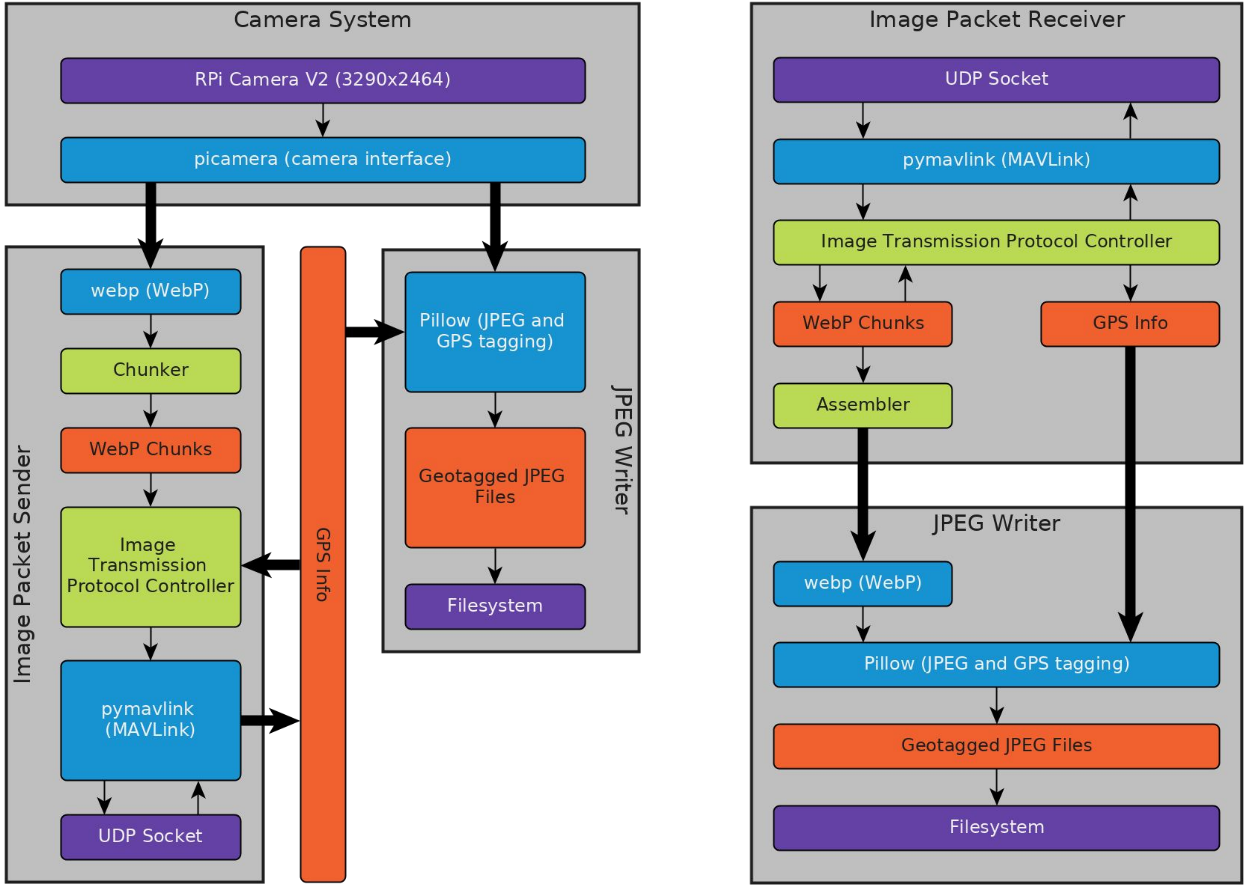


mavtables

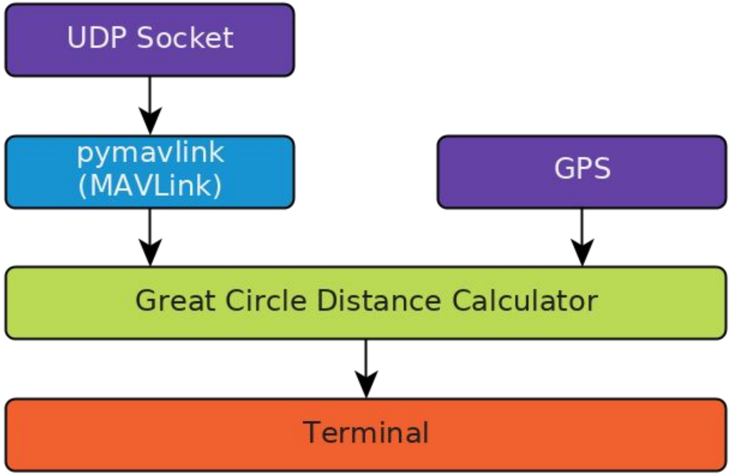


Master
Configuration File
Controller
UDP Connection
Pre Filter Queue (lock free)
Packet Filter
Post Filter Priority Queue
Packet Writer
UDP Connection
Pre Filter Queue (lock free)
Packet Filter
Post Filter Priority Queue
Packet Writer
Serial Connection
Pre Filter Queue (lock free)
Packet Filter
Post Filter Priority Queue
Packet Writer
Serial Connection
Pre Filter Queue (lock free)
Packet Filter
Post Filter Priority Queue
Packet Writer
UDP Interface
UDP Socket
MAVLink
Packet Reader
Serial Interface
Serial Port
MAVLink
Packet Reader
Serial Interface
Serial Port
MAVLink
Packet Reader
Router
System/Component ID Router
Routing Table

mavimage


Camera System
RPi Camera V2 (3290x2464)
picamera (camera interface)
Image Packet Sender
webp (WebP)
Chunker
WebP Chunks
Image Transmission Protocol Controller
pymavlink (MAVLink)
UDP Socket
GPS Info
JPEG Writer
Pillow (JPEG and GPS tagging)
Geotagged JPEG Files
Filesystem
Image Packet Receiver
UDP Socket
pymavlink (MAVLink)
Image Transmission Protocol Controller
WebP Chunks
GPS Info
Assembler
JPEG Writer
webp (WebP)
Pillow (JPEG and GPS tagging)
Geotagged JPEG Files
Filesystem

uavdistance



mavlogger

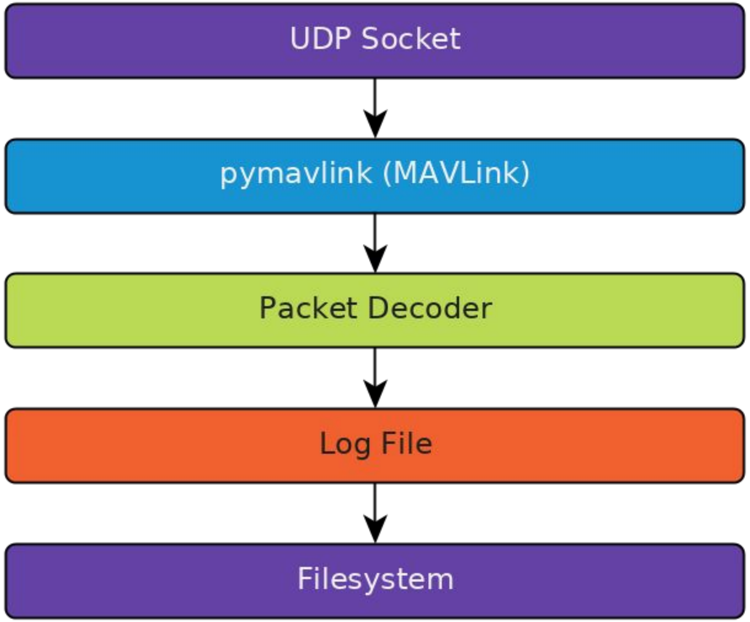
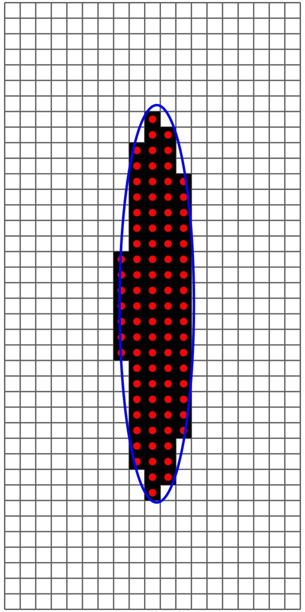
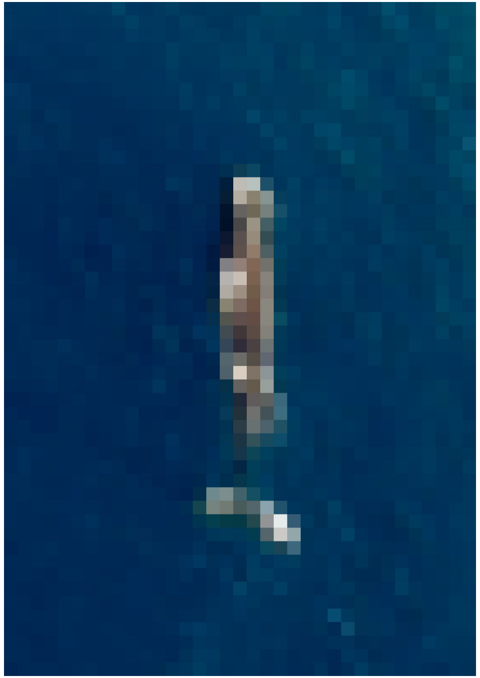


Image Resolution

- 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

Software Risk Management

- Bandwidth
  - *Concern:* Link quality could degrade in certain weather conditions.
  - *Mitigation:* mavtables will prioritize telemetry packets over image packets.
- Latency
  - *Concern:* Delay from data capture to display on the virtual cockpit could exceed acceptable values (~200 ms).
  - *Mitigation:* Fly within line of sight. Unlikely since new components are running of the fastest hardware (RPi and laptop).
- Time
  - *Concern:* Not enough time to finish the software.
  - *Mitigation:* Required time estimated and tripled to account for unit tests and debugging. Completion still estimated in April.

Landing preliminary cost estimate

Single Pulley x 6 @ 7.95 ea = $47.7
Double Pulley x 2 @ 15.20 ea = $30.4
54 ft of aluminum structure = $225
100 ft wire rope = $50
Misc, brackets and connectors = $75
Total = $428.1

Gantt Chart (CDR Schedule)

Scheduled
Margin