Rapid Aerial Photographic Target Recognition

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

Advisor: Dr. Dennis Akos

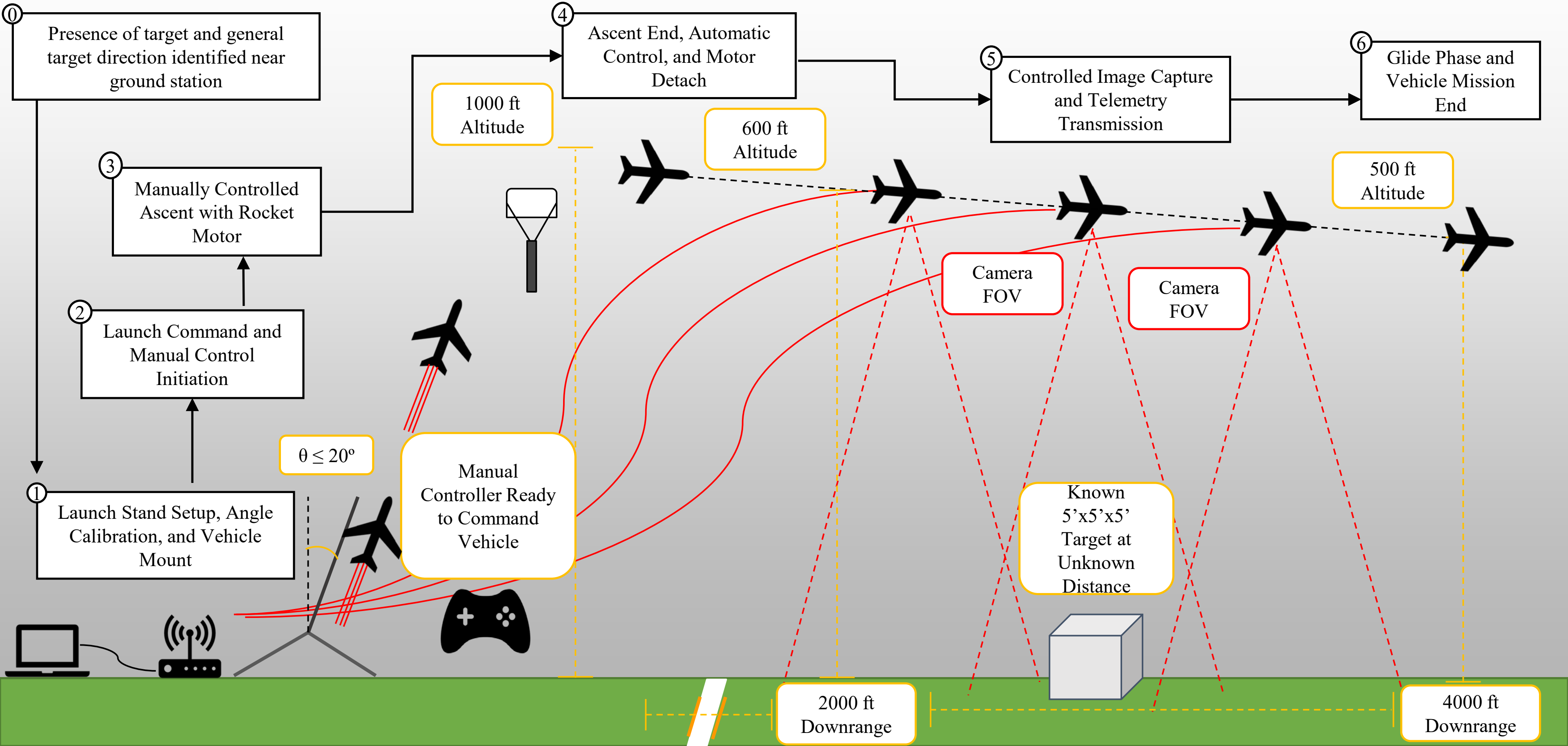
Project Purpose and Objectives

Project Motivation

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

RAPTR CONOPs

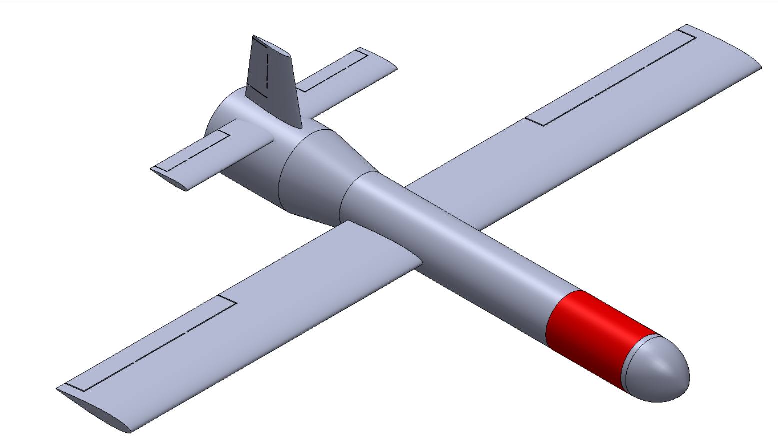
Objective: Image and locate target within area of interest

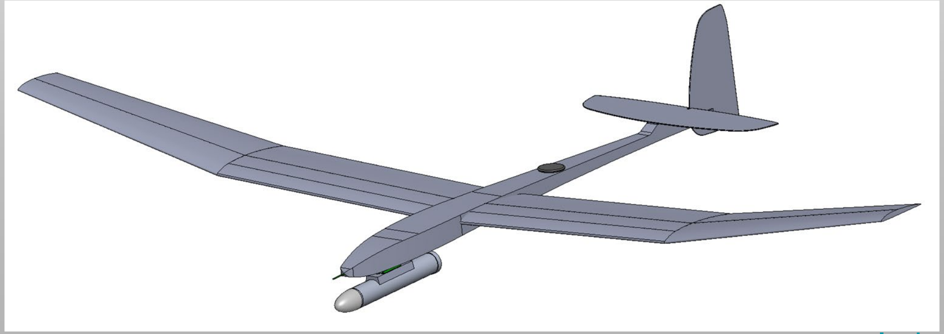


RAPTR

Major Changes From PDR

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





ASEN/ECEN Responsibility Division

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

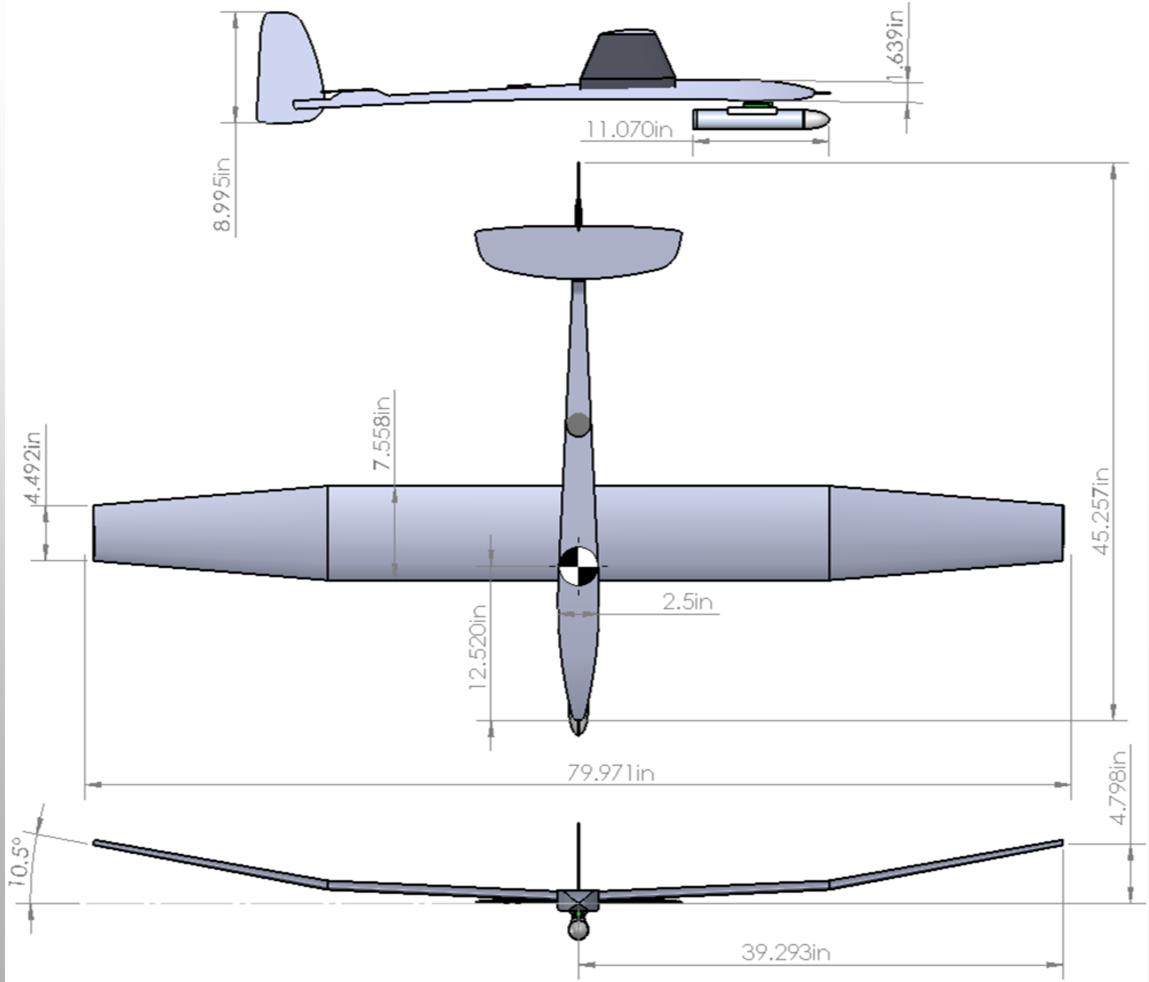
Functional Requirements

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

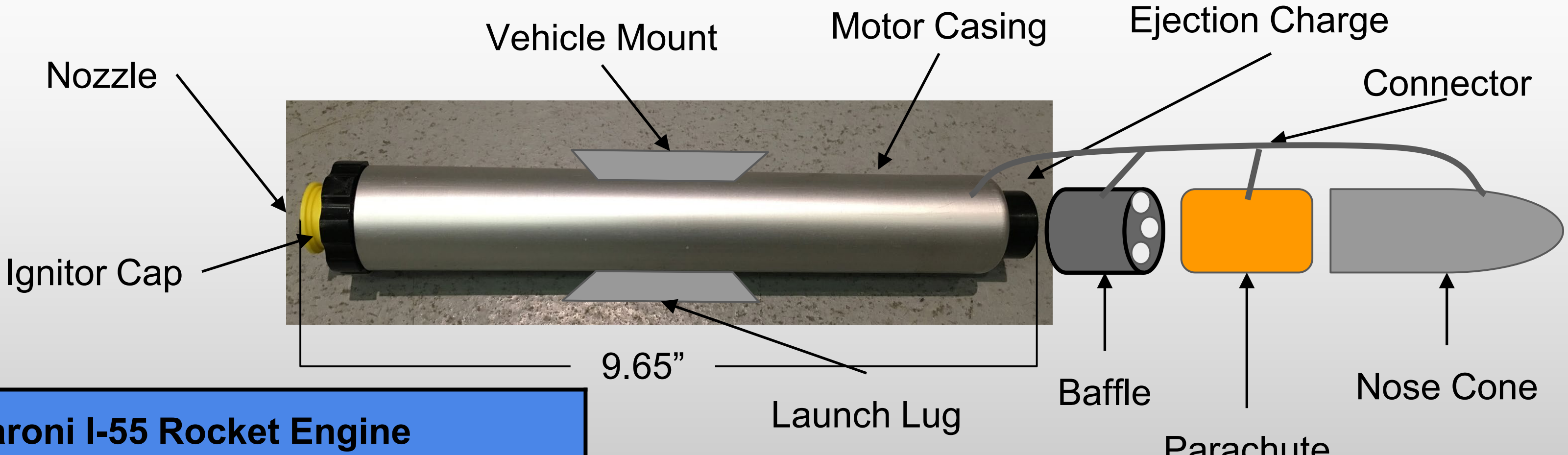
Design Solution

Hyperflight AndREaS

Item(s)	Mass [lb]
Airframe	1.14
Motor and Mount	1.50
Electronics	0.48
Payload	1.10
Total	**4.22**



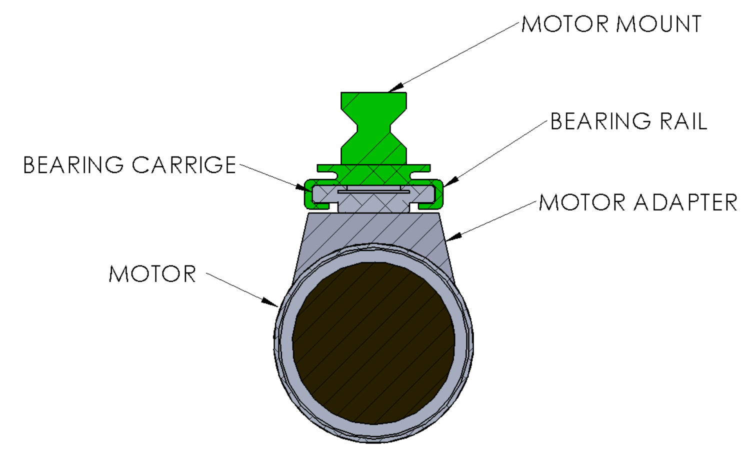
Propulsion Overview

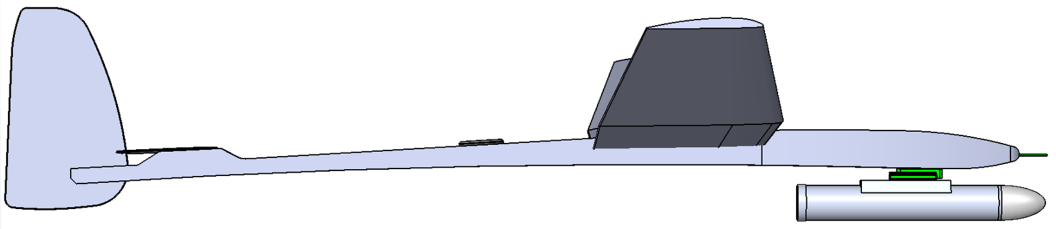


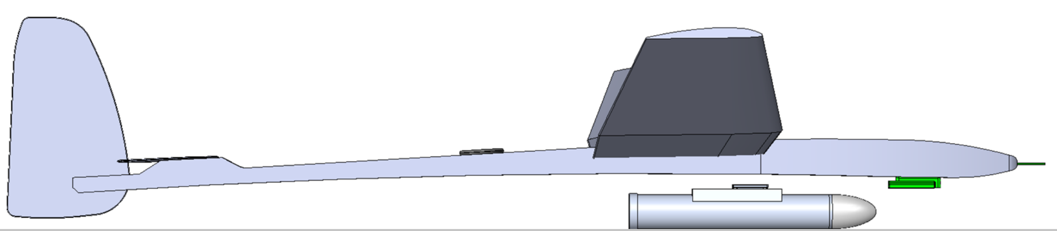
Cesaroni I-55 Rocket Engine COTS Reloadable Engine	
Maximum Thrust	21.25 lbf
Average Thrust	12.41 lbf
Burn Time	7.25 sec
Black Powder Ejection Charge	9 sec

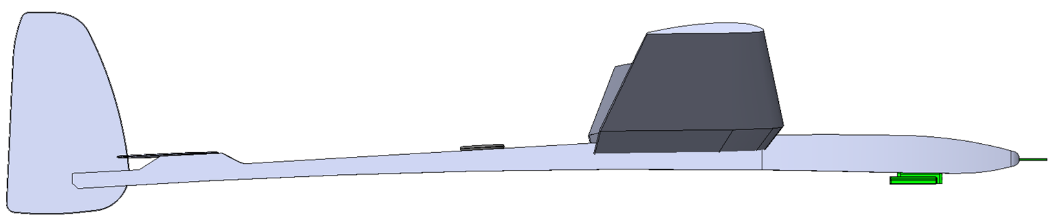
Motor Mounting and Separation

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

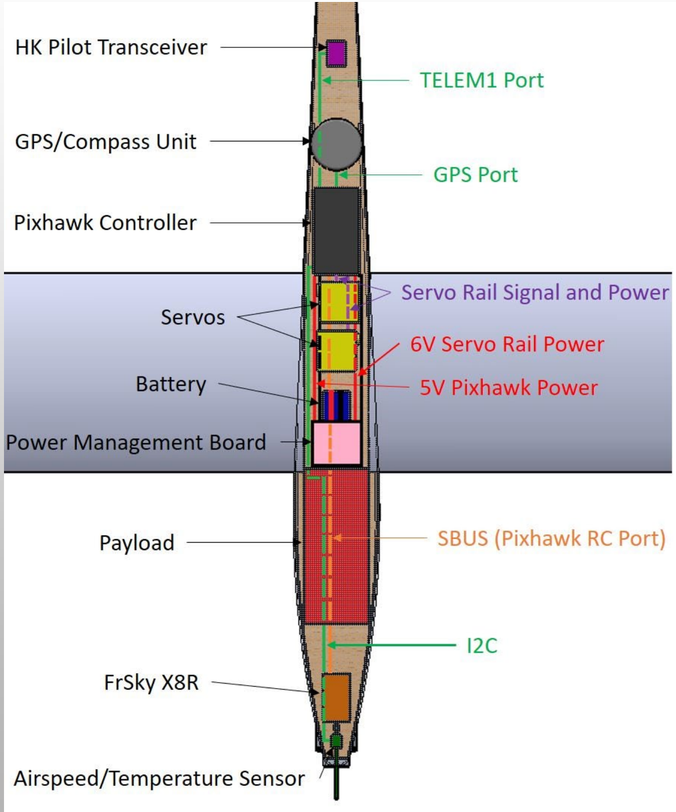


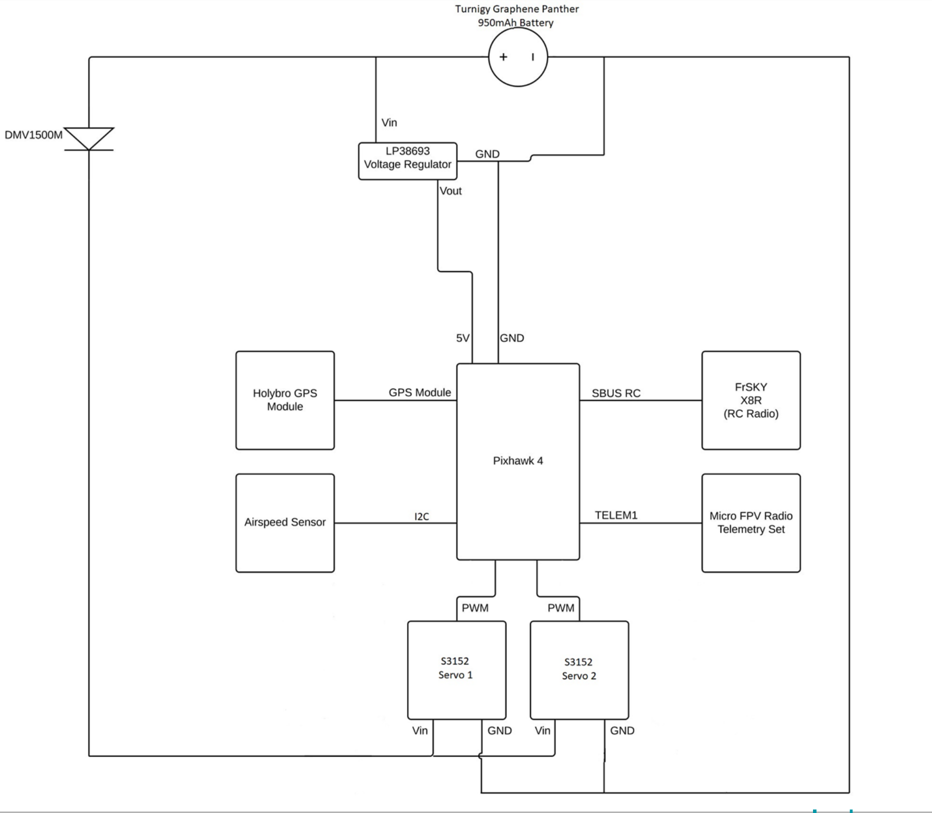




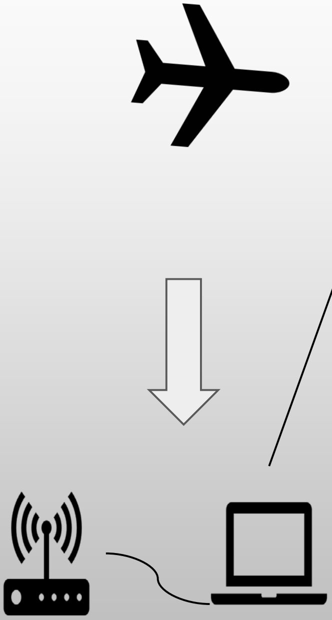


Electronics

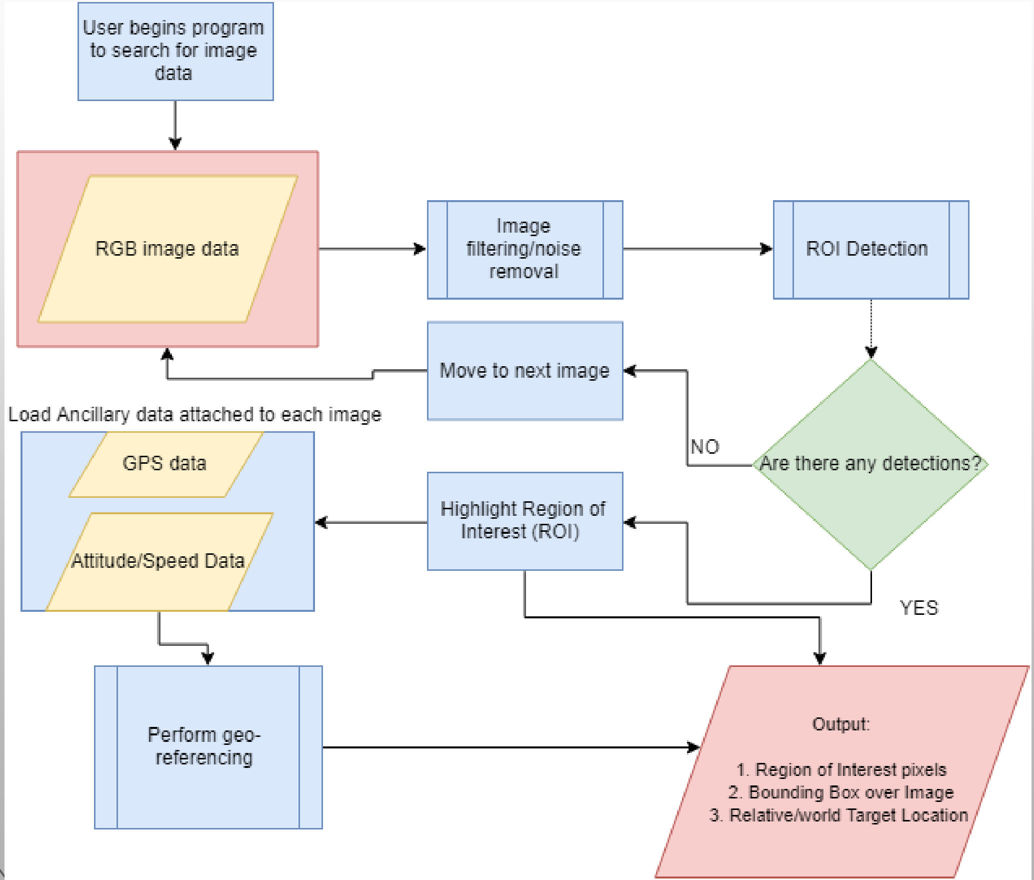




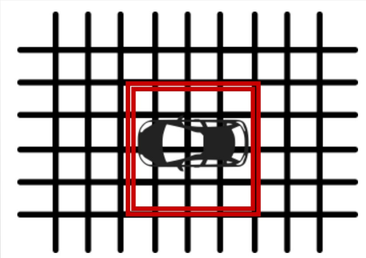
Ground Processing: Region of Interest Detection and Location During Glide



Images/Data Transmission



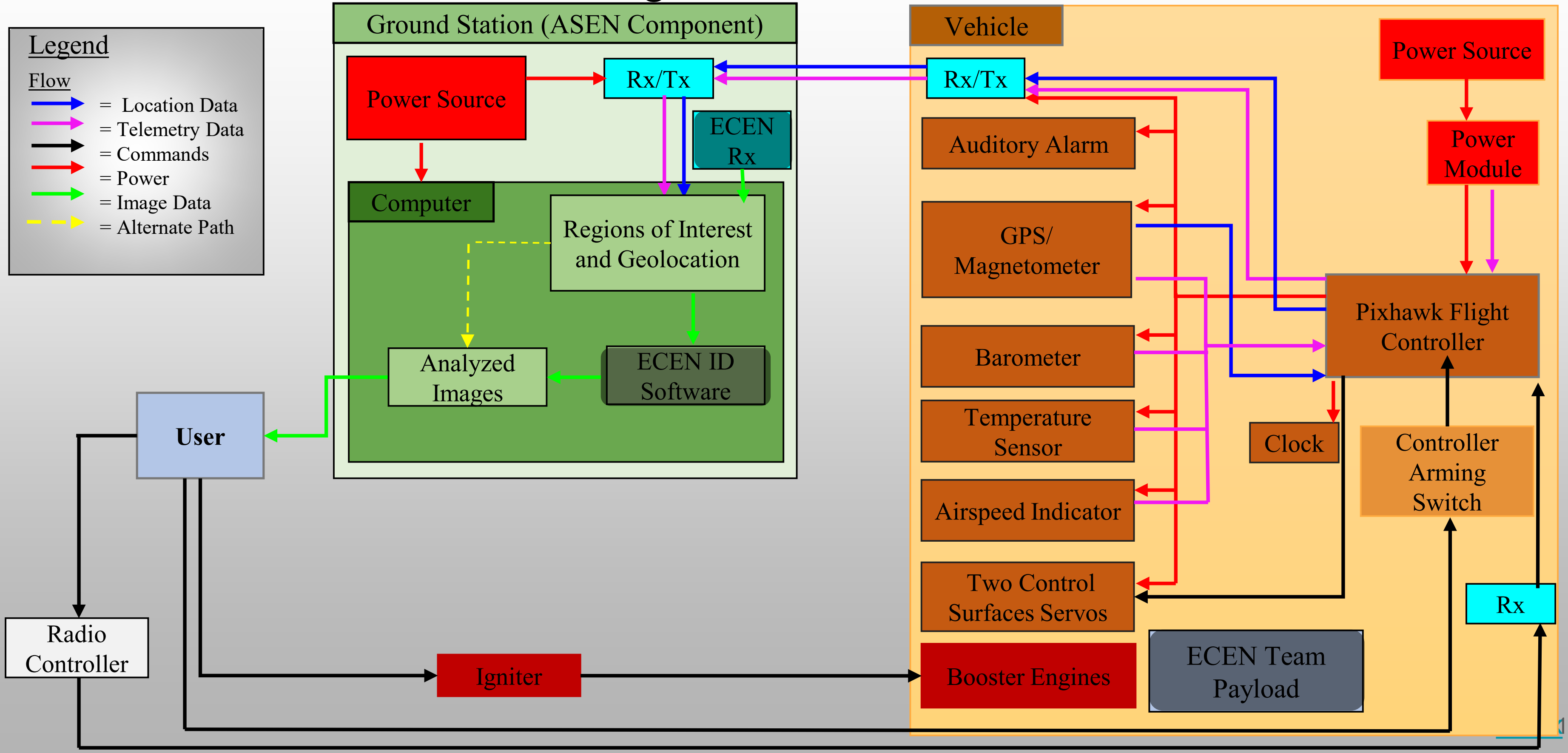
Output



Region of Interest Detected

Latitude:	
Longitude:	
Distance:	

RAPTR Functional Block Diagram



Critical Project Elements

CPE Selection

Aerial Vehicle Design
Vehicle and Payload Integration
Vehicle Electronics
Transmission and Reception
FAA compliance
Target Recognition/GeoLocation Software
Propulsion System
Control

Intense Performance Requirements (FR1)

Complex Theory (FR5)

High Risk Propulsion System (FR4)

High Speeds (FR1 & FR4)

Design Requirements and Satisfaction

Structural Requirements

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

Structural Integrity (DR 1.4)

Structural Requirements

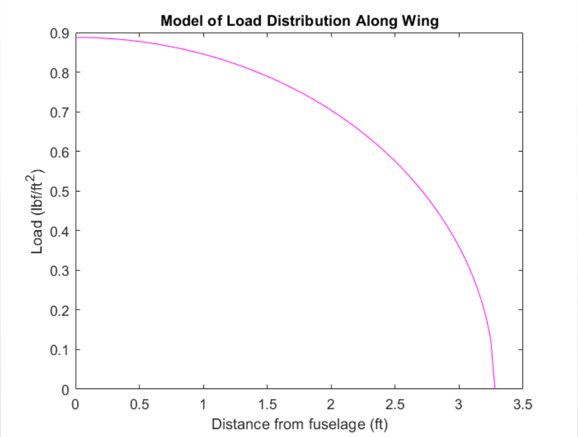
Derived Requirements	Description
DR 1.4	The vehicle shall withstand the forces of the launch and glide phases.

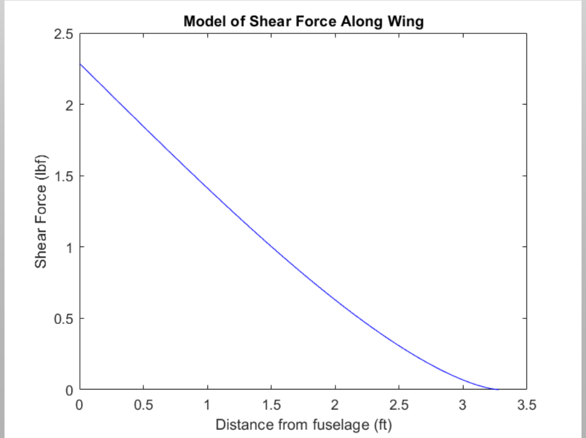
A Matlab model of shear force and bending moment along the wing.

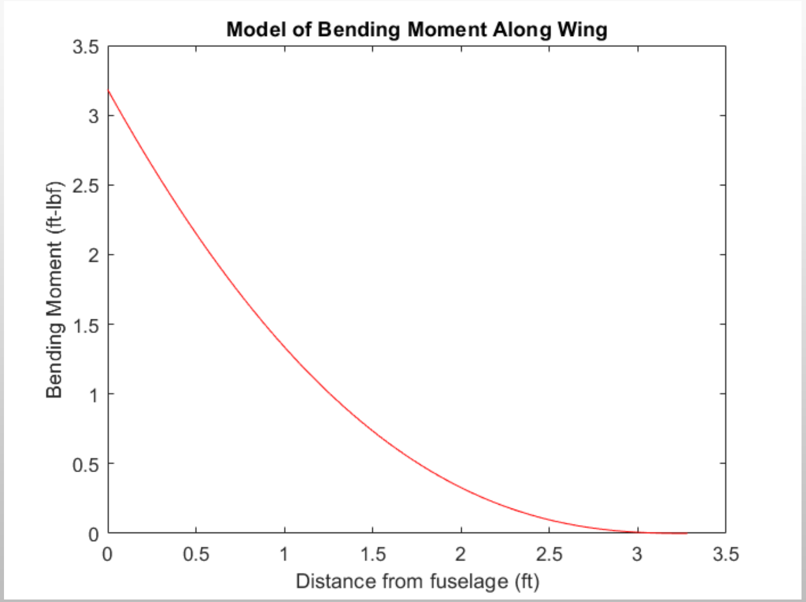
Flexure Formula for 0.25” diameter rod → slight climb σ_{max} = 12,457 psi

Material	**σ_y [psi]**	**FOS (slight climb)**
Balsa	2,828	0.227
Al-6061	40,000	3.211
Steel	53,700	4.310
Carbon Fiber	82,762	6.643

Structural Requirements







Structural Integrity

(DR 1.4) ✓

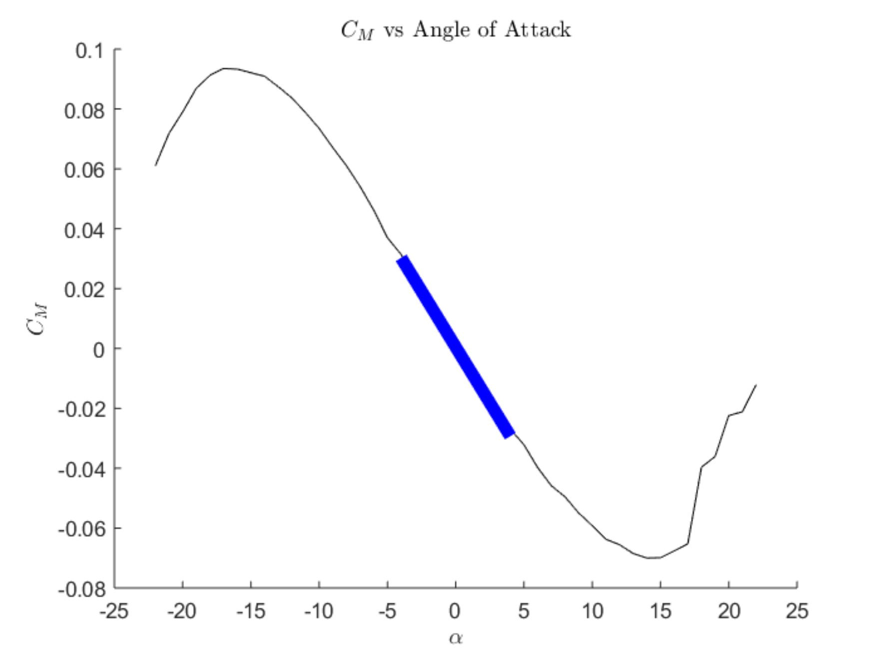
Vehicle Performance Requirements

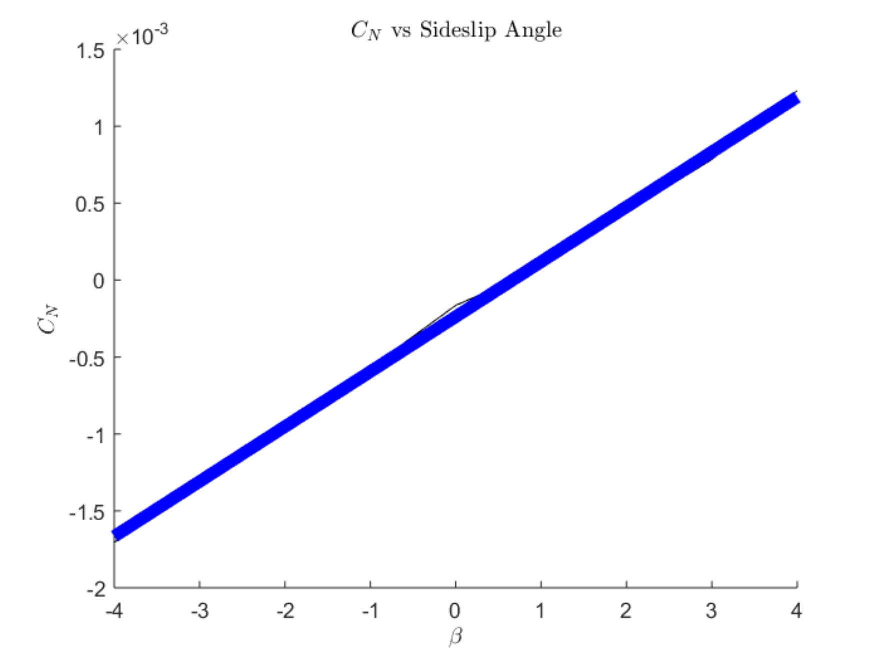
Requirement	Description
FR 1	The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.
DR 1.1.5	The vehicle shall be exhibit natural stability in all phases of flight.
DR 1.1.1	The vehicle shall be capable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

Aerodynamics - Stability Analysis

CFD Analysis	Datcom Analysis
Solidworks model imported to ANSYS Fluent	Input file containing geometry information
Vary angle of attack, sideslip angle, and velocity	Calculates most stability derivatives
Calculate [X,Y,Z] forces and [l,m,n] moments for each case	Used in conjunction with CFD to confirm and improve results

Stability Results





$$C_{m_\alpha} = -0.4143$$

$$C_{n_\beta} = 0.0248$$

Thrust and Glide Phase Stability

	Static Margin
Glide Phase	0.90
Thrust Phase	1.45

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

	C_{n_β}
Glide Phase	0.0248
Thrust Phase	0.0283

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

Range Requirements

Derived Requirements	Description
DR 1.2	The vehicle shall achieve a glide slope less than or equal to 5.7 degrees.

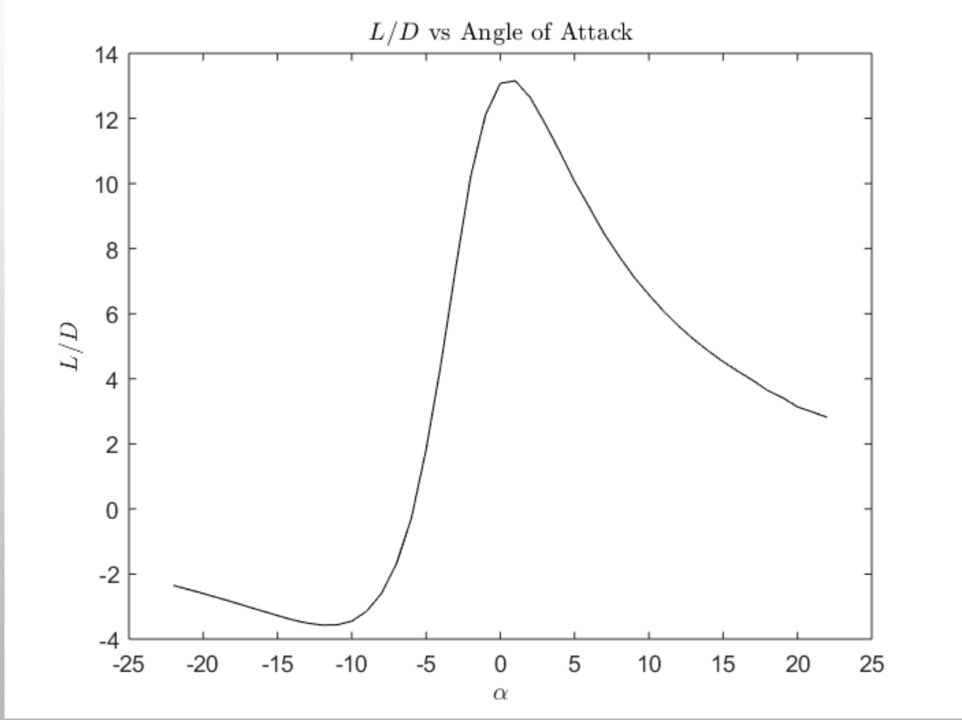
- Mission range: 3,000 foot glide with less than 300 foot drop

Satisfaction of DR 1.2

$$L/D_{max} = 13$$

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

$$\gamma = 4.4°$$

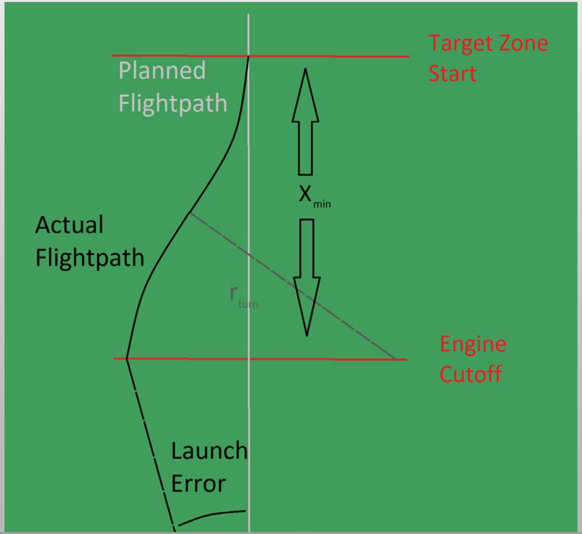


Maneuver Requirements

Derived Requirements	Description
DR 1.1.1	The vehicle shall be capable of a turn radius of 350 feet.

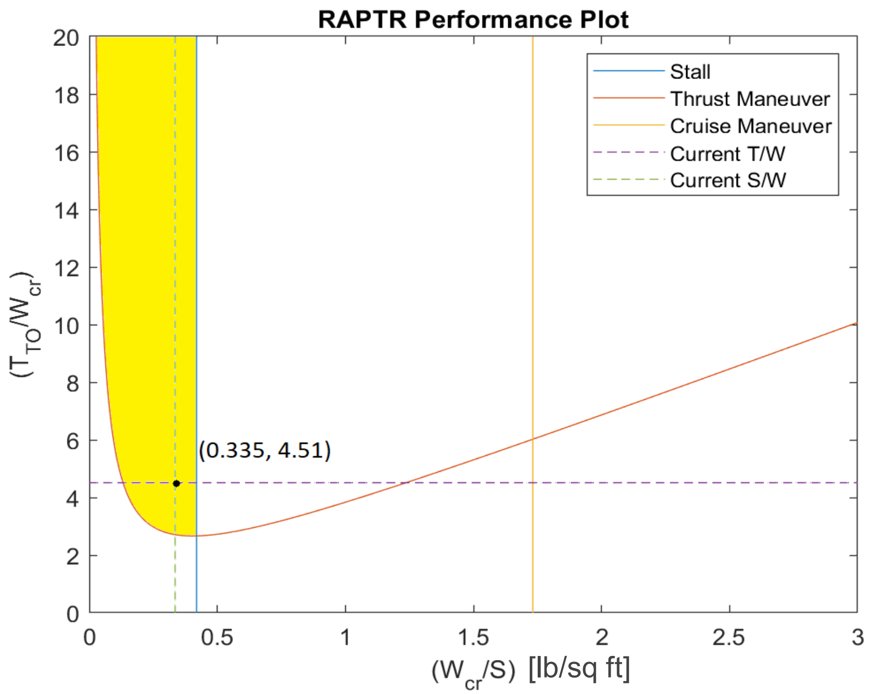
- Course correction - After engine cut-off
- Roughly 1000 feet of downrange to correct

$$r_{turn} = X_{min}[2\sin(\arctan\frac{1000\tan\sigma_{launch}}{X_{min}})]^{-1}$$



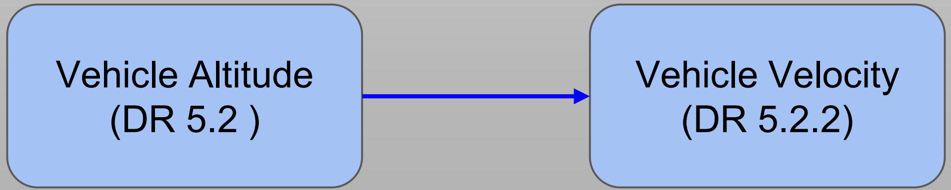
Satisfaction of DR 1.1.1

Requirement: Capable of executing 350 foot radius turn



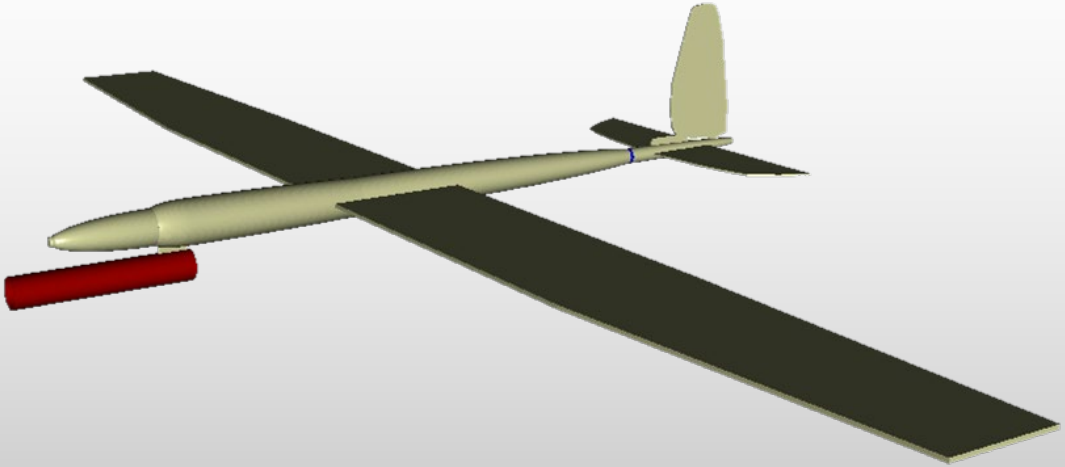
Propulsion Requirements

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



Propulsion Model

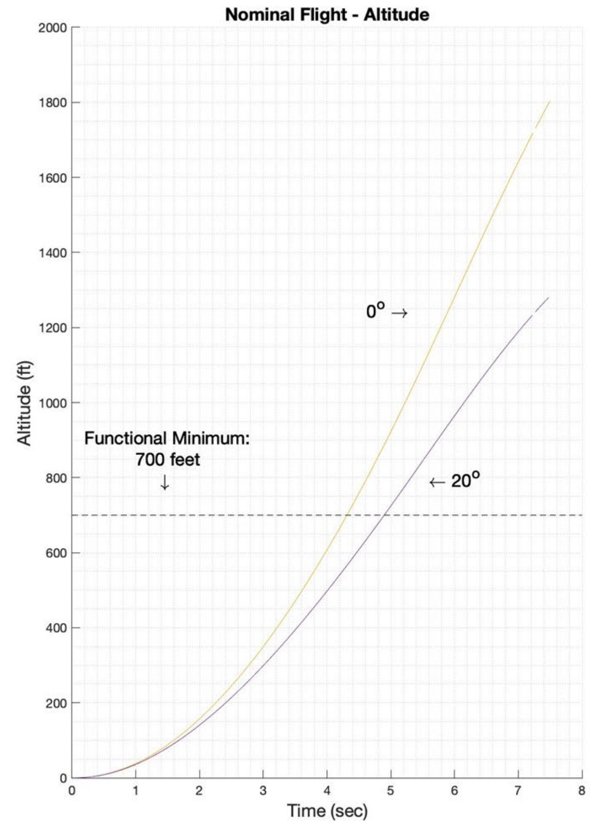
- Three Models
  - RockSim: 3D CAD model
  - **OpenRocket**: 3D CAD model
  - MATLAB: Point -mass model
- Structural Differences
  - Cylindrical Frame
  - No Rocket Nose Cone
  - No Polyhedral Wings

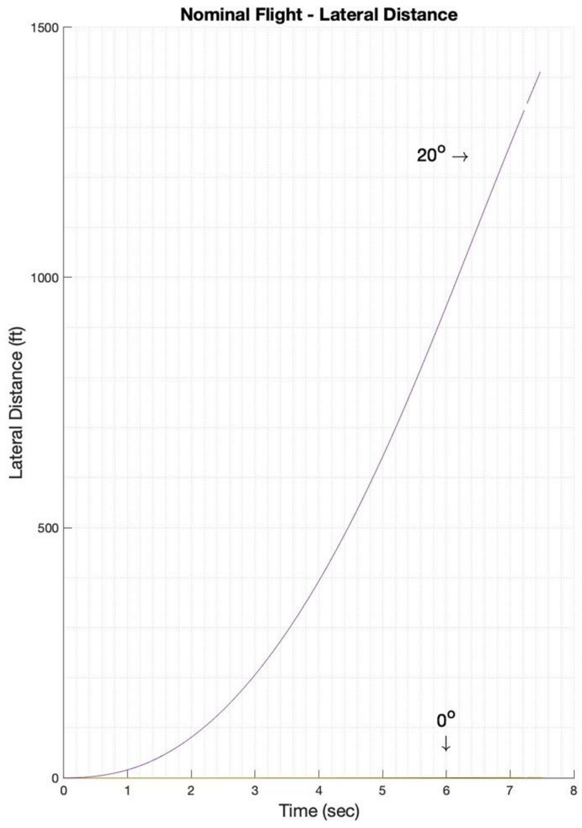


Initialization → Atmospheric Conditions → Flight Parameters → **Aerodynamic Forces and Moments** → **Thrust and Gravitational Forces** → Mass and Moment of Inertia → **Runge-Kutta 4th Order Numerical Integration**

Vehicle Altitude (DR 5.2)	Vehicle Velocity (DR 5.2.2)

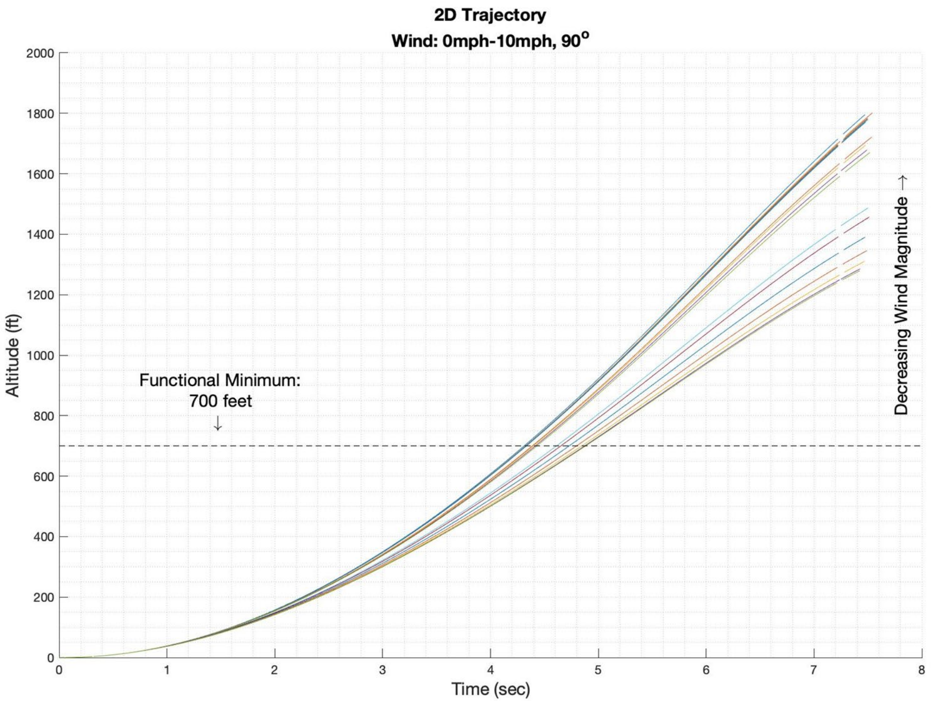
Nominal Propulsion Model

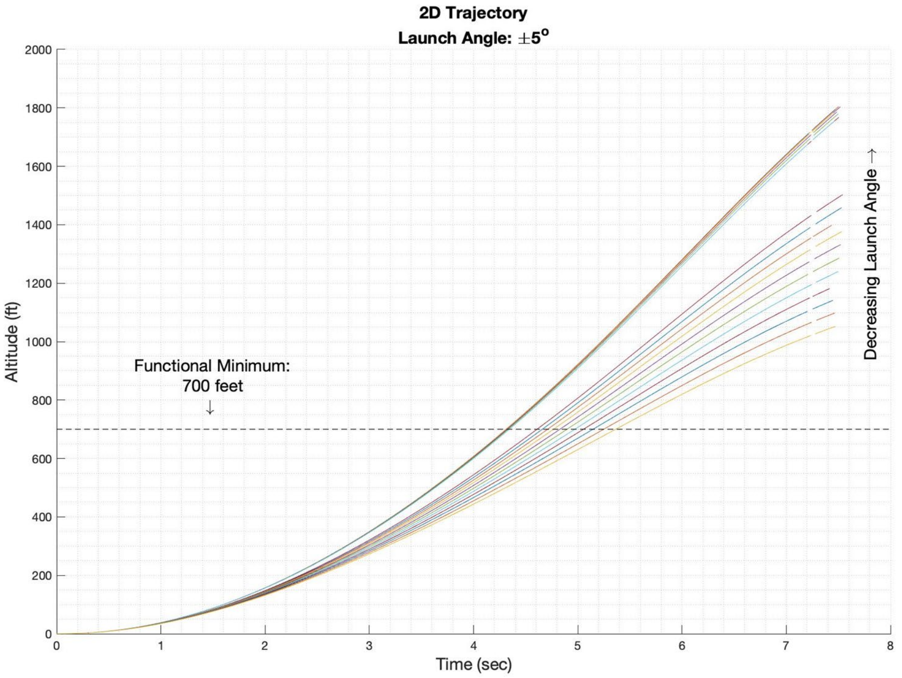




Vehicle Altitude (DR 5.2)	Vehicle Velocity (DR 5.2.2)

Propulsion: Monte-Carlo





Vehicle Altitude (DR 5.2)✓	Vehicle Velocity (DR 5.2.2)

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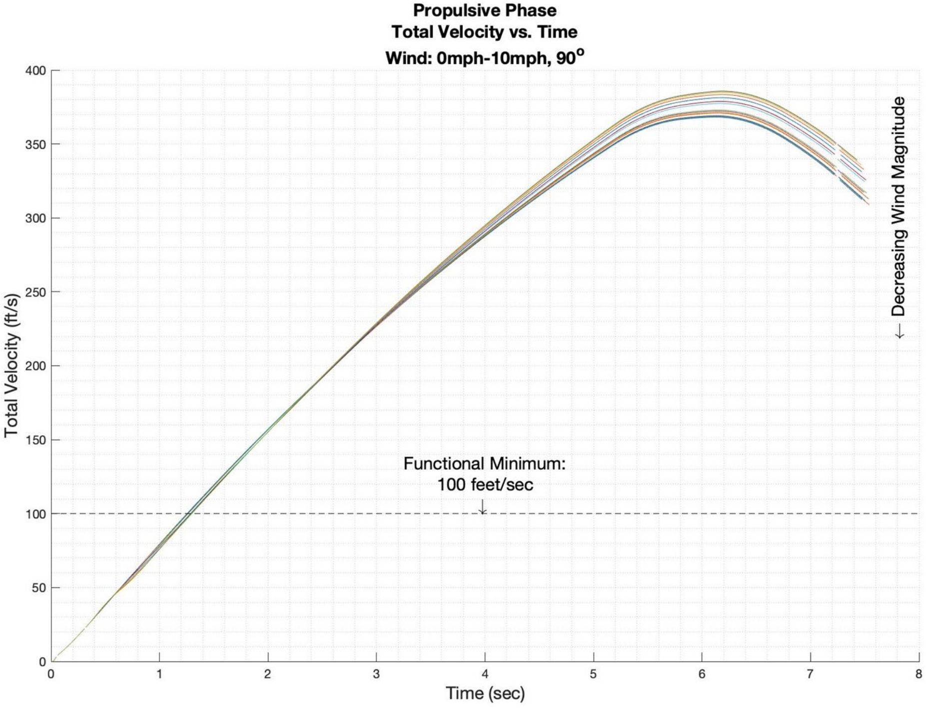
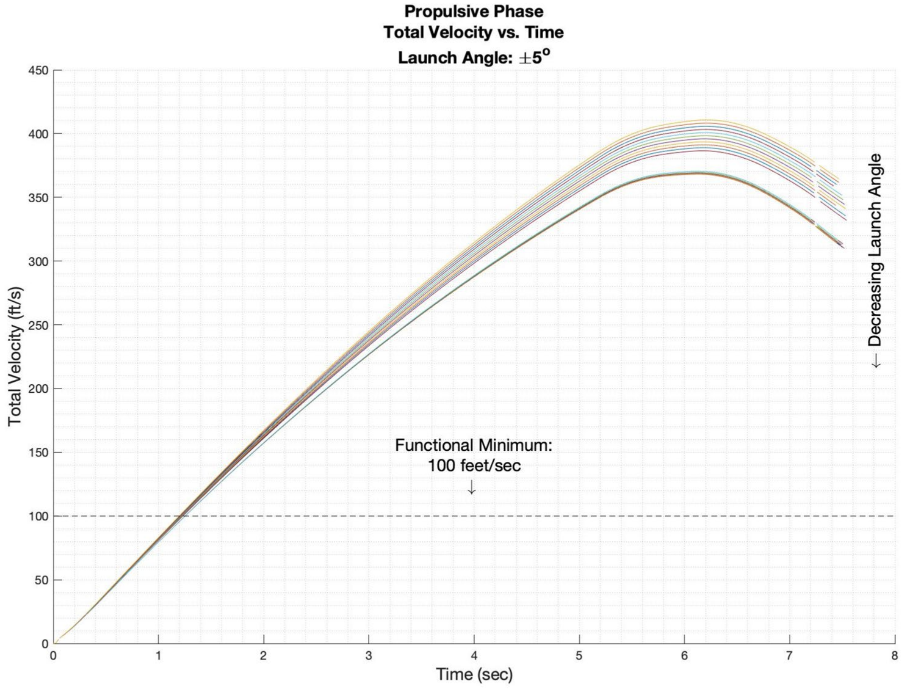
Propulsion: Monte-Carlo





Vehicle Altitude (DR 5.2)	Vehicle Velocity (DR 5.2.2)✓

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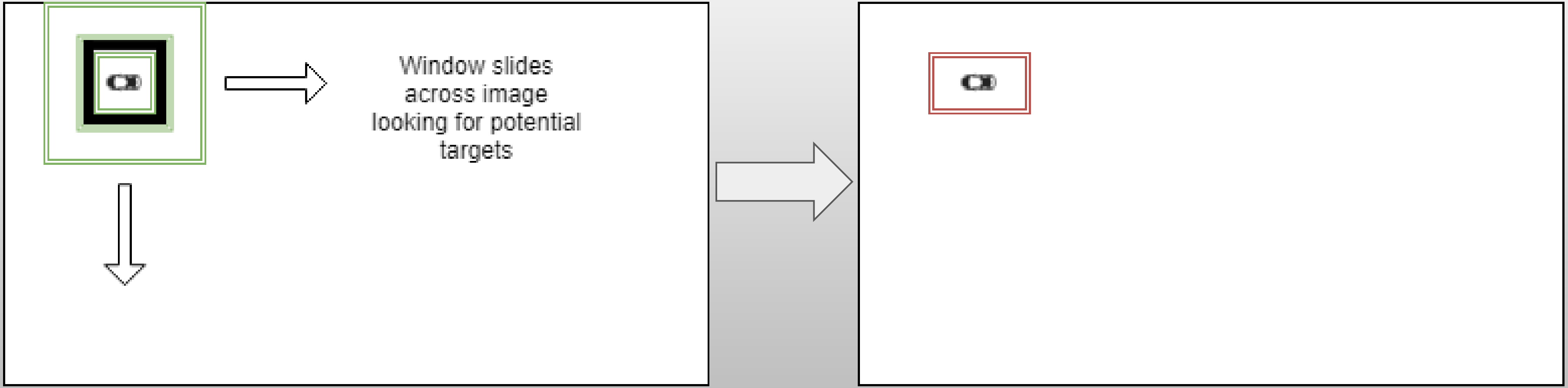
Target Recognition/Geolocation Software

Requirement	Description
FR 4	The system shall identify a distinctly colored target and relay the target's latitude and longitude.
DR 4.1	The ground station shall output a bounding box over potential targets.
DR 4.2	The ground station shall compute local relative coordinates of the target as well as global latitude and longitude of the target within 150 feet of its true location.

Software: Target Detection

Compare statistics between windows using T-test:

Highlight regions of interest for classification and geolocation



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

$\bar{X} = mean, s = \text{variance}$

Detection

Identify Potential Target Pixels

Output Bounding Box over ROI

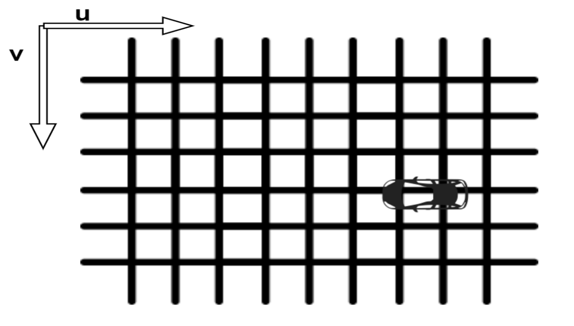
Output Bounding Box (DR 4.1) ✓	Determine Location of ROI (DR 4.2)

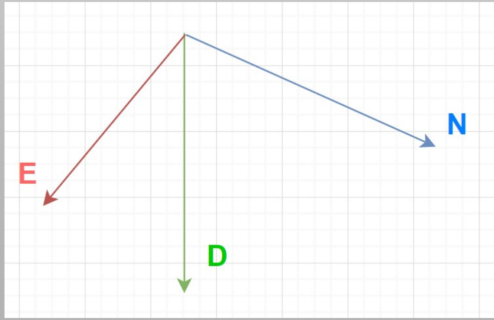
Pixel to World Transformation

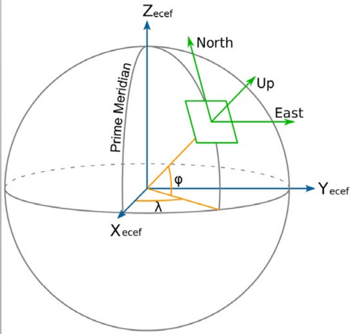
Knowns: Pixels and altitude

Unknown: World Coordinates

$$\begin{bmatrix} u \\ v \\ R\ (\text{range}) \end{bmatrix} \rightarrow \begin{bmatrix} N\ (\text{north}) \\ E\ (\text{east}) \\ D\ (\text{down}) \end{bmatrix}$$







Pixel to World Transformation

Problem to solve:

$$\tilde{P}\widetilde{p_w} = x_s$$

$$x_s = \begin{bmatrix} u \\ v \\ 1 \\ R(range) \end{bmatrix}$$

$$\widetilde{p_w} = \begin{bmatrix} N(north) \\ E(east) \\ D(down) \\ 1 \end{bmatrix}$$

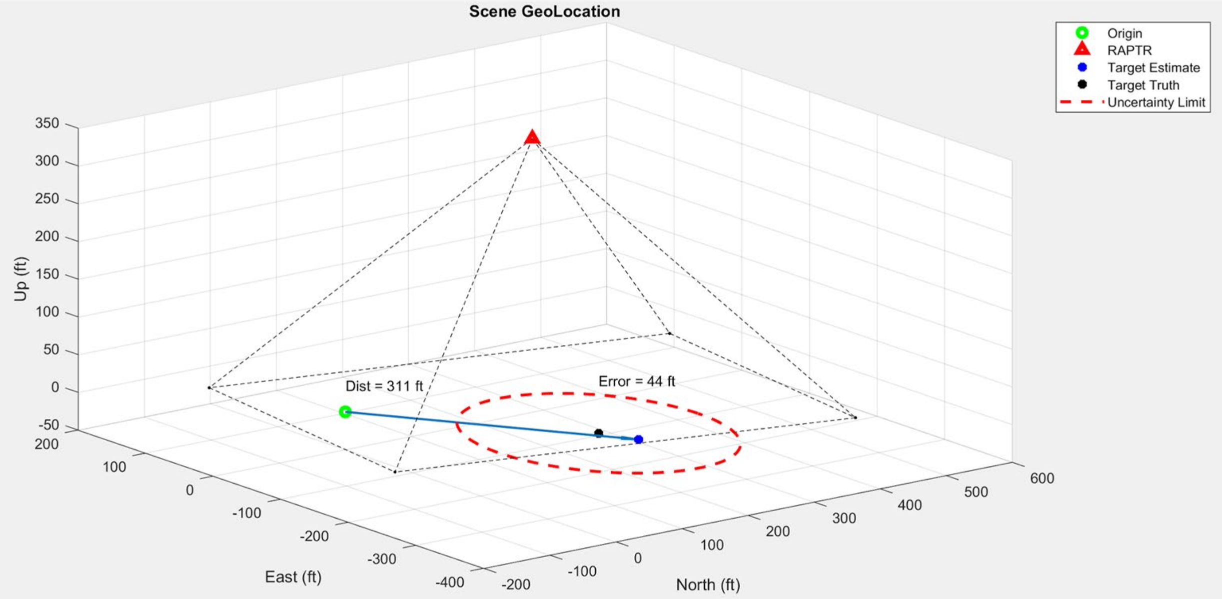
$$P = K(R|t) \quad \tilde{P} = \begin{pmatrix} \mathbf{K} & 0 \\ \mathbf{0}^T & 1 \end{pmatrix} \begin{pmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}^T & 1 \end{pmatrix}$$

$K \equiv Camera\ Matrix$

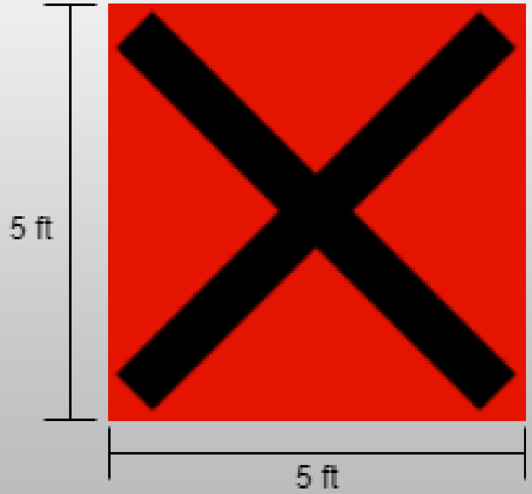
$R \equiv world\ to\ camera\ rotation$

$t \equiv world\ to\ camera$ translation

Geo-Location Preliminary Testing



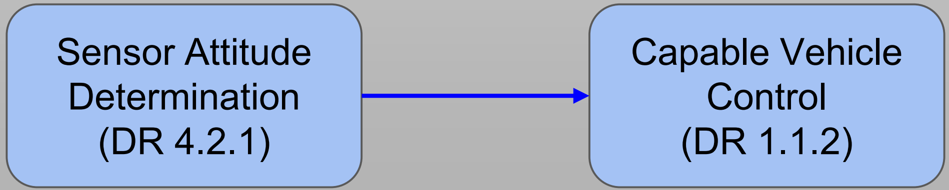
Example Target:



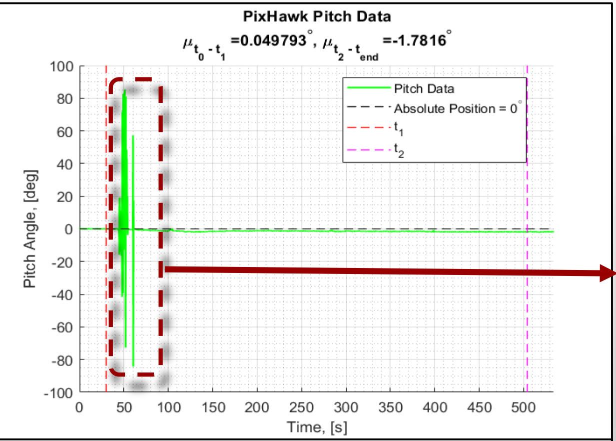
Output Bounding Box (DR 4.1)	Determine Location of ROI (DR 4.2) ✓

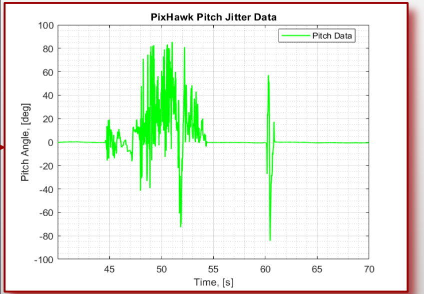
Vehicle Control Requirements

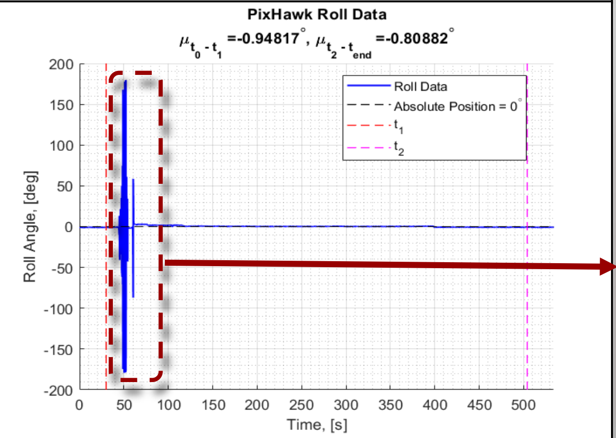
Derived Requirements	Description
FR 1	The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.
FR 4	The system shall identify a distinctly colored target and relay the target's latitude and longitude.
DR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

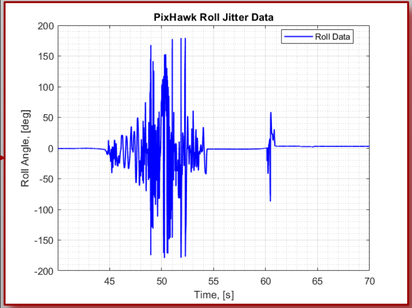


Sensor Attitude Determination









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

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

Vehicle Control

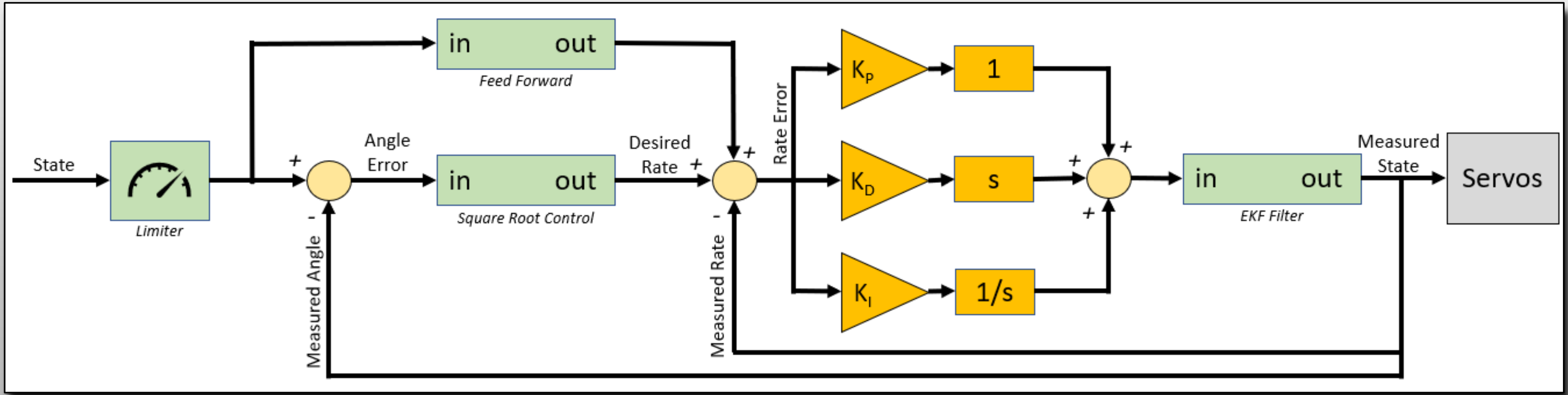
Control Surface	Function
Rudder	Enable both yaw and roll control due to RAPTR's dual dihedral. Enables lateral stability
Elevator	Enables pitch control and longitudinal stability

RAPTR <u>does not</u> have ailerons so servo roll gains are irrelevant.

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

Vehicle Control

Pixhawk Control Architecture



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

Vehicle Control

Fundamental Equations

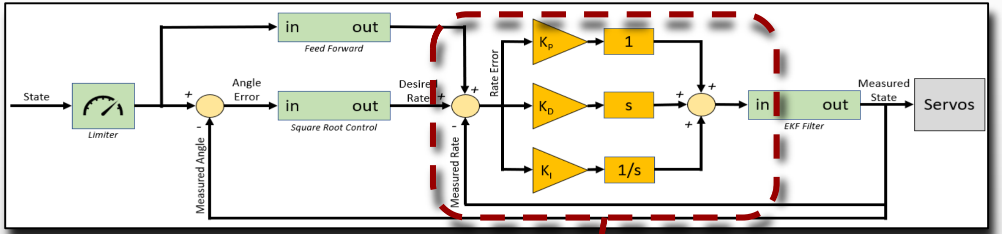
$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad y = C\vec{x} + D\vec{u}$$

$$X(s) = C(sI - A)^{-1}B\vec{u}$$

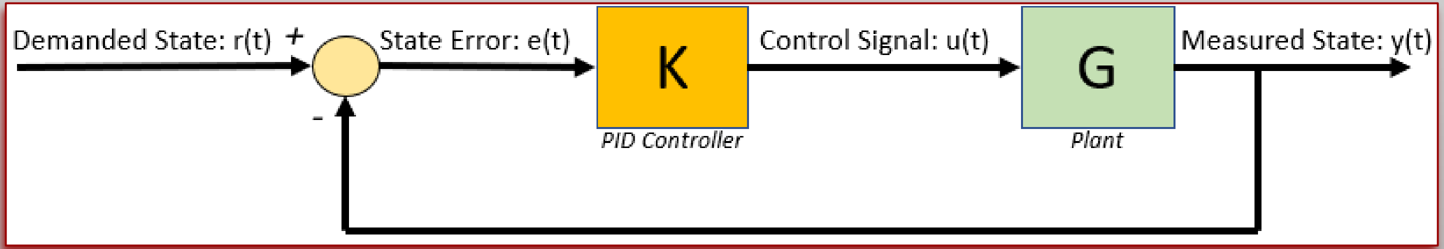
G(s)

$$K(s) = K_P + K_D s + K_I \frac{1}{s}$$

Pixhawk Control Architecture

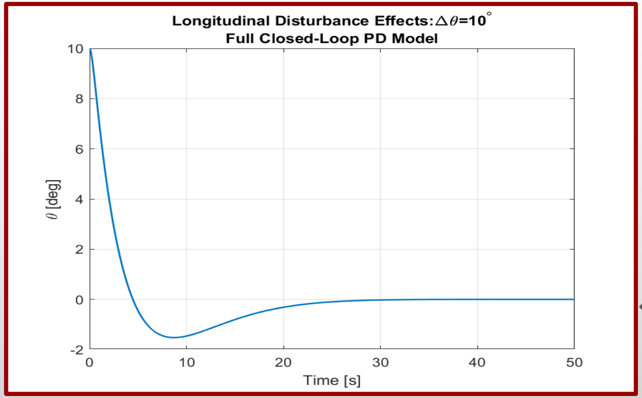


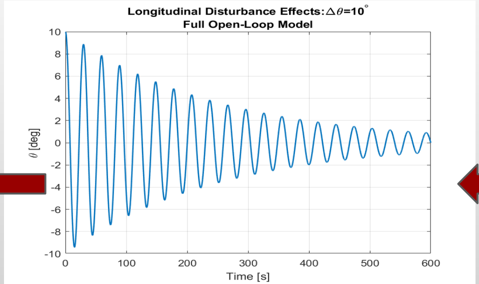
PID Gain Approximation Architecture



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

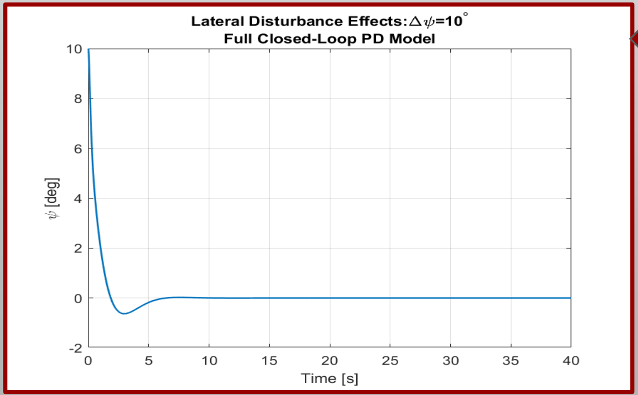
Vehicle Control

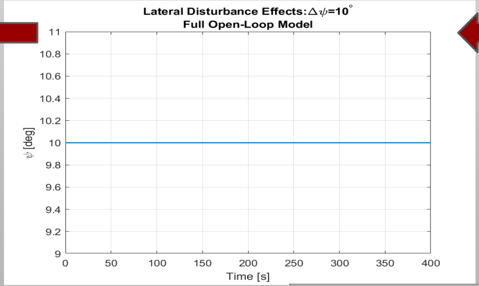




Closed-Loop Dynamics

Open-Loop Dynamics





Dynamic Modes	PID Servo Gains
Pitch	K_P = 0.0154 K_D = 0.0069 K_I = 0, assumption
Yaw	K_P = 0.178 K_D = 0.075 K_I = 0, assumption

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

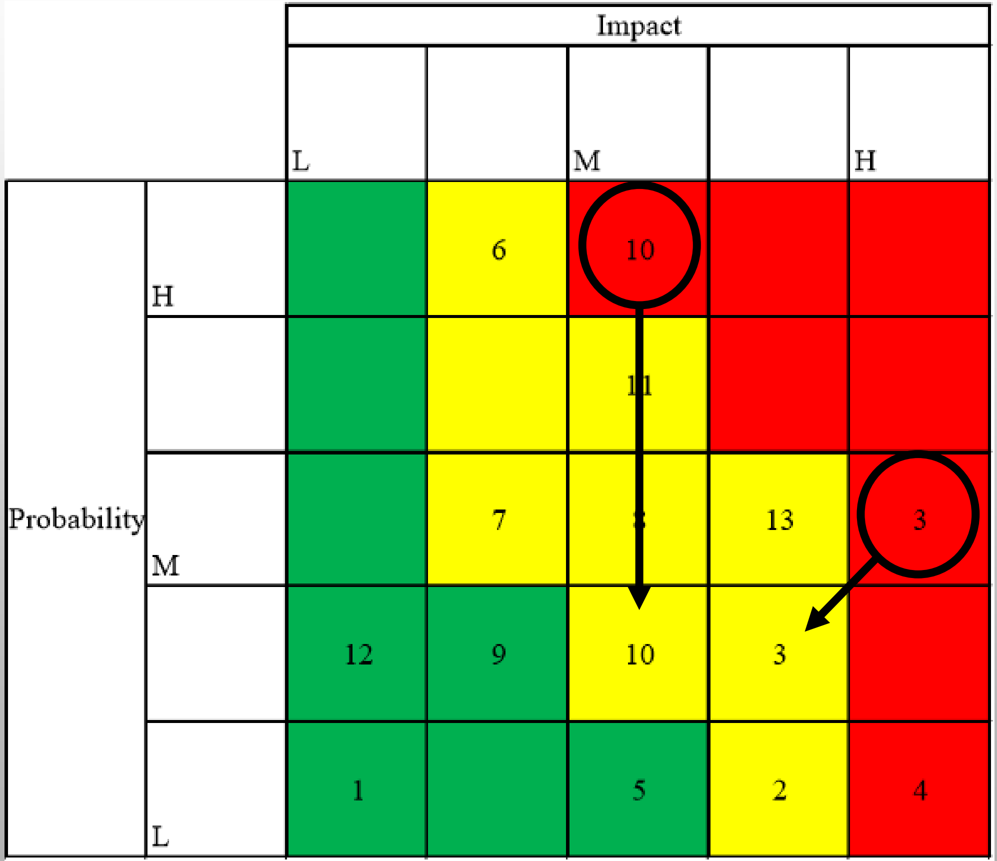
Project Risks

Risk Matrix

		Impact				
		L		M		H
Probability	H		6	10		
				11		
	M		7	8	13	3
		12	9			
	L	1		5	2	4

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

Risk Mitigation



Risk	Mitigation	Off-Ramp
3. Ascent Pitch Control Authority	Short Motor Mount	Utilize Smaller Rocket Motor or Electric Propeller System
10. Rocket Thermal Effects	Coat Vehicle Belly with Thermal Tape	Electric Propeller System

Verification and Validation

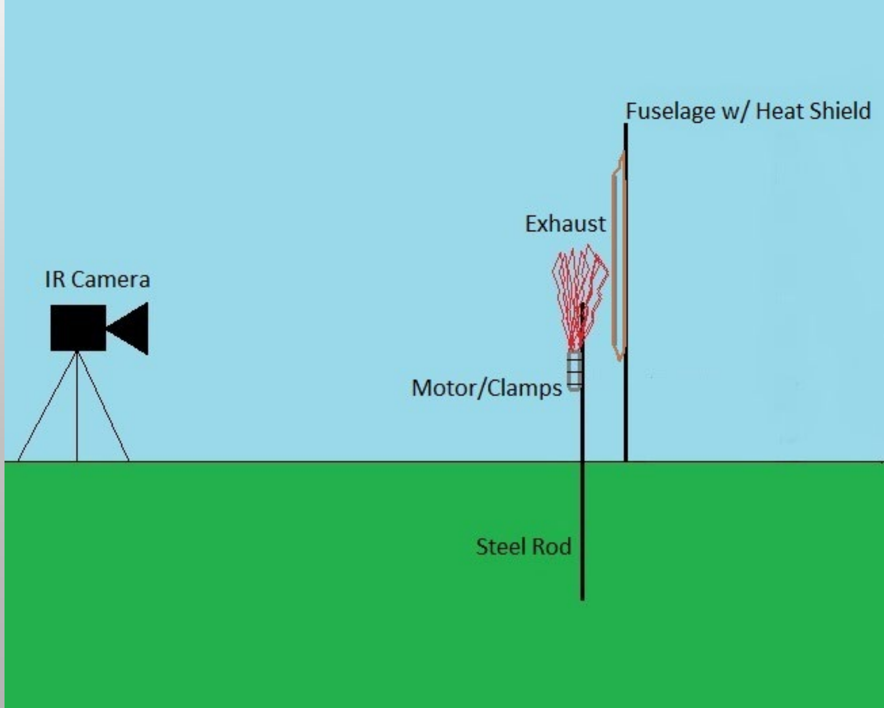
Test Overview

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

Thermal Testing

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

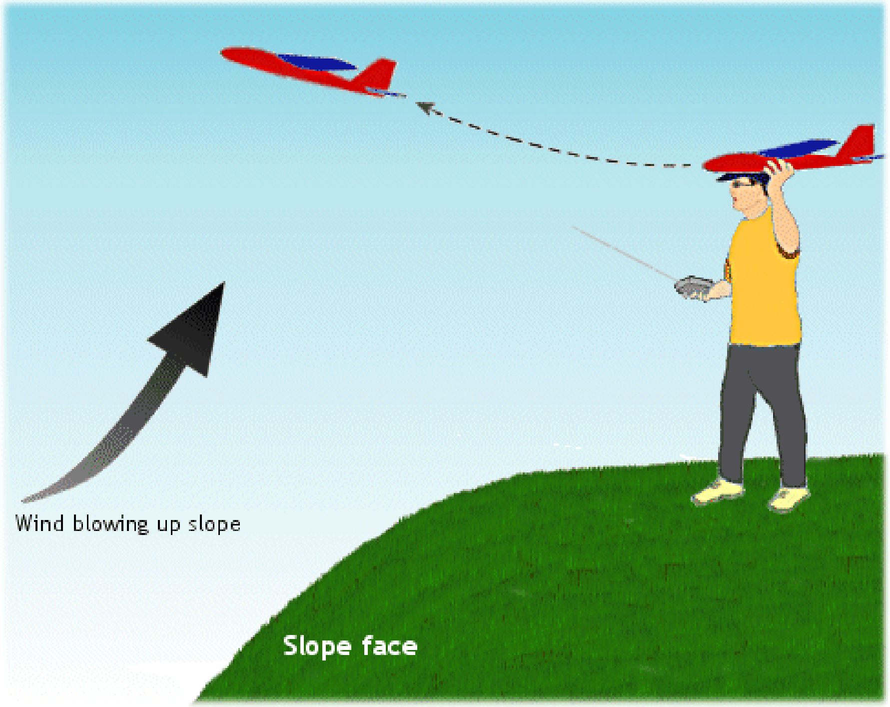
Purpose	Verify no damage to vehicle during engine burn
Methods	Static burn of motor positioned near fuselage
Location	Boulder East Campus
Key Equipment	Aluminum tape, Lava Heat Shield, I55 Motor, IR camera
Measurements	Temperature of exhaust, Dimensions of exhaust



Controls/Pixhawk

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

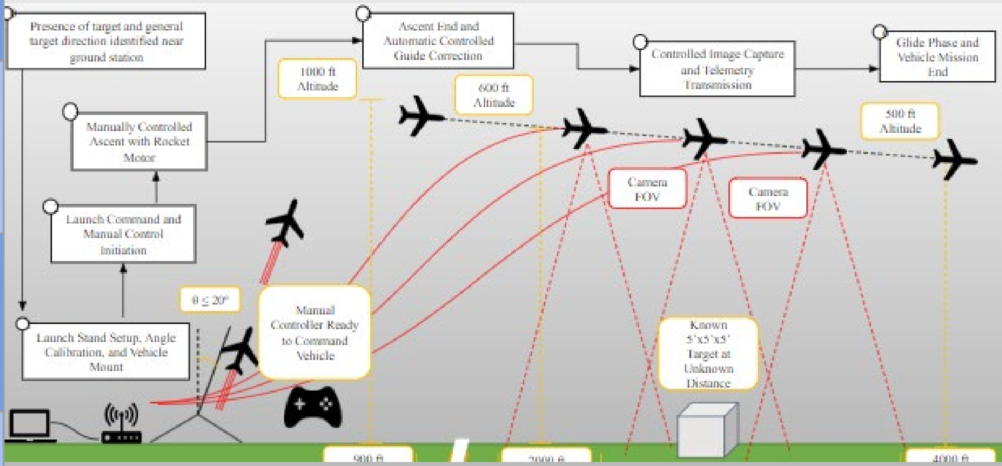
FR 1	The system shall survey a 2,000 foot long and at least 400 foot wide corridor beginning 2,000 feet from the user and aligned with a user defined heading.



Full systems testing

Setup → Launch → Glide → Image → Land

Purpose	Validate success criteria of project are met
Methods	Full systems launch through NCR with and without payload
Location	Atlas Site, North Site (West of Pawnee Grasslands)
Key Equipment	Fully built AndREaS vehicle, launch rails, test target
Measurements	Vehicle position, velocity, attitude, time for setup/detection, images of target



Project Planning

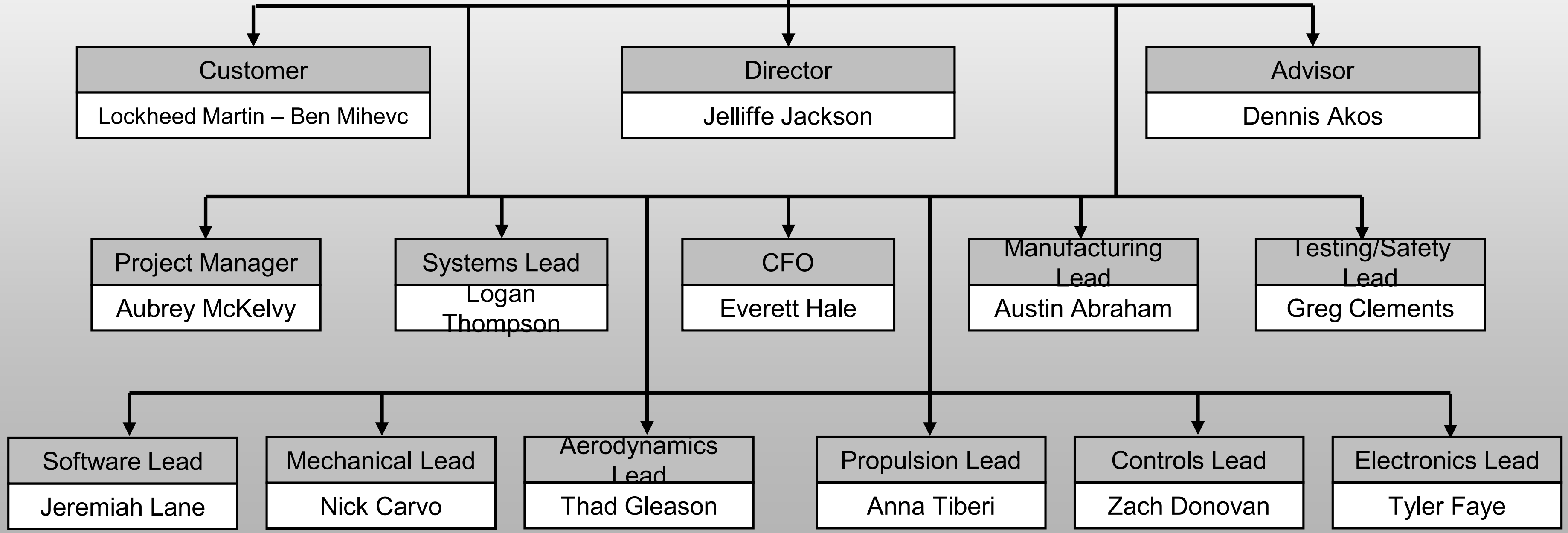
Test Plan

Thermal Testing: Access to IR camera and static launch site

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

Test Imaging (Software)	11/19/18 (Additional Tests TBD)	Capture images for software testing	Boulder North Park
Structural Test	12/01/18	Verify structural integrity	ITLL
Thermal Test	01/14/19 - 02/01/19 (Exact Date TBD)	Verify thermal protection	East Campus
Wind Tunnel Testing	01/28/19 - 02/01/19 (Exact Date TBD)	Verify CFD Analysis	ITLL
Communications Integration Test	02/04/19 - 02/08/19 (Exact Date TBD)	Verify comm. systems	ITLL
Controls Testing/Tuning	02/04/19 - 02/15/19 (Exact Date TBD)	Tune PixHawk and verify controllability	South NCAR
Vehicle Systems Testing	03/02/19 03/09/19 03/30/19	Test launch vehicle without payload	Northern Colorado
Full Systems Testing	04/06/19 04/13/19 05/03/19	Test launch vehicle with payload	Northern Colorado

Organizational Chart

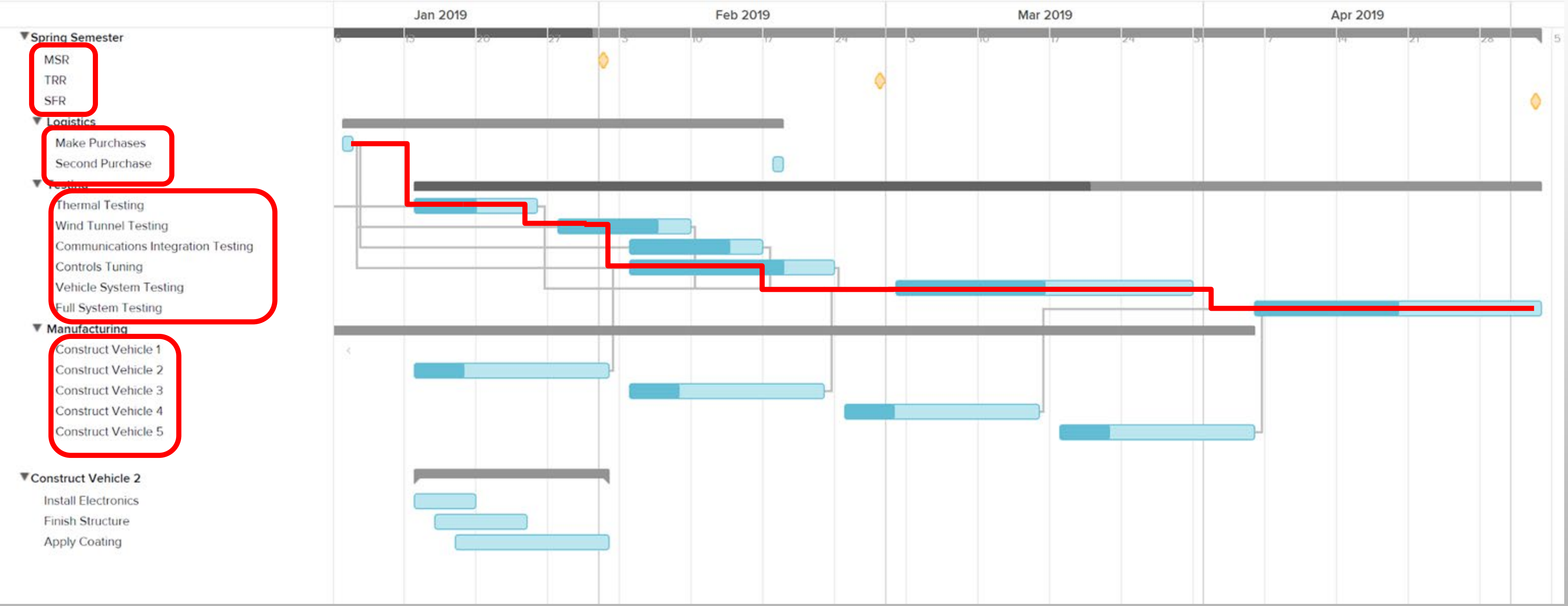


Work Breakdown

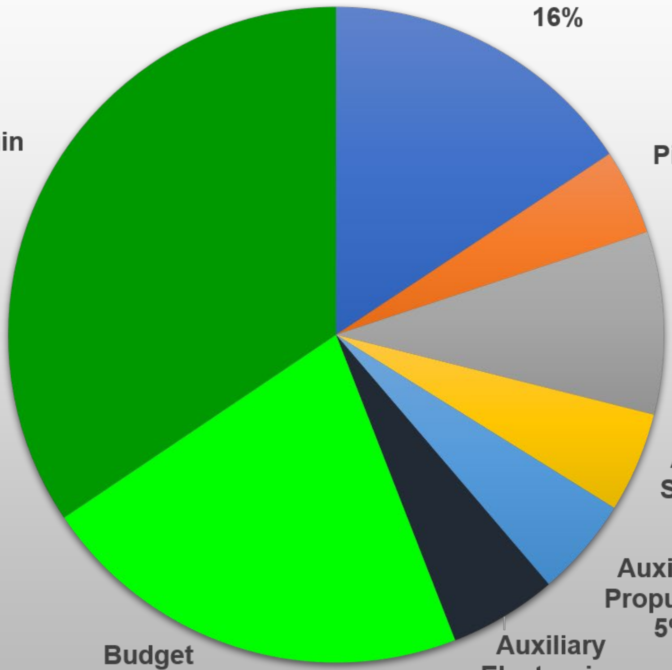
Legend
(green) = Complete
(red) = Planned

Hardware	Software	Electronics & Controls	Propulsion	Aerodynamics	Fall Deliverables	Spring Deliverables
Vehicle CAD Model	Geolocation Algorithm	Wiring Diagram	Launch Dates and Sites	CFD Modeling	PDD	MSR
Structural Analysis	ROI ID Algorithm	Approximate Gains	Motor Selection	Stability Derivatives	CDD	TRR
Vehicle Assembly	Uncertainty Propagation	Controller Simulation	Propulsive Simulation	Stability Verification	PDR	SFR
Structural Testing	Preliminary Test Validation	Finalize Gains	Motor Acquisition	Control Derivatives	CDR	
Finalize Vehicle	Optimization	Validate Controls	Thermal Testing	Wind Tunnel Testing	FFR	
Integration and Test	Integration and Test	Integration and Test	Integration and Test	Integration and Test		

Gantt Chart


Jan 2019
Feb 2019
Mar 2019
Apr 2019
Spring Semester
MSR
TRR
SFR
Logistics
Make Purchases
Second Purchase
Thermal Testing
Wind Tunnel Testing
Communications Integration Testing
Controls Tuning
Vehicle System Testing
Full System Testing
Manufacturing
Construct Vehicle 1
Construct Vehicle 2
Construct Vehicle 3
Construct Vehicle 4
Construct Vehicle 5
Construct Vehicle 2
Install Electronics
Finish Structure
Apply Coating

Cost Plan



Expenditure	Cost
Vehicles	$785
Pixhawk 4	$211
I-55 Engines	$450
Auxiliary Structures	$247
Auxiliary Propulsion	$245
Auxiliary Electronics	$266
Expected Cost	**$2204**
Budget Uncertainties	$1075
Maximum Cost	**$3279**
Budget Margin	**$1721**

Acknowledgements

- Ben Mihevc
- Theresa Brown
- Tim Moon
- Eileen Liu
- Dr. Akos
- Professor Gerren
- Professor Holzinger
- Professor Rhode
- Professor Lopez
- Christine Reilly & Ian Cooke
- Professor Nabity
- Professor Ahmed
- Professor Lawrence
- Arielle Blum
- CU Boulder Quadcopter Club
- IRIS
- James Mack
- Dan Hesselius
- Joe Hinton

Questions?

References

- Department of Aerospace Engineering. (2018, Fall). ASEN 2003 Lab 3 assignment document. University of Colorado, Boulder
- http://openrocket.sourceforge.net/thesis.pdf
- https://www.activaripg.com/torsion-springs.html
- http://www.pdas.com/datcom.html
- Markforged Material Properties Data Sheet
- https://aip.scitation.org/doi/pdf/10.1063/1.4918424
- http://www.farnell.com/datasheets/2310520.pdf
- Collins, Robert. CSE 486, Penn State. “Lecture 12: Camera Projection”. http://www.cse.psu.edu/~rtc12/CSE486/lecture12.pdf
- https://en.wikipedia.org/wiki/File:ECEF_ENU_Longitude_Latitude_relationships.svg
- Schachter, Bruce J. “Automatic Target Recognition”. Second Edition. https://app.knovel.com/web/view/khtml/show.v/rcid:kpATRE0005/cid:kt011ER1F1/viewerType:khtml//root_slug:2-target-detection-strategies/url_slug:target-detection-strategies?b-toc-cid=kpATRE0005&b-toc-root-slug=&b-toc-url-slug=target-detection-strategies&b-toc-title=Automatic%20Target%20Recognition%20(2nd%20Edition)&page=1&view=collapsed&zoom=1
- Szeliski, Richard. Computer Vision: Algorithms and Applications. http://szeliski.org/Book/drafts/SzeliskiBook_20100903_draft.pdf
- https://www.rocketarium.com/Build/Ejection-Baffles
- http://www.aerospaceweb.org/question/propulsion/q0220.shtml
- http://knight-mfg.com/folding_launch_pads

References

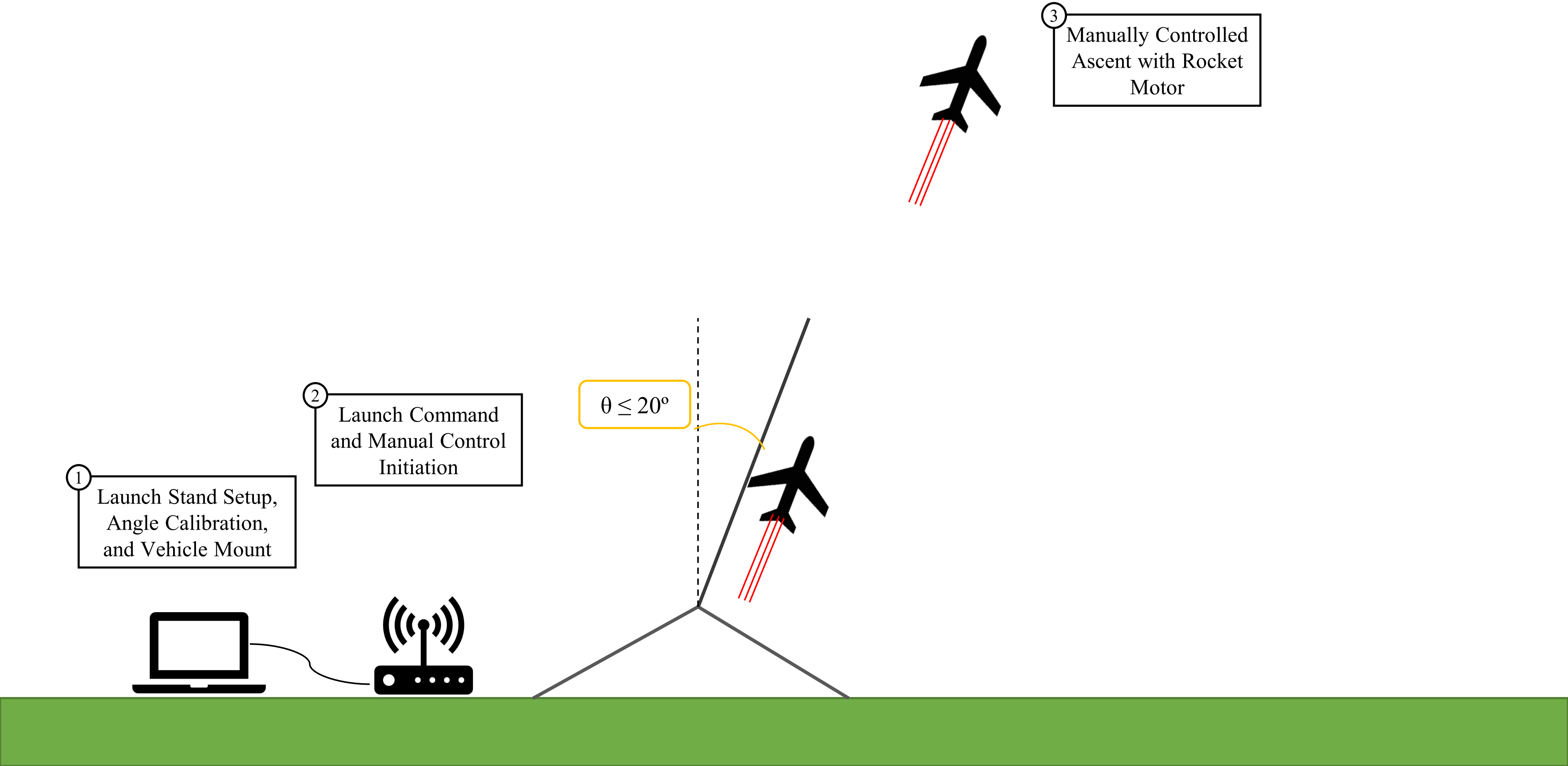
- CU Boulder Quadcopter Club
- https://ieeexplore-ieee-org.colorado.idm.oclc.org/document/7774772
- http://ardupilot.org/dev/docs/extended-kalman-filter.html
- https://journals.sagepub.com/doi/pdf/10.5772/52500
- https://cdn.automationdirect.com/static/manuals/d4user/ch8.pdf
- https://www.eucass.eu/doi/EUCASS2017-411.pdf
- https://core.ac.uk/download/pdf/52106533.pdf
- https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7110817
- http://www.chrobotics.com/library/attitude-estimation
- http://www.naturalspublishing.com/files/published/n2q04bk1j849k8.pdf
- Attitude Estimation of Quadcopter through EXK by Wenjing Liang
- Design of Robust Controller of Fixed-Wing UAV for Transition Flight by Satoshi Kohno and Kenji Uchiyama
- Attitude Estimation for UAV Using Extended Kalman Filter by ofei Jing1, Jiarui Cui1, Hongtai He2, Bo Zhang3, Dawei Ding1, Yue Yang1
- Experimental validation of Unmanned Aerial Vehicles to tune PID controllers in open source autopilots by Pedro L. Jimenez*, Jorge A. Silva** and Juan S. Hernandez***
- Modeling of Closed Loop PID Controller for an Auto-Pilot Aircraft Roll Control by E.Gouthami and M. Asha Rani
- Quadrotor Tuning for Attitude Control based on PID Controller using Fictitious Reference Iterative Tuning (FRIT) by Arthit Julkananusart∗, Itthisek Nilkhamhang∗, Rangsarit Vanijjirattikhan† and Atsushi Takahashi‡
- PIXHAWK: A System for Autonomous Flight using Onboard Computer Visionby Lorenz Meier, Petri Tanskanen, Friedrich Fraundorfer and Marc Pollefeys
- Dynamics of Flight Stability and Control by Bernard Etkin and Lloyd Duff Reid
- Feedback COntrol of Dynamic Systems by Gene Franklin

Backup Slides

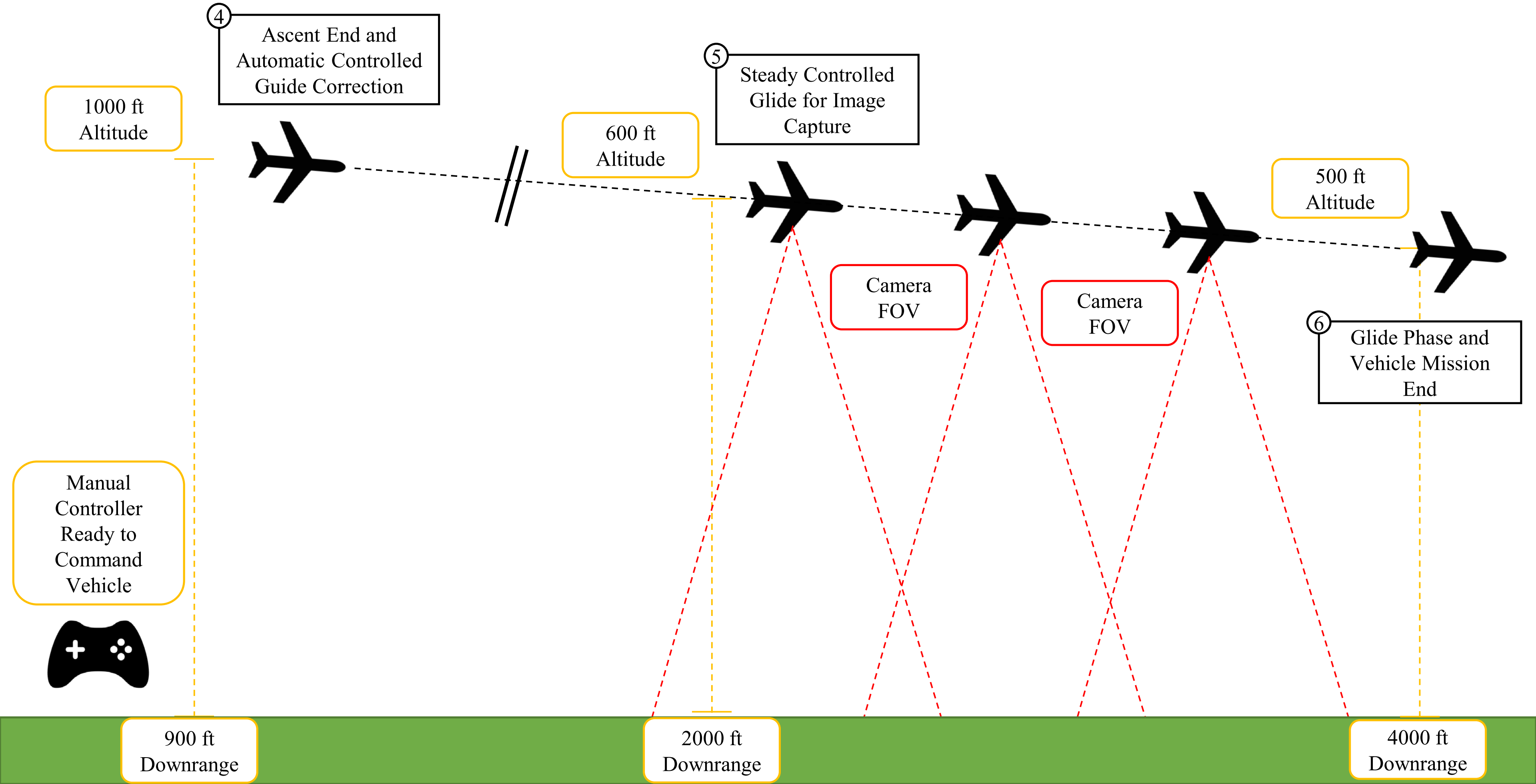
Backup Slides

Backup Slides Index
Project Planning
Aerodynamics
Electronics
Controls
Propulsion
Software
Structures
Testing

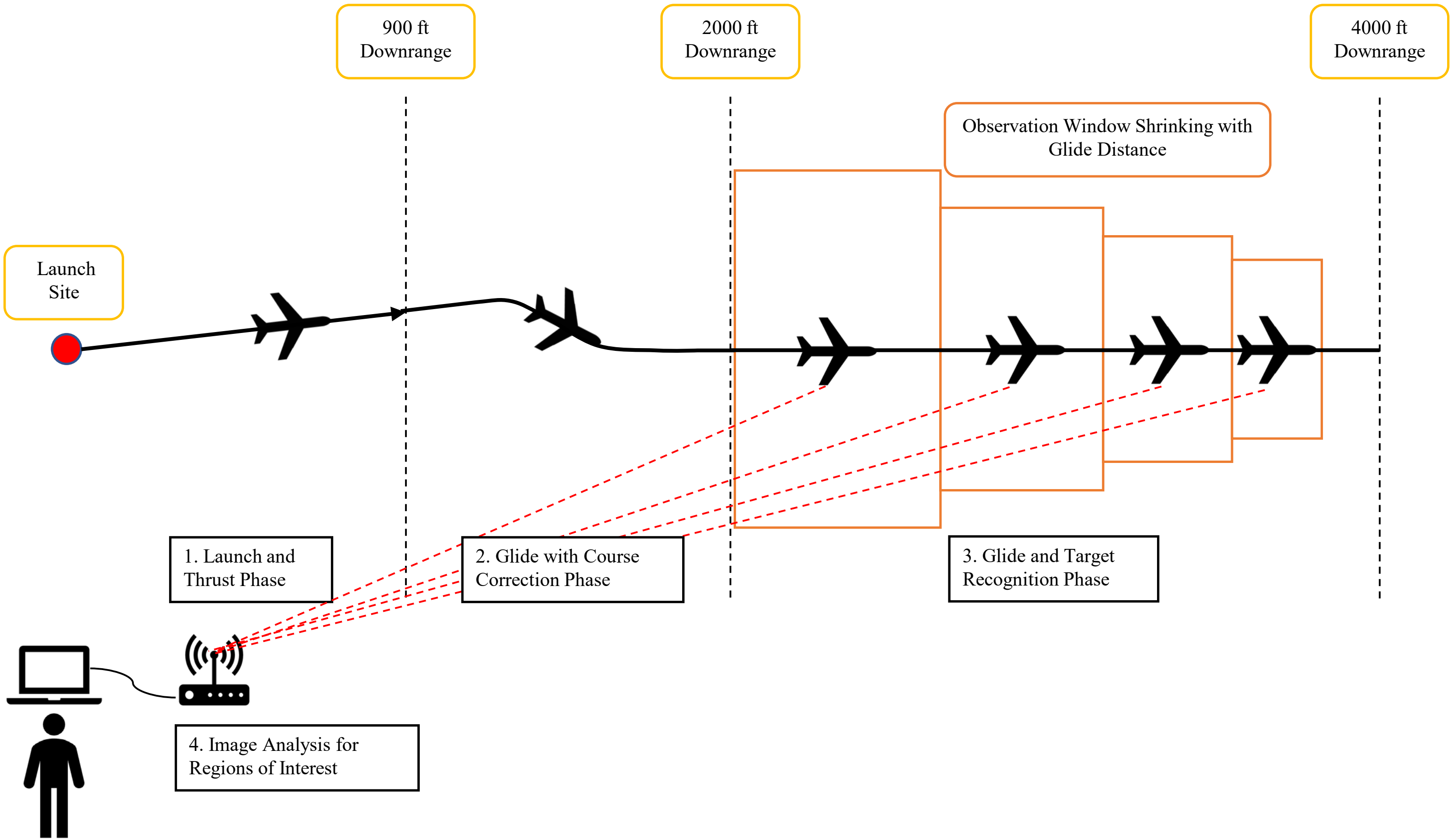
RAPTR CONOPs – Launch Phase



RAPTR CONOPs – Glide Phase



RAPTR CONOPs – Mission Profile Top View



Detailed Cost Breakdown - Subteams

Subteam	Minimum Budget	Budget Uncertainty	Maximum Budget
Electronics and Controls	$477	$405	$882
Structures	$1032	$340	$1372
Propulsion	$695	$330	$1025
Totals	$2204	$1075	$3279

Detailed Cost Breakdown - Electronics

Item	Cost
Pixhawk 4 and GPS Module	$211
Digital Airspeed Sensor	$64.59
FrSky X8R Receiver	$34.99
Radio Telemetry Set	$45.00
Sevos (x2)	$71.98
950mAh Battery	$12.24
Voltage Regulator (x6)	$3.24
Diode (x6)	$9.42
Printed Circuit Board (x10)	$15.00

Detailed Cost Breakdown - Structures

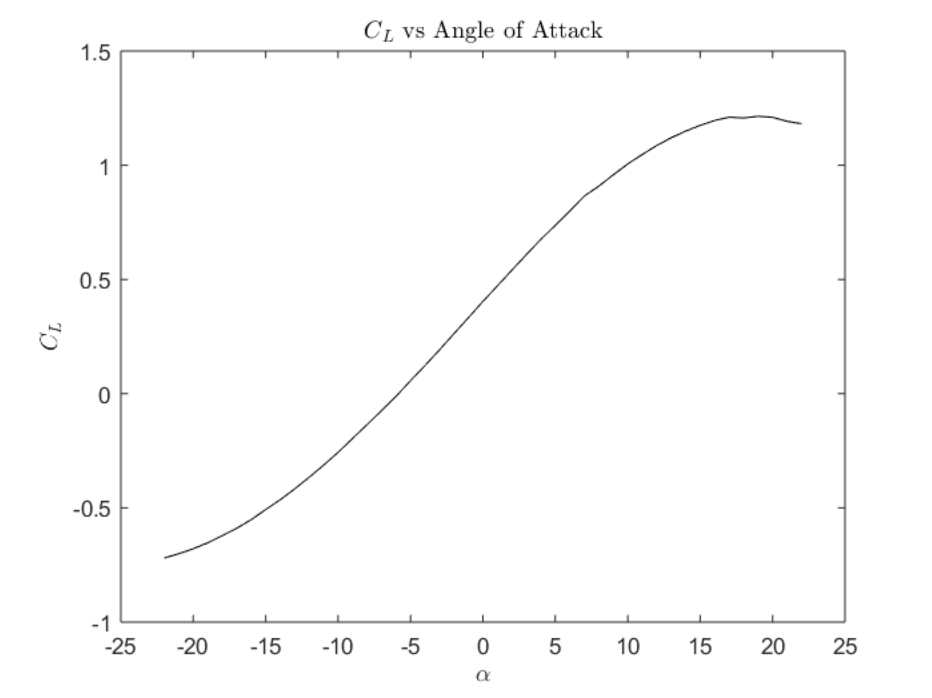
Item	Cost
AndREaS Glider (x4)	$560.32
Oracover Monokote (x4)	$77.92
Carbon Rod (x4)	$21.92
Bearing Carriage	$6.26
Guide Rails	$15.00
Manufacturing Supplies	$36.86
Pre-CDR Purchases	$314.05

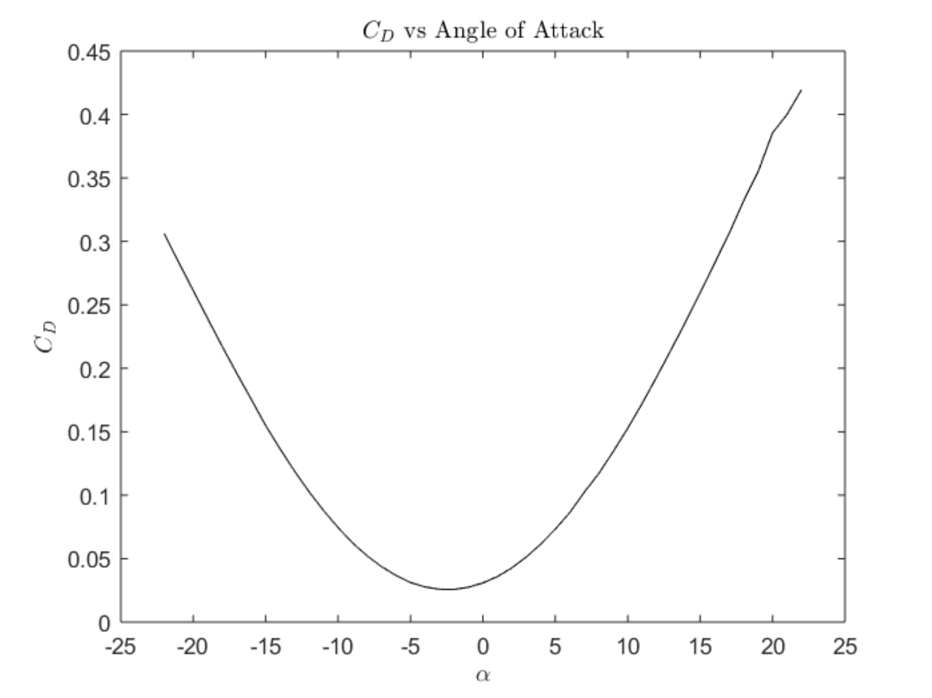
Detailed Breakdown - Propulsion

Item	Cost
Nose Cone (x3)	$24.94
Parachute (x3)	$3.63
I-55 Engine (x10)	$450.00
Grain Casing (x3)	$39.75
Launch Controller	$39.99

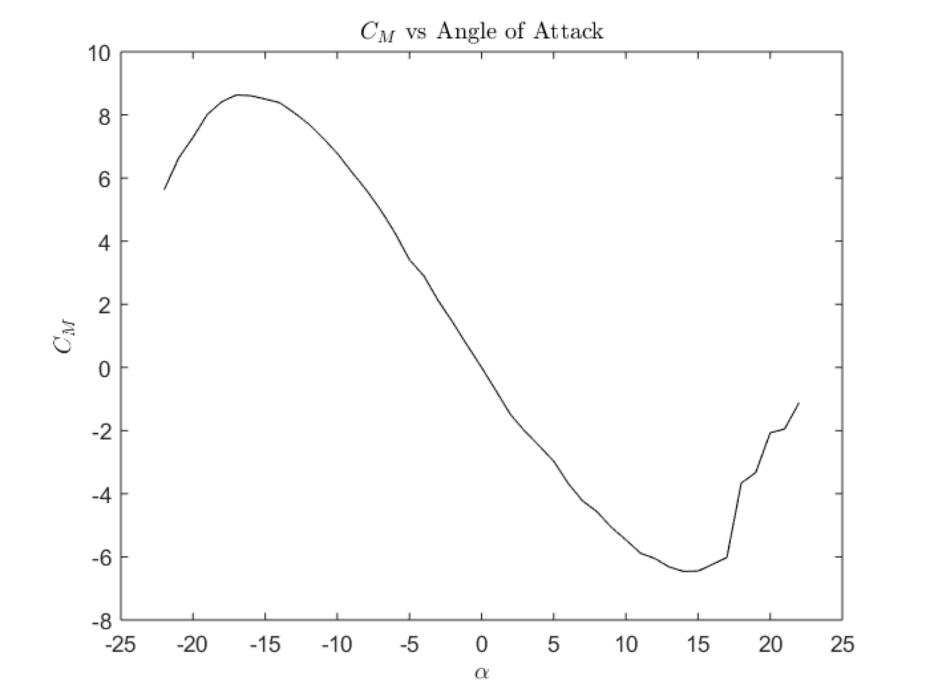
Aero Backup Slides

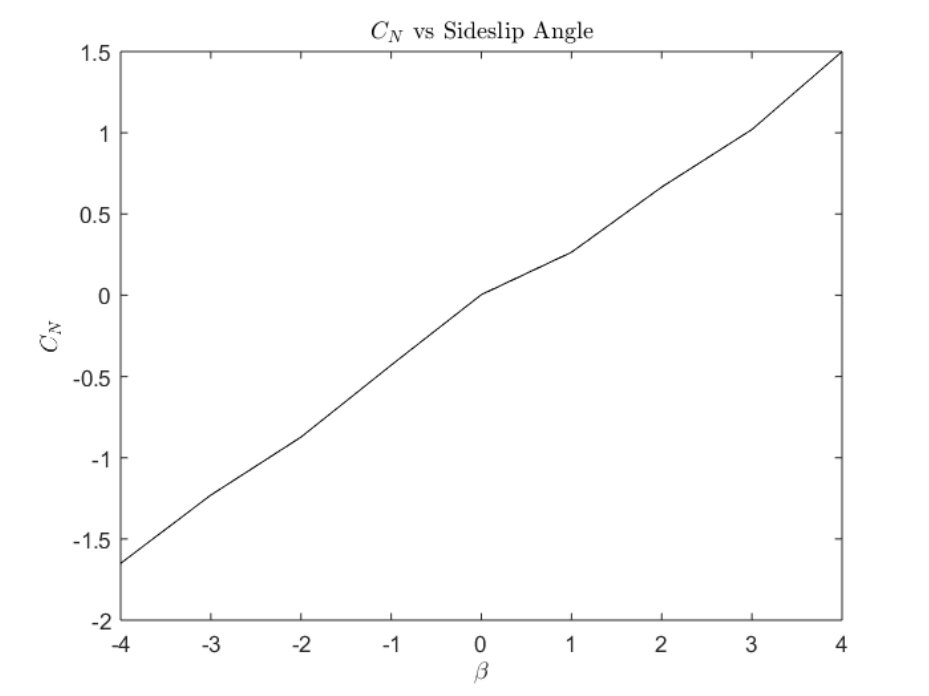
Lift and Drag - CFD





Pitching and yawing moment - CFD





Digital Datcom Input

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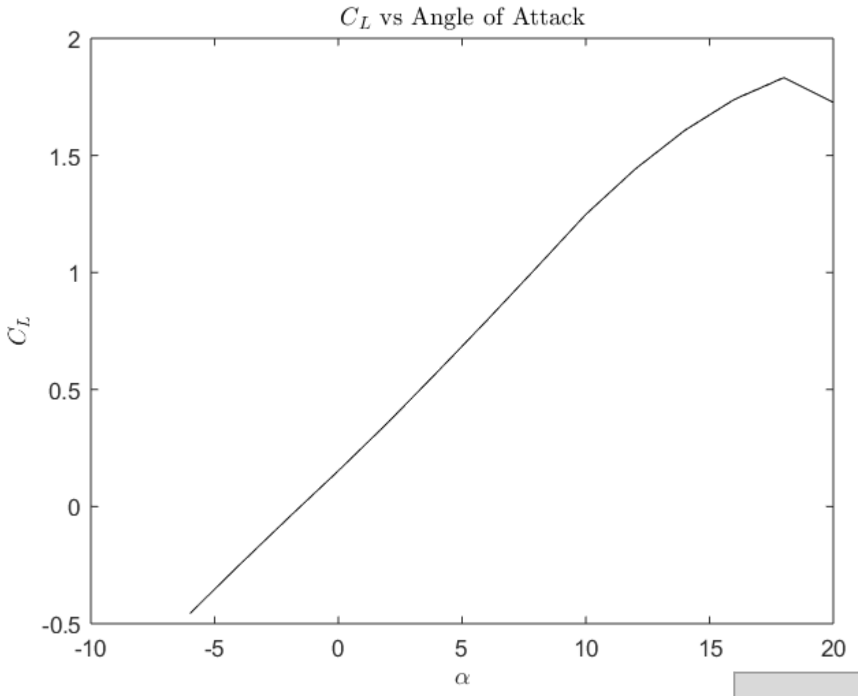
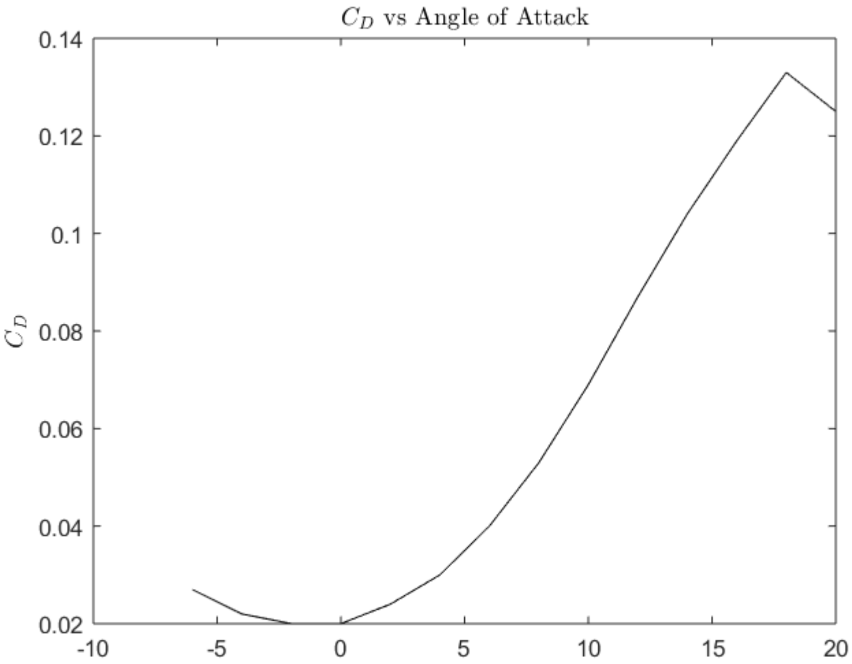
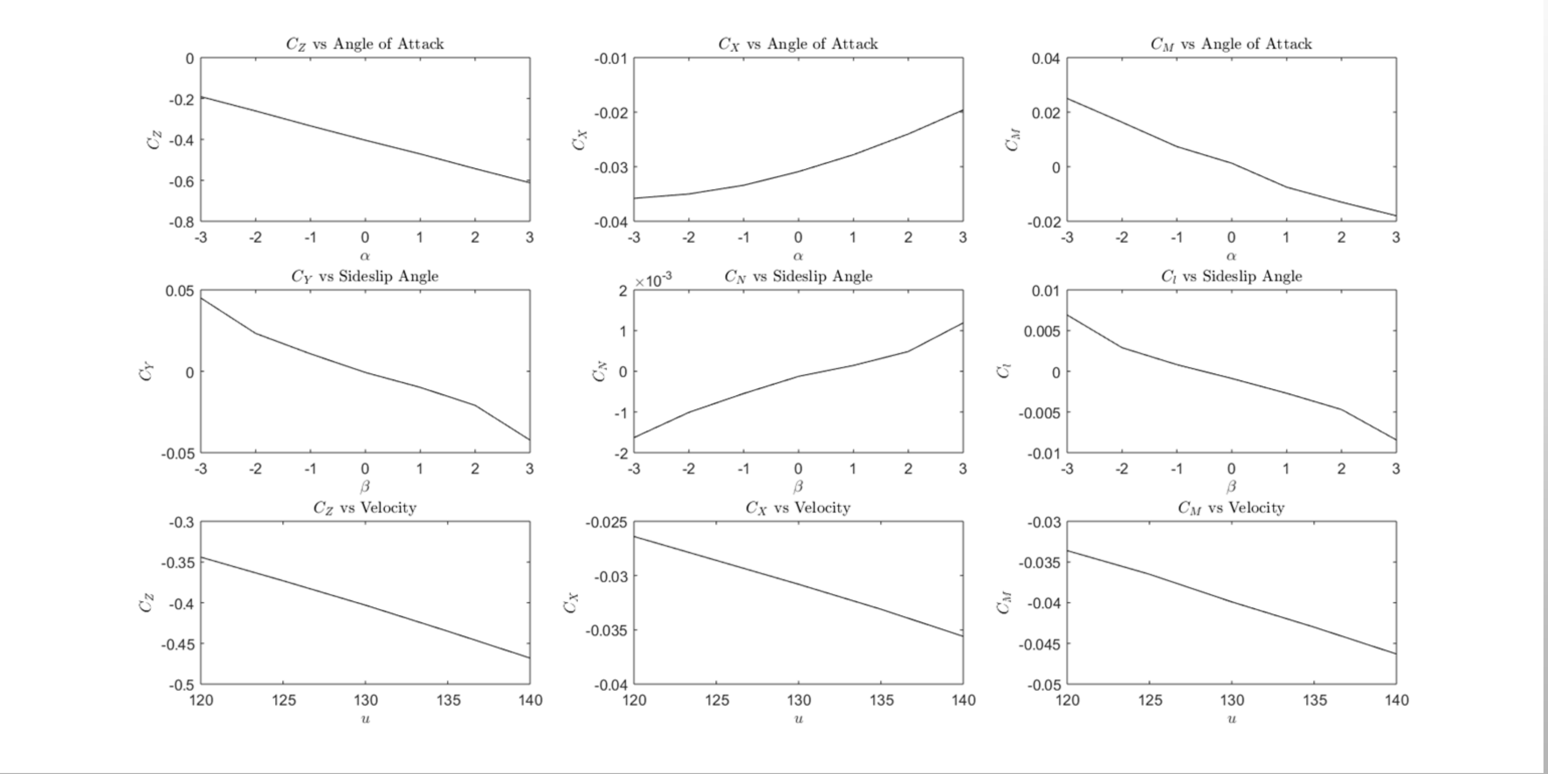
Lift and Drag - Datcom





Stability Plots



Control Derivatives

Results from CFD analysis

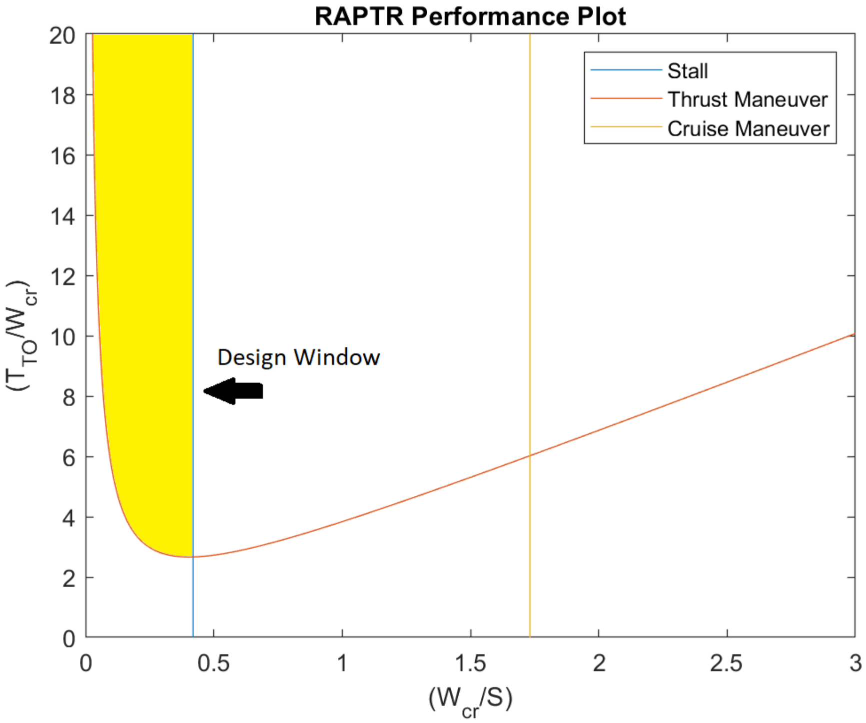
	C_x	C_z	C_m
u	$-4.58 \cdot 10^{-4}$	-0.0062	$-6.38 \cdot 10^{-4}$
α	0.1559	-4.0189	-0.4143
$\dot{\alpha}$	0	-1.4944	-5.1164
q	0	-4.9263	-16.866

	C_y	C_l	C_n
β	-0.7589	-0.1326	0.0248
p	-0.0124	-	0.0045
r	1.9344	0.0045	-0.0178

Results from Datcom analysis

	C_x	C_z	C_m
u	$-4.58 \cdot 10^{-4}$	-0.0062	$-6.38 \cdot 10^{-4}$
α	0.1559	-5.8041	-1.6604
$\dot{\alpha}$	0	-2.3715	-8.0042
q	0	-8.6001	-24.3335

	C_y	C_l	C_n
β	-0.1112	-0.0019	0.0347
p	-0.0139	-0.5091	-0.018
r	1.9344	0.0386	-0.0296



Stall: $$\frac{W_{cr}}{S} = \frac{1}{2}\rho V_s^2 C_{L_{max}}$$

Thrust Man.: $$\frac{T}{W_{cr}} = \frac{qC_{D_o}}{\frac{W_{cr}}{S}} + \frac{n^2}{q\pi ARe}\frac{W_{cr}}{S}$$

Cruise Man.: $$\frac{W_{cr}}{S} = V\left(\frac{2n}{\rho C_L}\right)^{-\frac{1}{2}}$$

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

$$n_{thrust} = \frac{V_{max}^2}{h_{end}}$$

Electronics Backup Slides

Electronics Slides Appendix

1. Electronics Hardware
2. Servo Design Envelope

Sensor Attitude Determination *(Electronics Assembly Procedure)*

PCB

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

Pixhawk and Sensors

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

Servos

- Plug into appropriate servo rail pins (3-pin PWM JST SM connectors)
  - Rudder connects to pin 4
  - Elevator connects to pin 2

Sensor Attitude Determination *(Power Consumption and Physical Specifications)*

Battery (Turnigy Graphene Panther 950mAh)

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

Servos (Futaba S3152, 2 used)

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

Pixhawk

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

Airspeed/Temperature Sensor

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

GPS/Compass Module

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

FrSky X8R

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

HK Pilot Transceiver

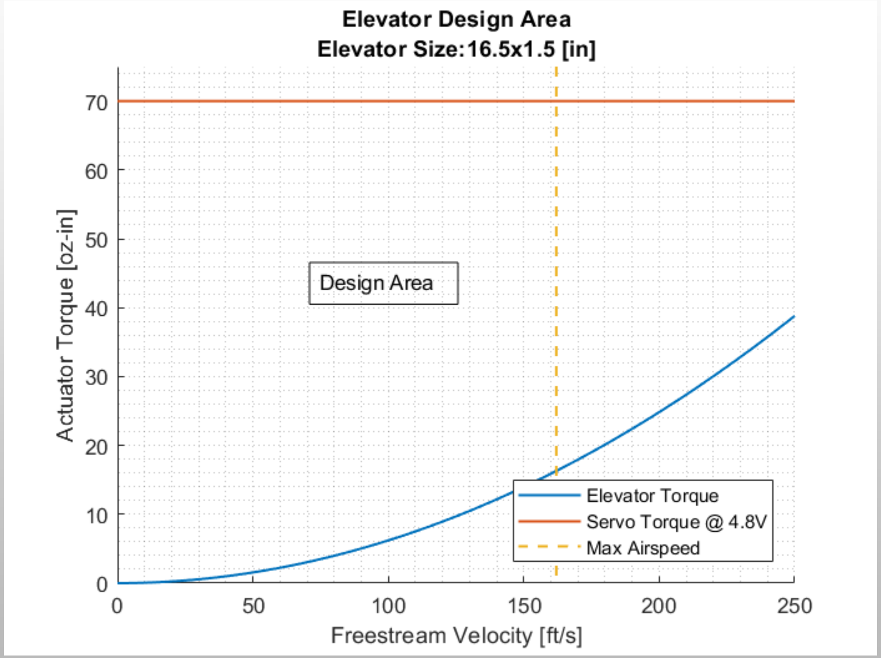
- Operating current draw of 25mA and 100mA at 5V (receiving and transmitting)
- Weight of approximately 20g with antenna

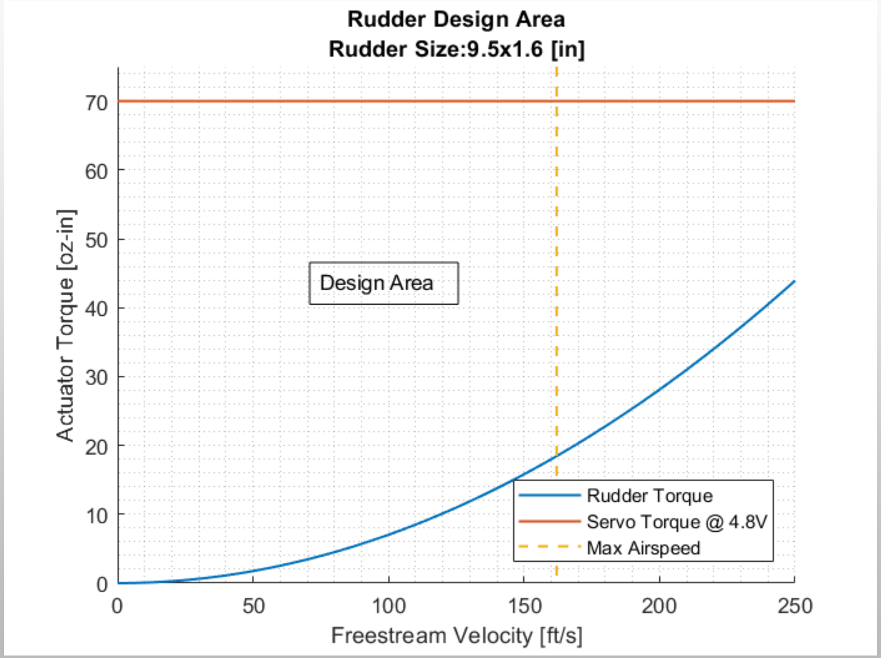
Totals

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

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

Servo Design Envelope





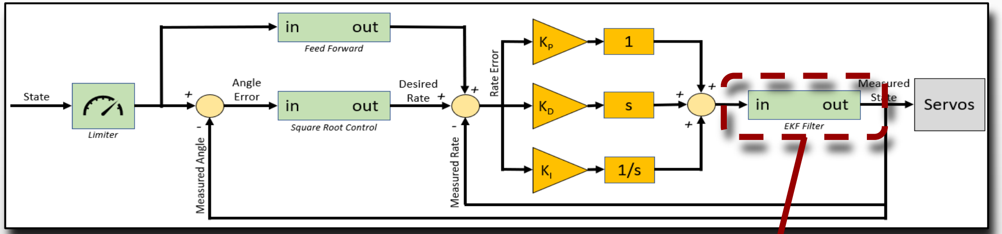
Controls Backup Slides

Controls Slides Appendix

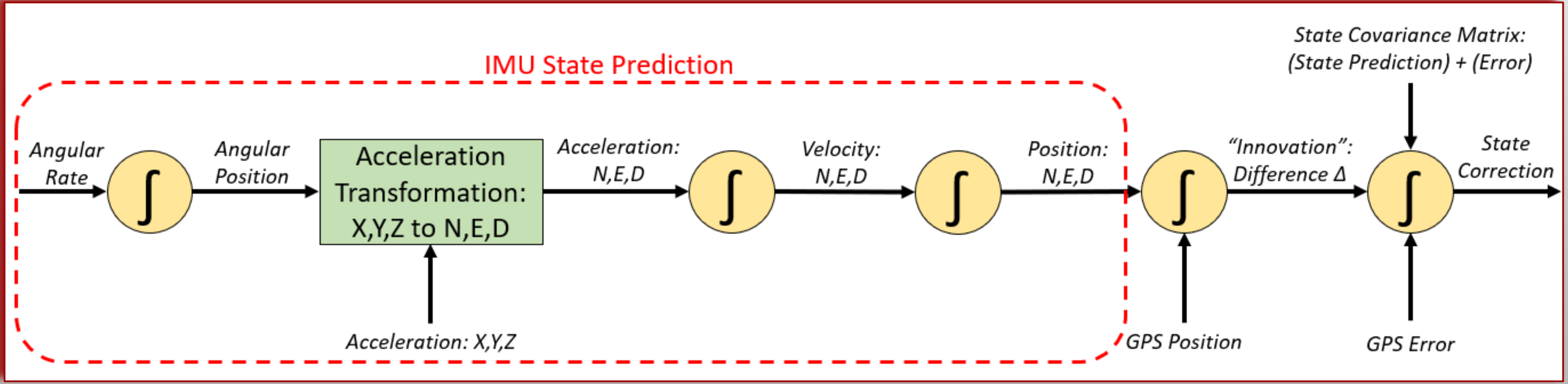
- EKF FBD
- Longitudinal and Lateral dynamics
- Gains

Vehicle Control

Pixhawk Control Architecture

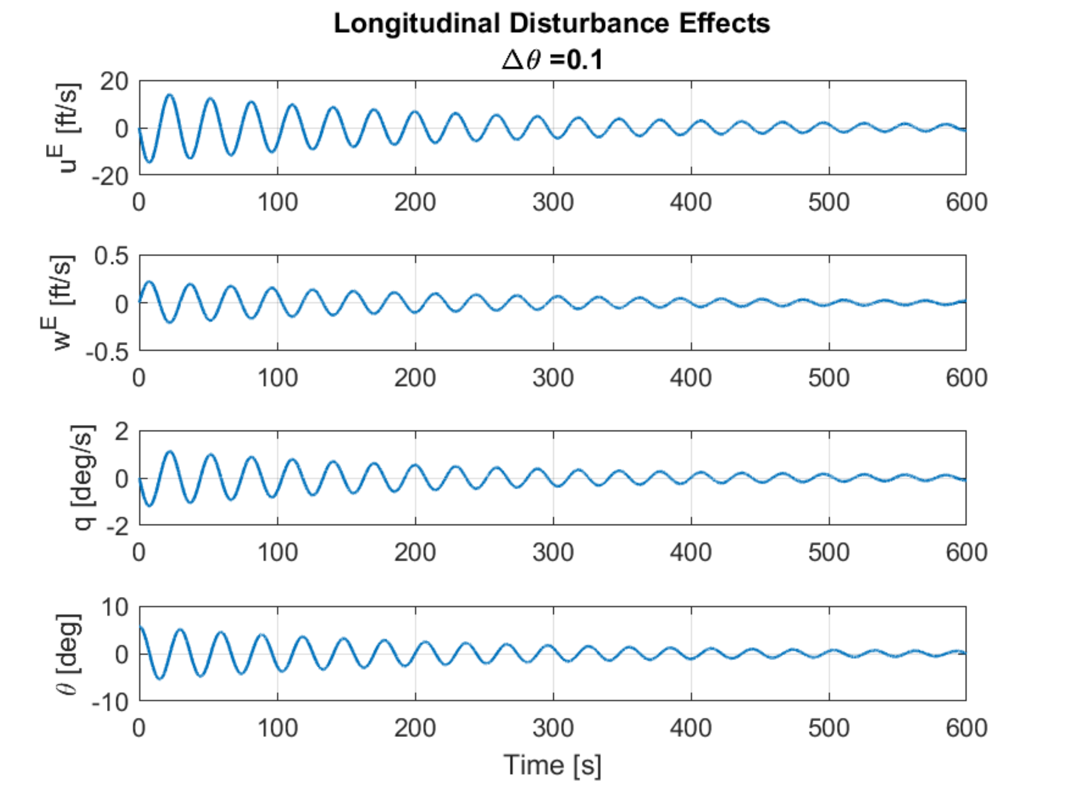


Extended Kalman Filter Architecture

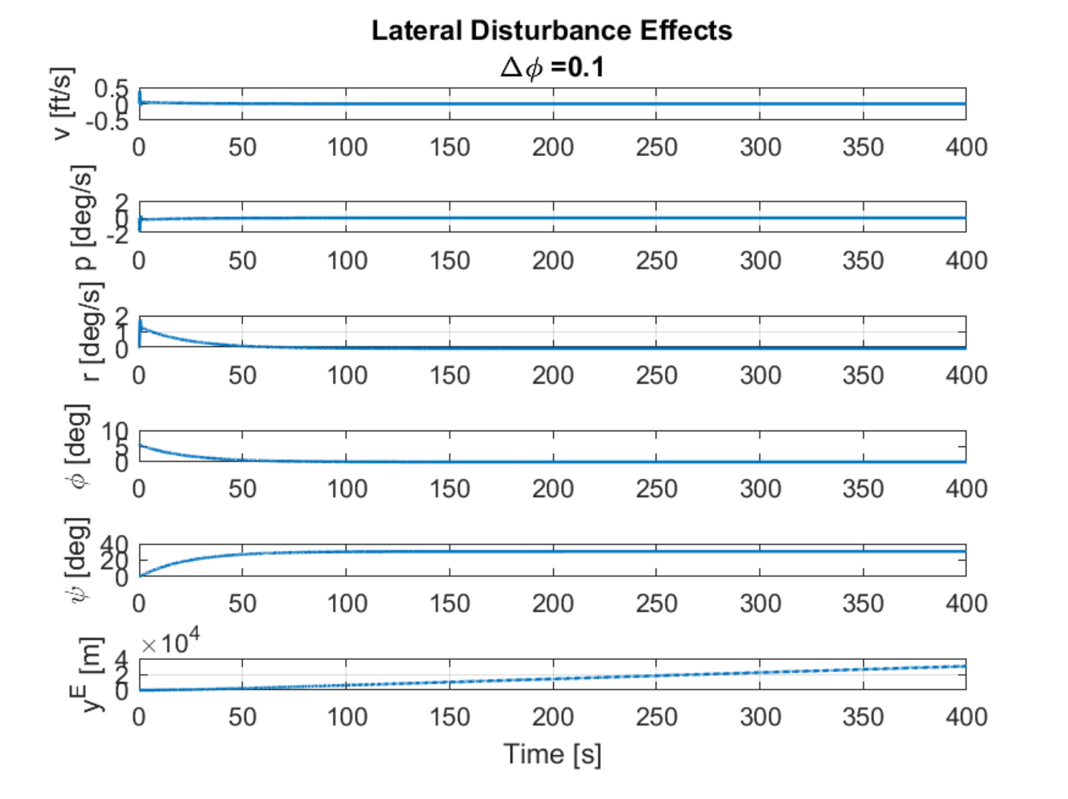


Sensor Attitude Determination (DR 4.2.1)	Capable Vehicle Control (DR 1.1.2)

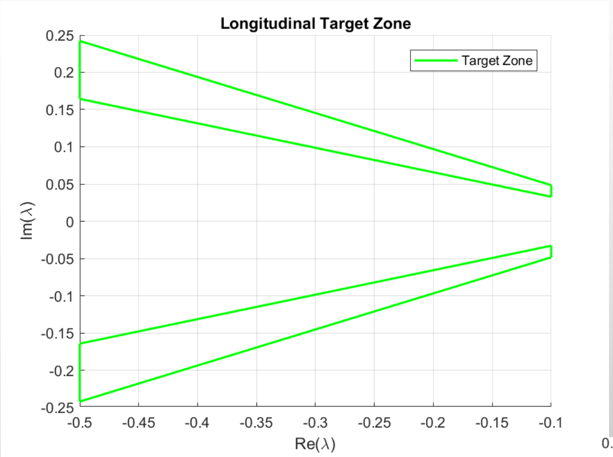
Longitudinal Open-Loop Dynamics

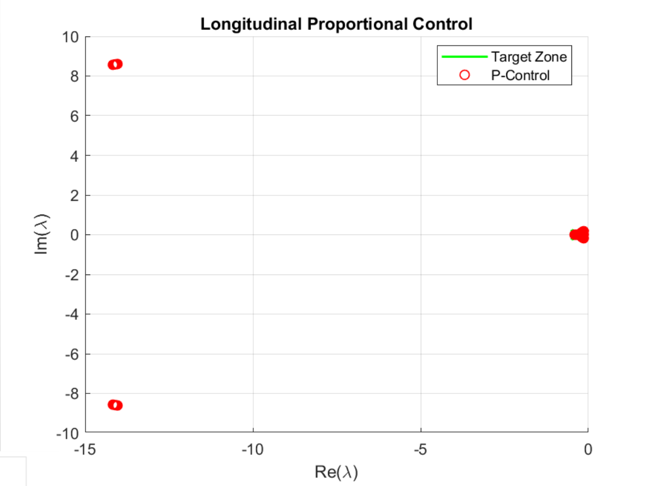


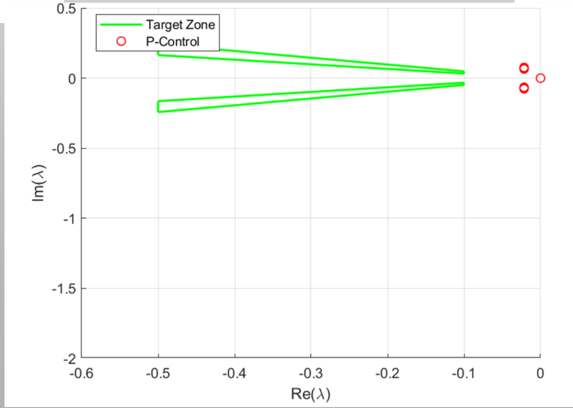
Lateral Open-Loop Dynamics



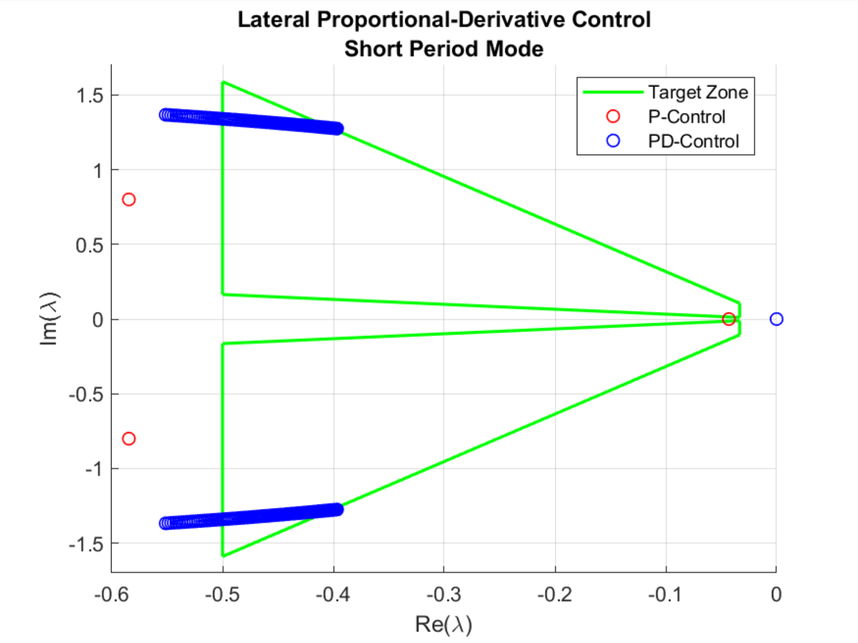
Longitudinal Gains

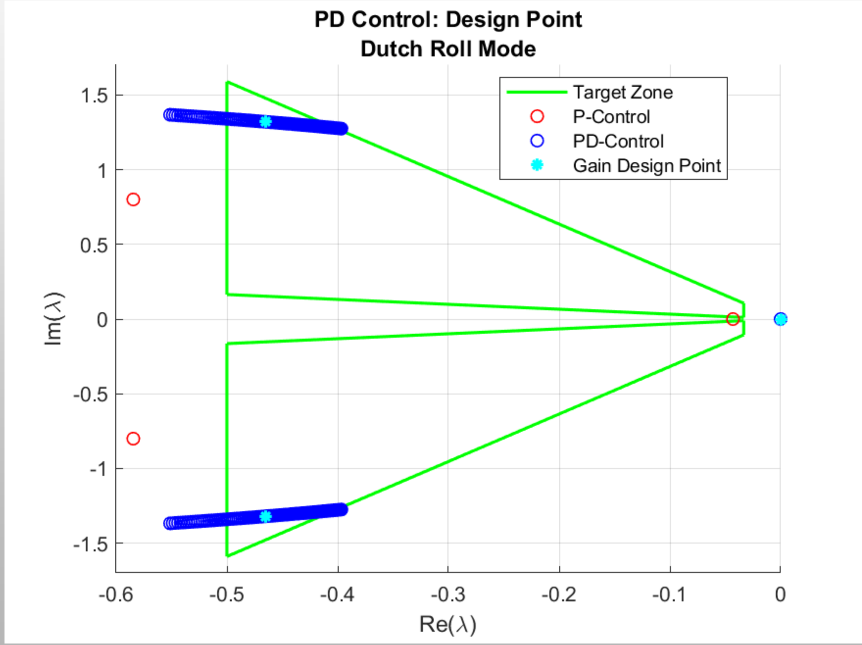




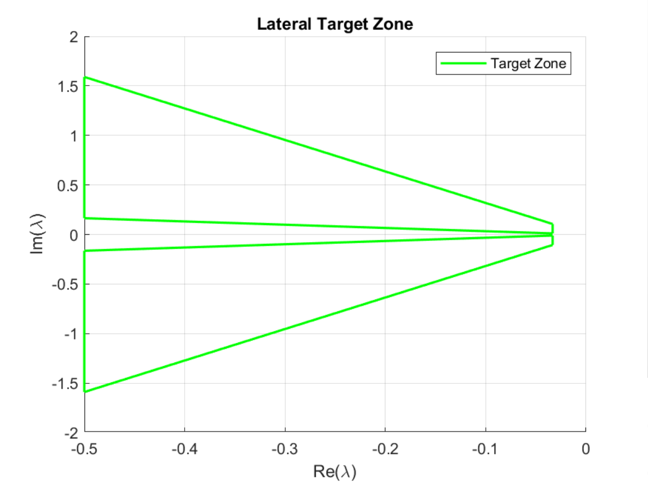


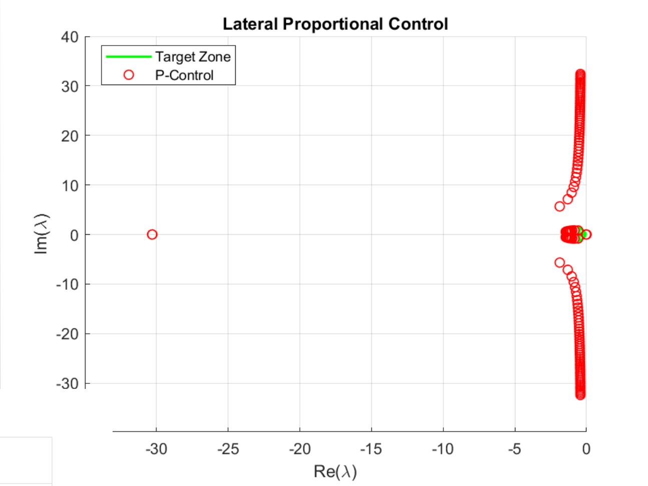
Longitudinal Gains

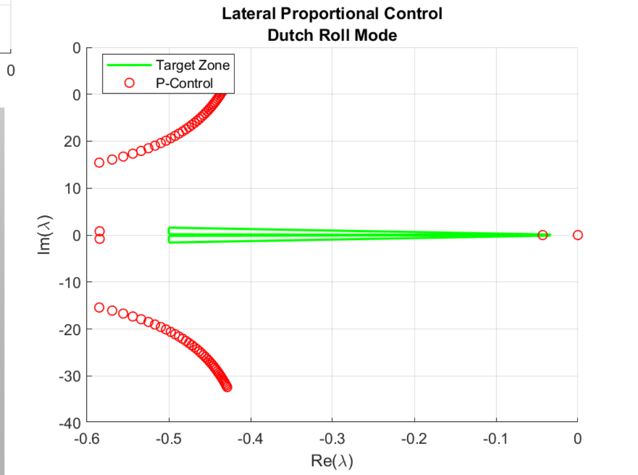




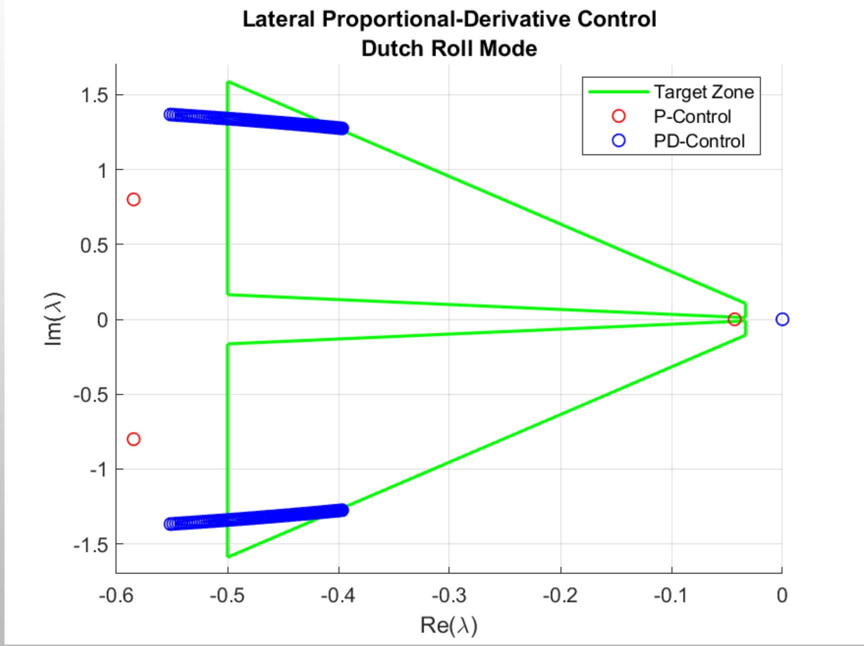
Lateral Gains

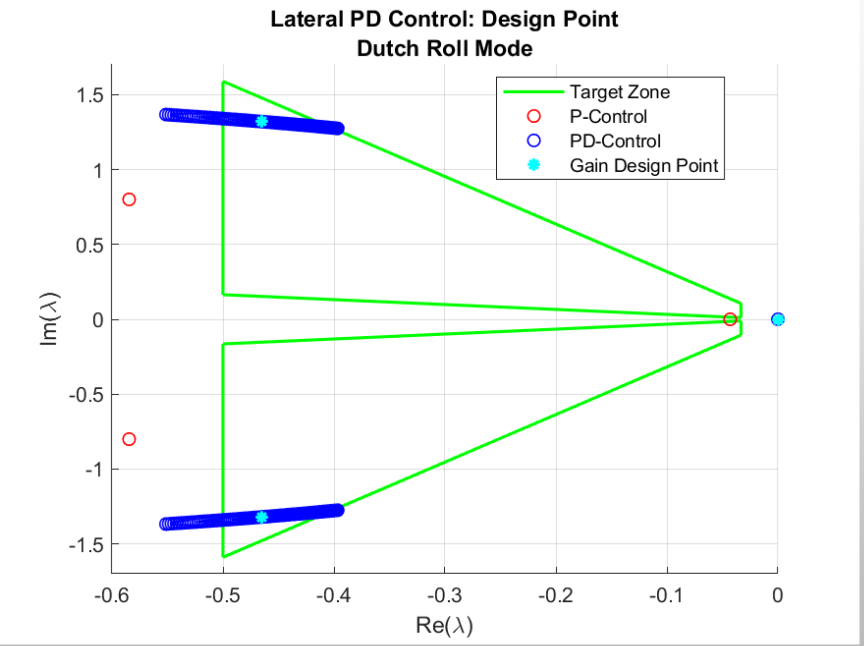




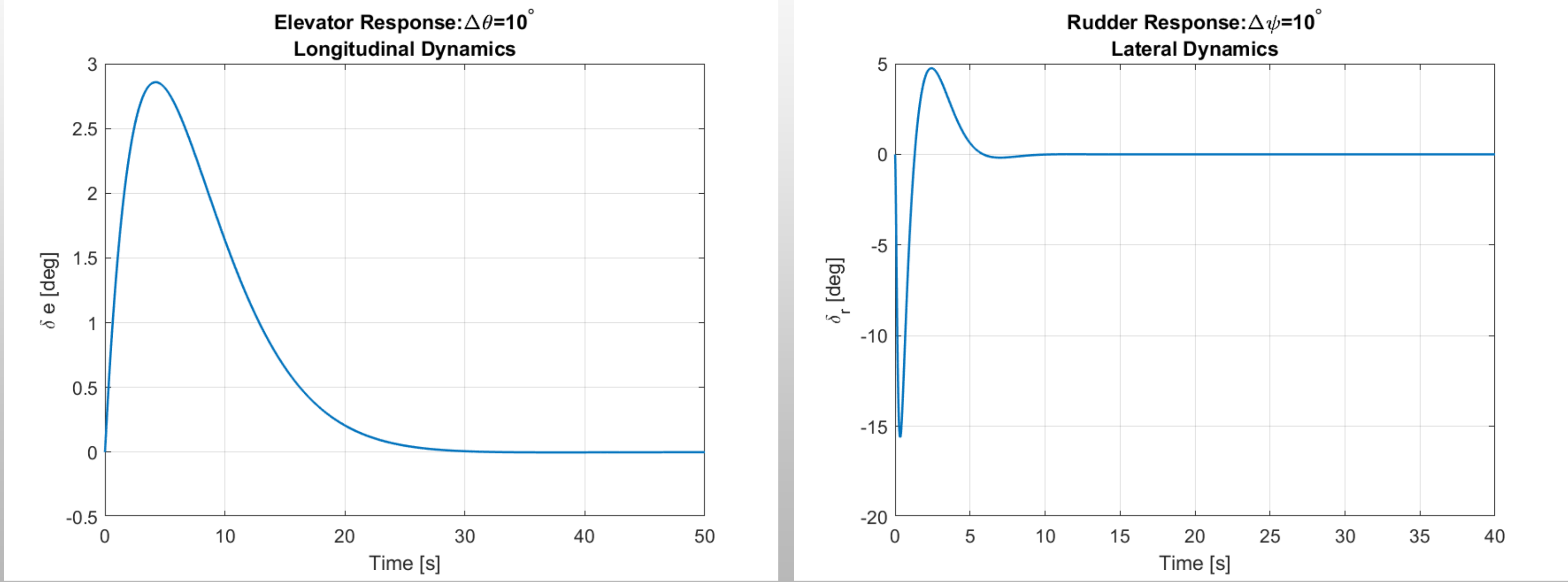


Lateral Gains





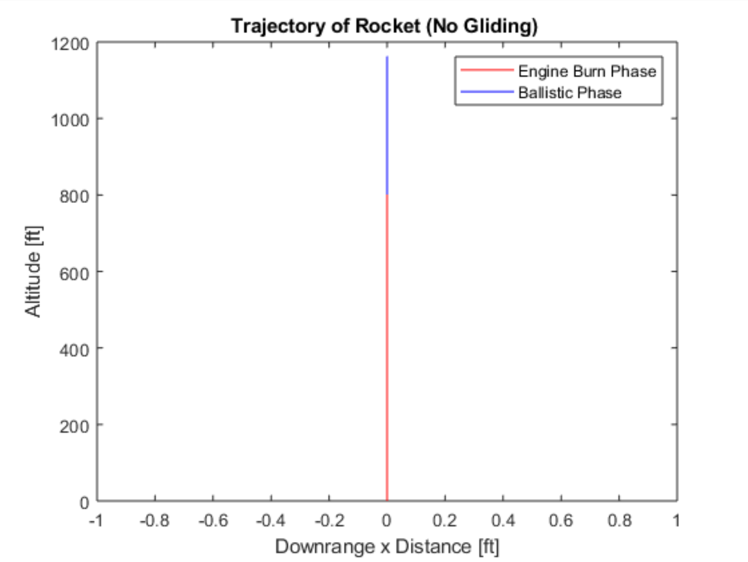
Control Surface Deflection

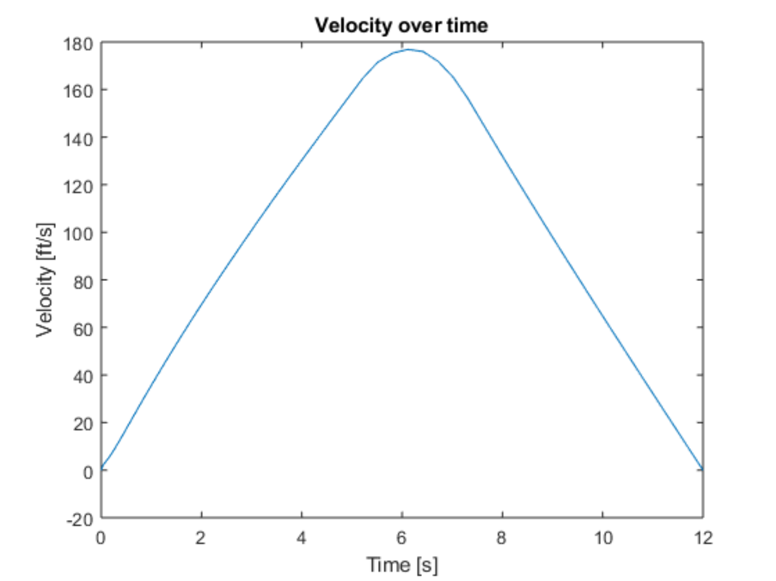


Propulsion Backup Slides

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

MATLAB Model - Trajectory/Velocity





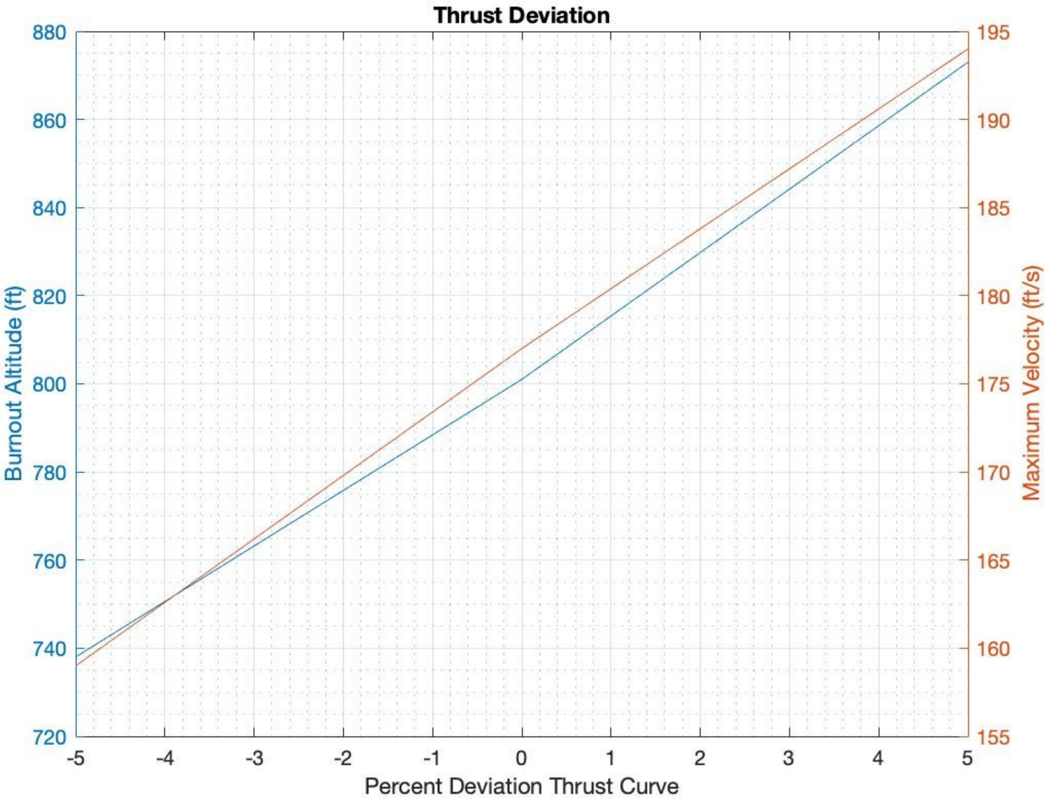
Max Altitude: 1163 ft

Burnout Altitude: 801 ft

Max Speed: 177 ft/s

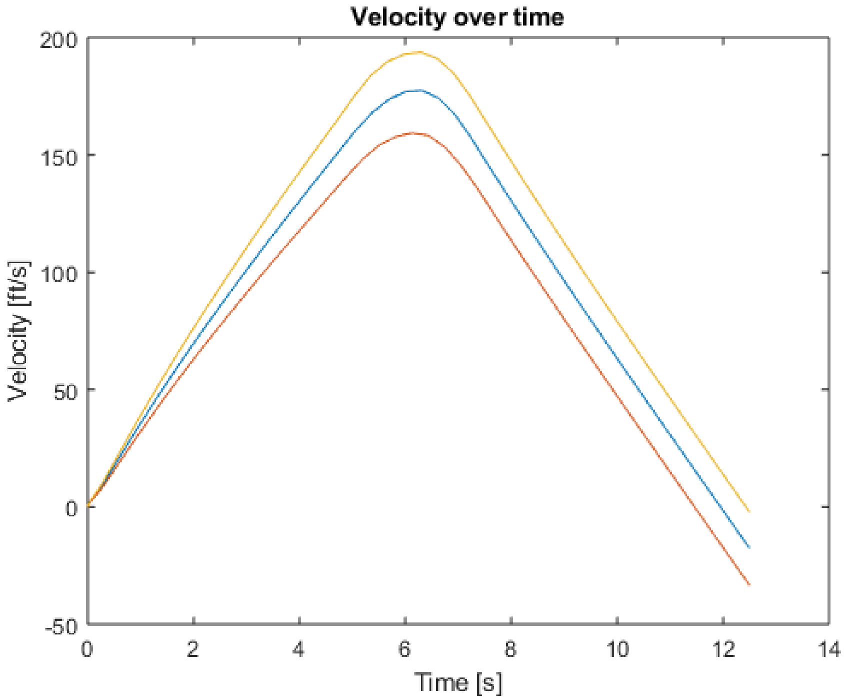
Time to Apogee : 11.9s

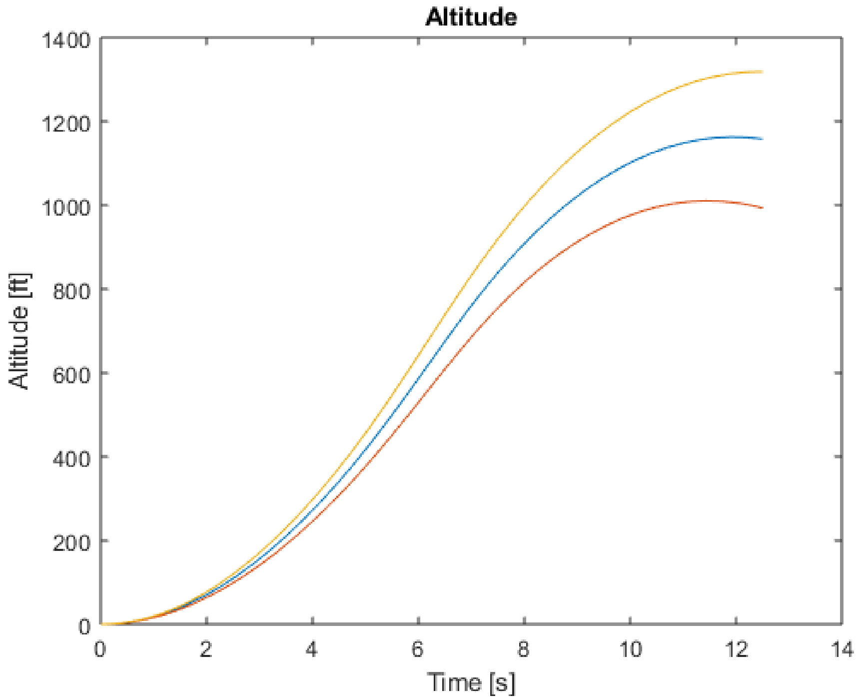
MATLAB Model - Thrust Uncertainty



Deviation	Burnout Altitude [ft]	Max Speed [ft/s]
0%	801	177
-5%	738	159
+5%	873	194

MATLAB Model - Thrust Uncertainty





OpenRocket Equations - Aerodynamics

$$C_D = \frac{D}{\frac{1}{2}\rho v_0^2 \, A_{\text{ref}}}.$$

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

$$C_m = \frac{m}{\frac{1}{2}\rho v_0^2 \, A_{\text{ref}} \, d}.$$

$$C_f = \frac{D_{\text{friction}}}{\frac{1}{2}\rho v_0^2 \, A_{\text{wet}}}$$

$$C_N = \frac{N}{\frac{1}{2}\rho v_0^2 \, A_{\text{ref}}}$$

$$X = \frac{C_m}{C_N} d$$

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

$$\bar{c} = \frac{1}{A_{\text{fin}}} \int_0^s c^2(y)\, \mathrm{d}y$$

$$y_{\text{MAC}} = \frac{1}{A_{\text{fin}}} \int_0^s y c(y)\, \mathrm{d}y$$

$$x_{\text{MAC,LE}} = \frac{1}{A_{\text{fin}}} \int_0^s x_{\text{LE}}(y) c(y)\, \mathrm{d}y$$

Wind Turbulence Equation:

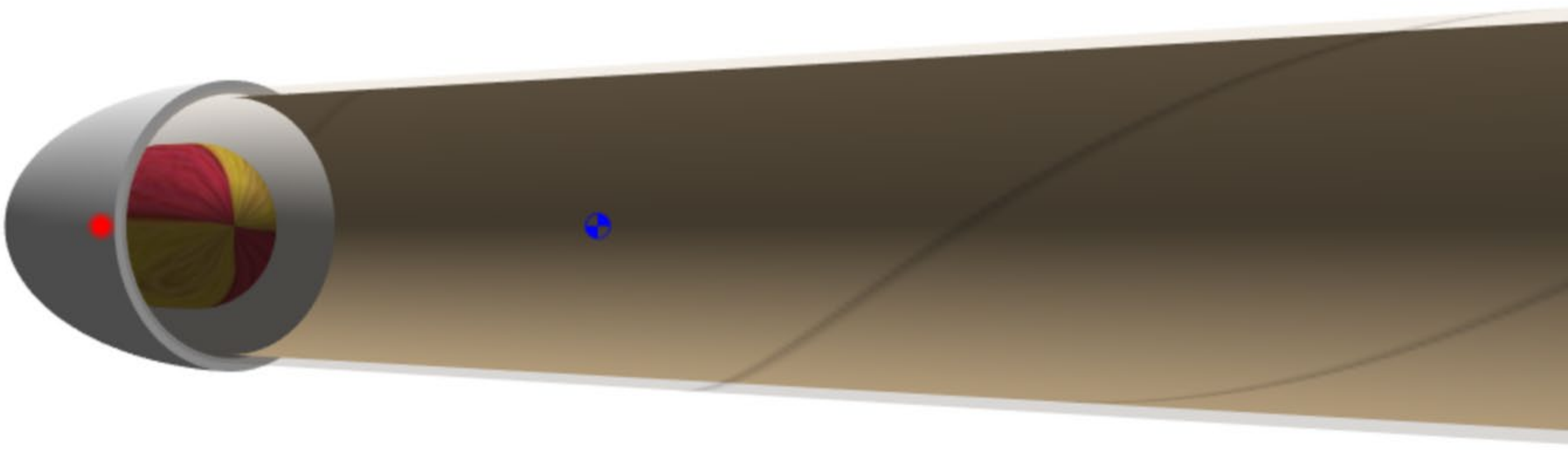
$$\text{Kaimal:} \quad \frac{S_u(f)}{\sigma_u^2} = \frac{4L_{1u}/U}{(1 + 6fL_{1u}/U)^{5/3}}$$

$$\text{von Kármán:} \quad \frac{S_u(f)}{\sigma_u^2} = \frac{4L_{2u}/U}{(1 + 70.8(fL_{2u}/U)^2)^{5/6}}$$

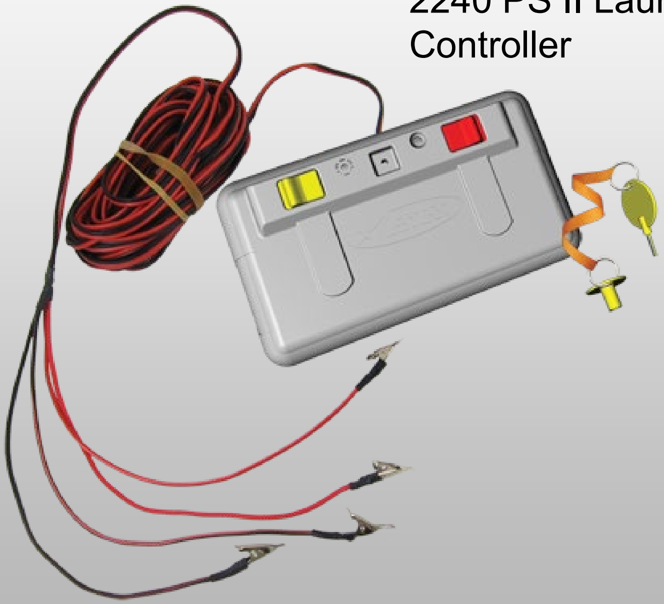
Parachute Choice

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

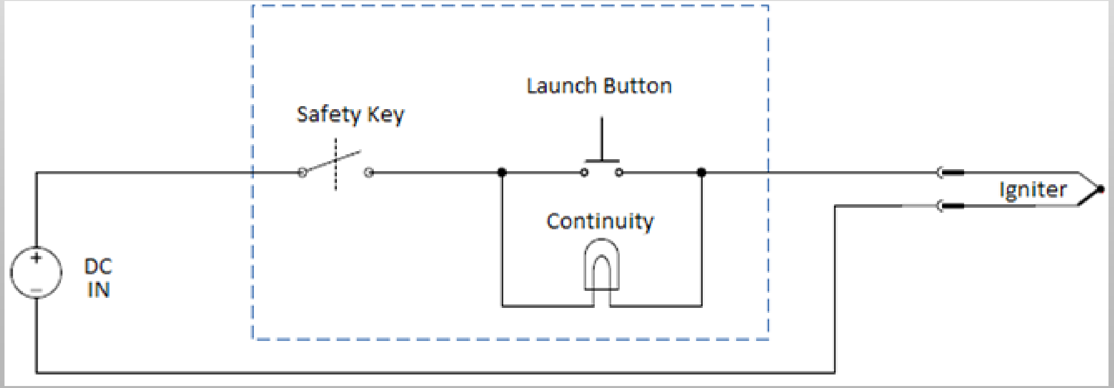
Motor Recovery



Launch Controllers

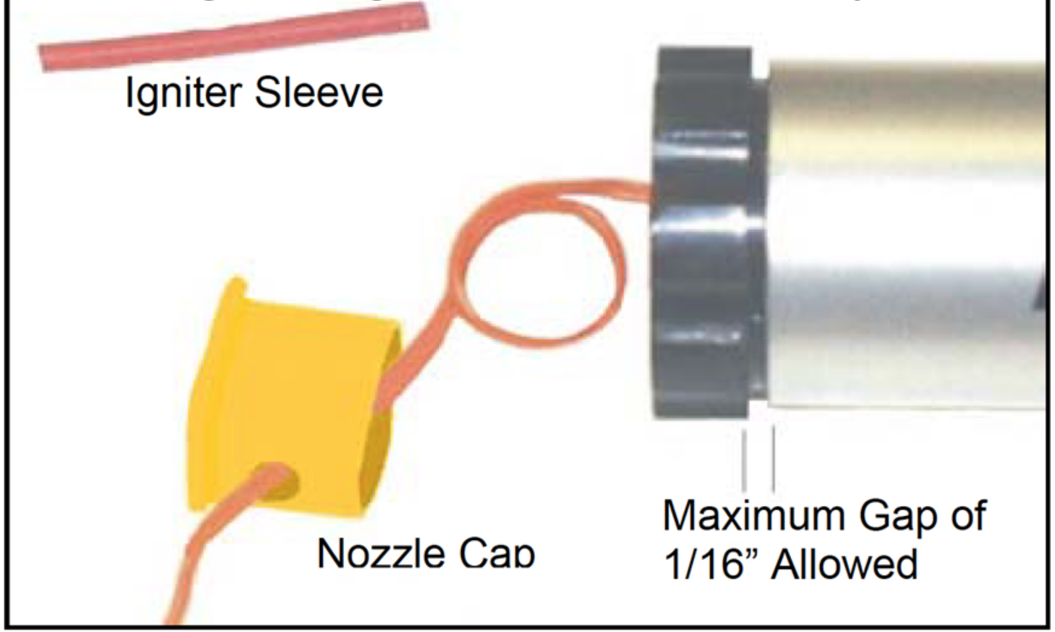


2240 PS II Launch Controller



Igniter

Figure 4. Igniter and Motor Assembly



Igniter specifications*:

Bridgewire resistance:
1.2 – 1.8Ω

Rated all-fire current:
1.2 Amps for 10 milliseconds

Typical response:
2.3ms @ 1.2 Amps

(*) These are manufacturer's specs. CTI assumes no responsibility for their use or misinterpretation

Exhaust Plume Regions

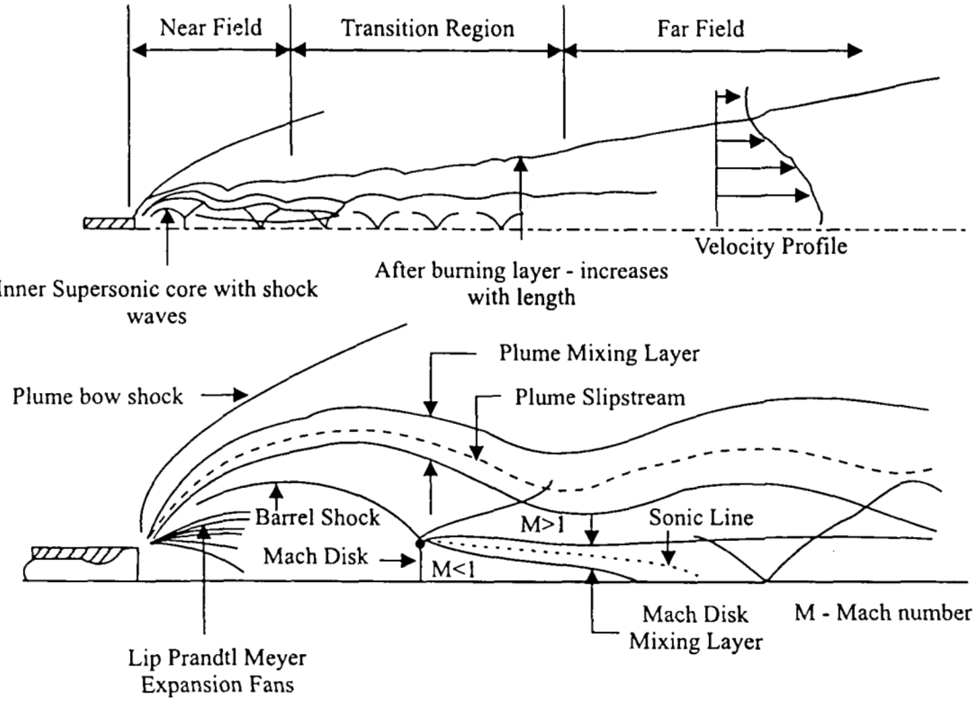


Fig. 3.1.2 Description of a Typical Supersonic Plume

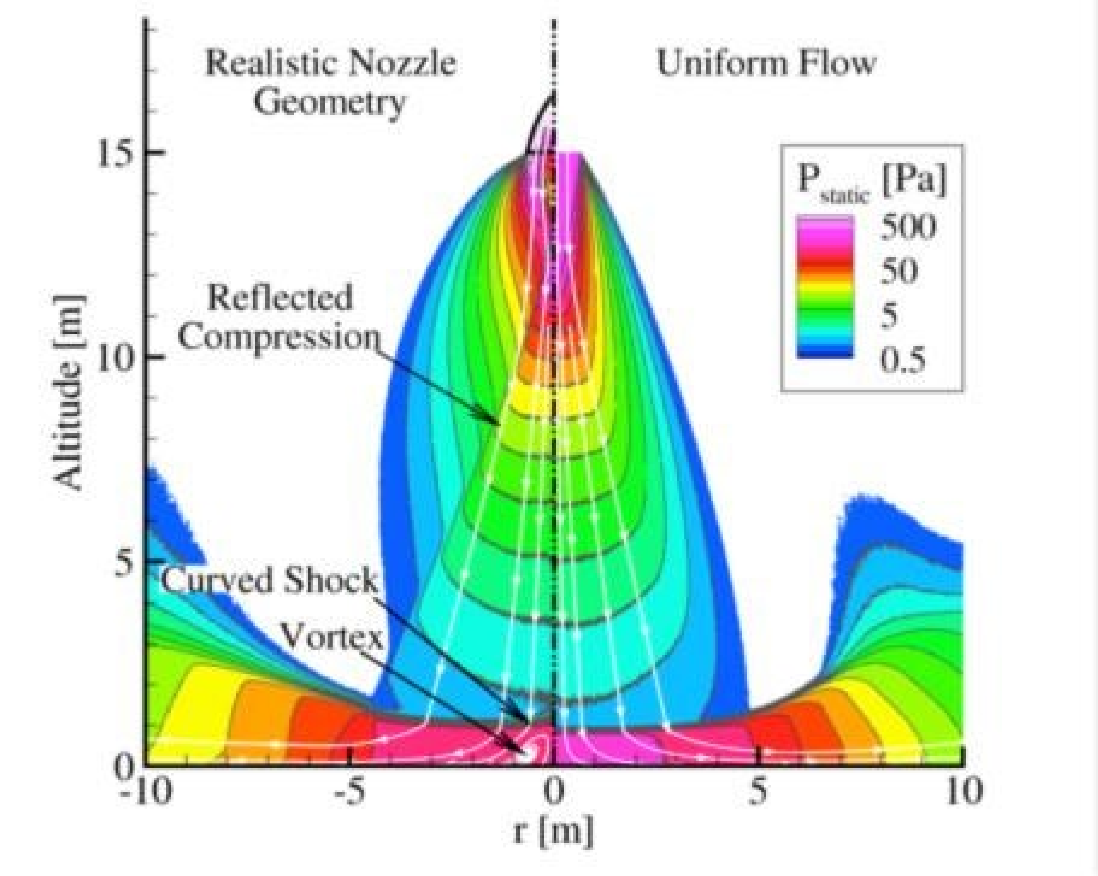
Rocket Engine Integration

Grain Integration

Motor Integration

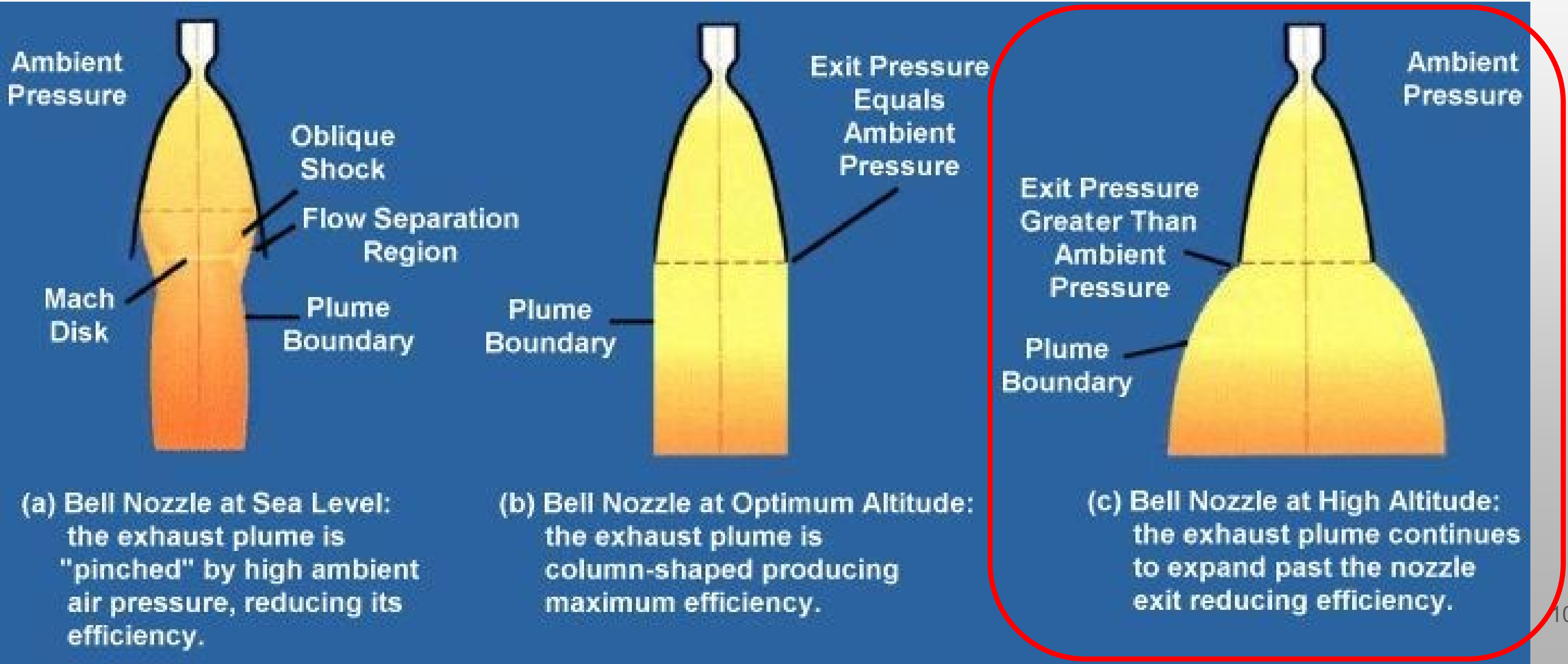
Fully Integrated Motor and Casing

Nozzle Flow - Ideal vs. Realistic

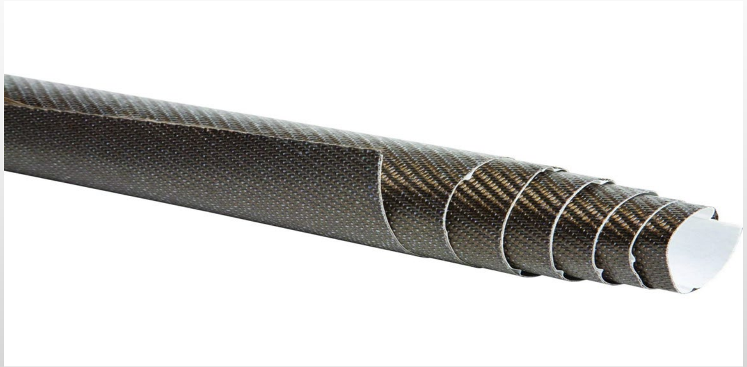


Exhaust Plume Expansion

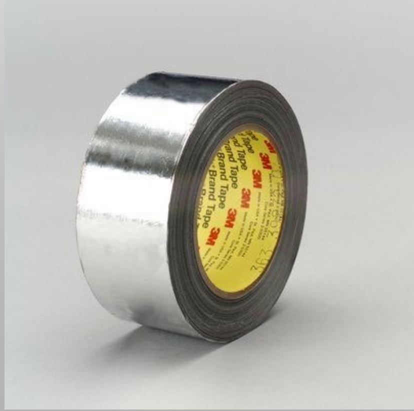
- Underexpanded nozzle at altitude leads to expanded exhaust plume



Thermal Risk Mitigation



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



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

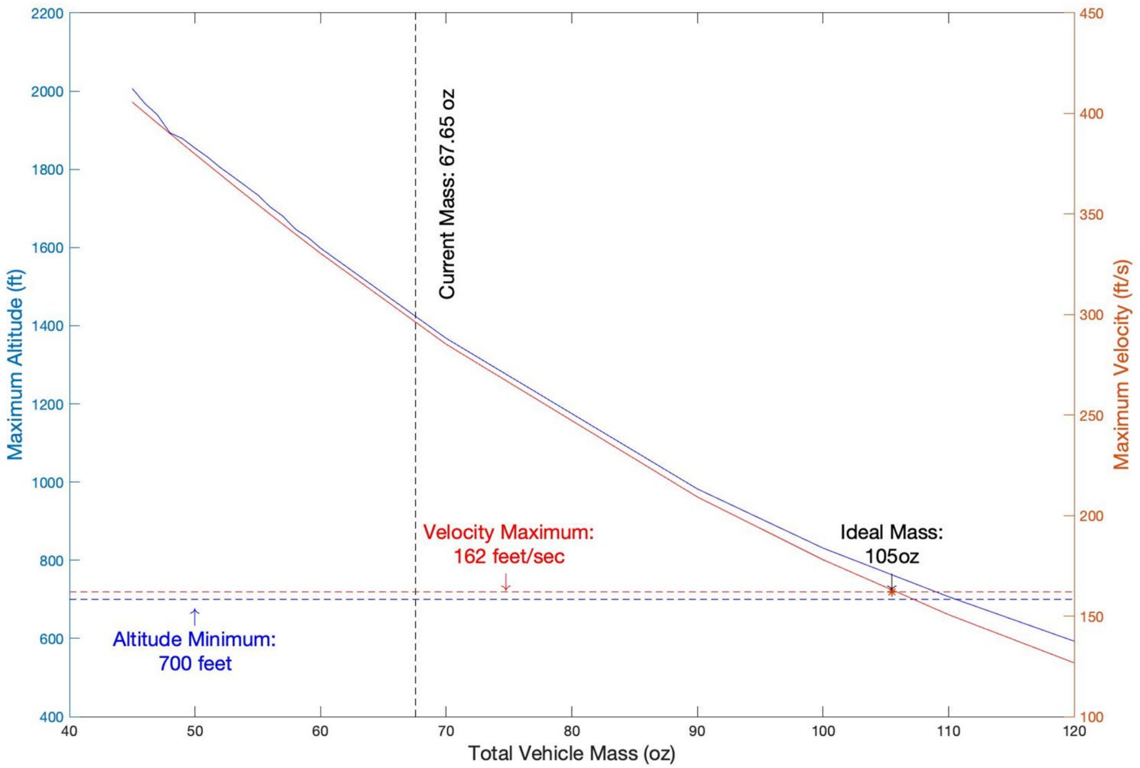
What is a Baffle?

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

Launchpad and Launch Lug

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

Reducing Velocity



Software Backup

Preliminary Testing Targets

Example Image from Drone:

Same target pixel size compared to mission profile

Pixel to World Transformation

Problem to solve:

$$\tilde{P}\widetilde{p_w} = x_s$$

$$x_s = \begin{bmatrix} u \\ v \\ 1 \\ R(range) \end{bmatrix}$$

$$\widetilde{p_w} = \begin{bmatrix} N(north) \\ E(east) \\ D(down) \\ 1 \end{bmatrix}$$

$$P = K(R|t) \quad \tilde{P} = \begin{pmatrix} \mathbf{K} & 0 \\ \mathbf{0}^{\mathrm{T}} & 1 \end{pmatrix} \begin{pmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}^{\mathrm{T}} & 1 \end{pmatrix}$$

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

$$K \equiv Camera\ Matrix$$

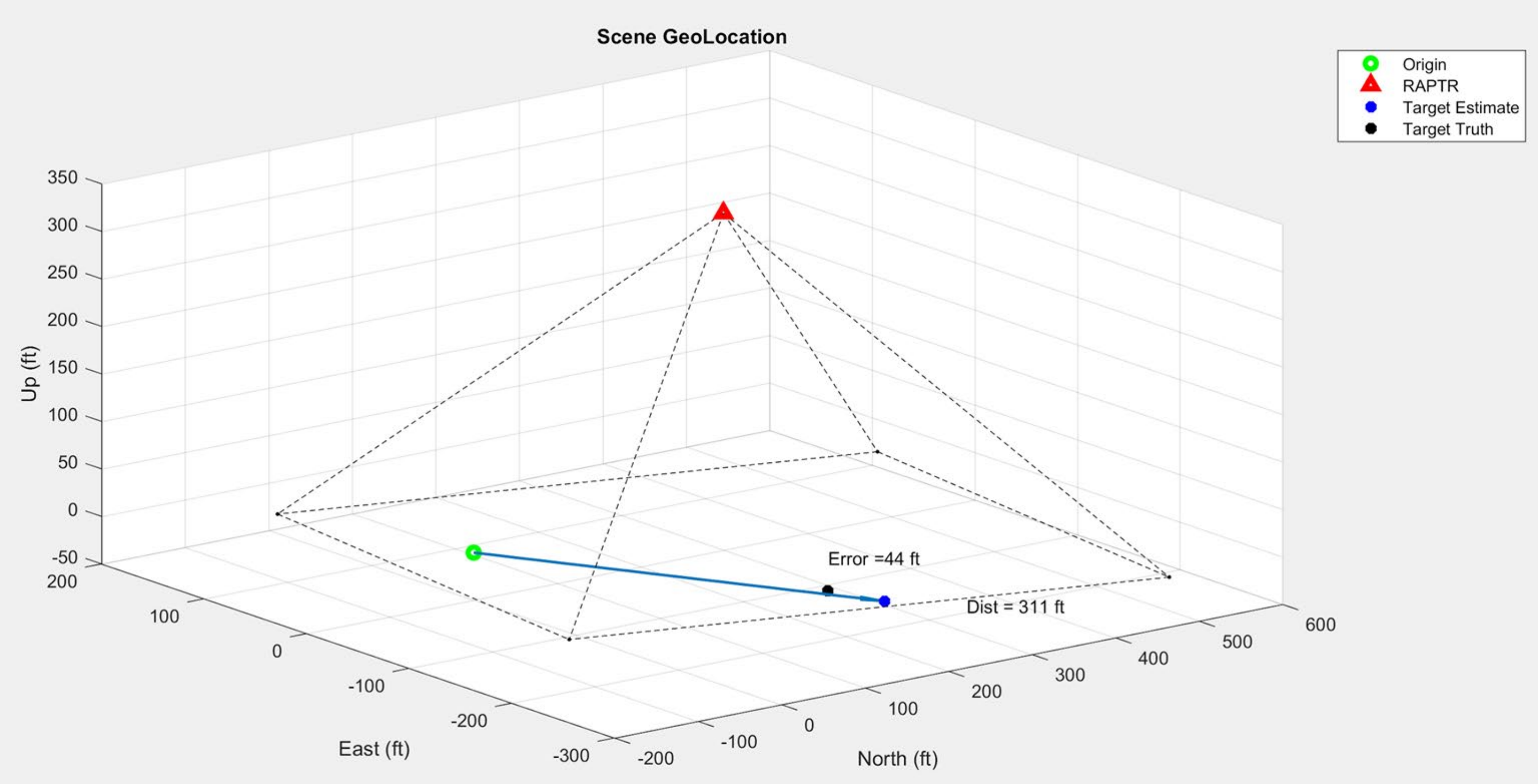
$$R \equiv world\ to\ camera\ rotation$$

$$t \equiv world\ to\ camera\ \text{translation}$$

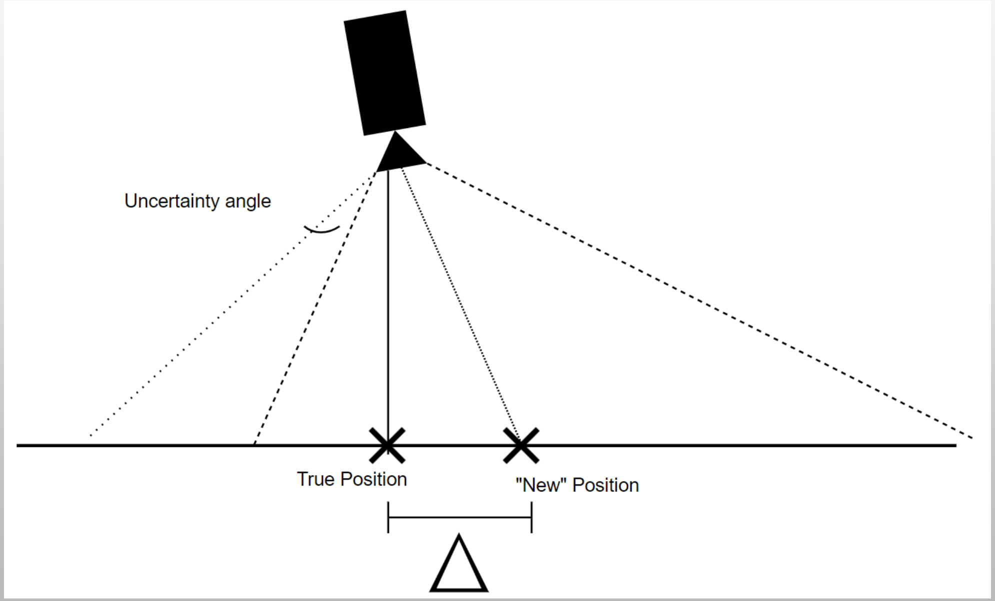
$$R = R_1(\phi)R_2(\theta)R_3(\psi)$$

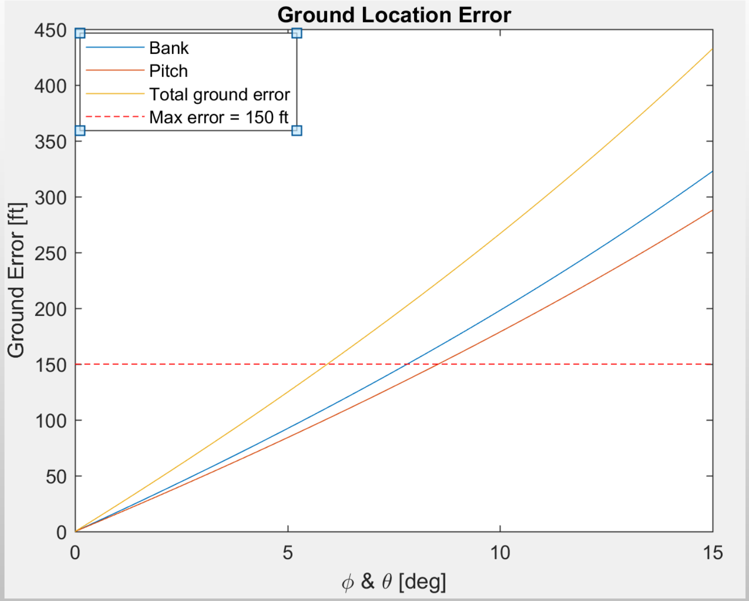
Vehicle Roll, pitch, yaw

Geolocation Compared to Truth:



Attitude Uncertainty for Geo-Location:





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

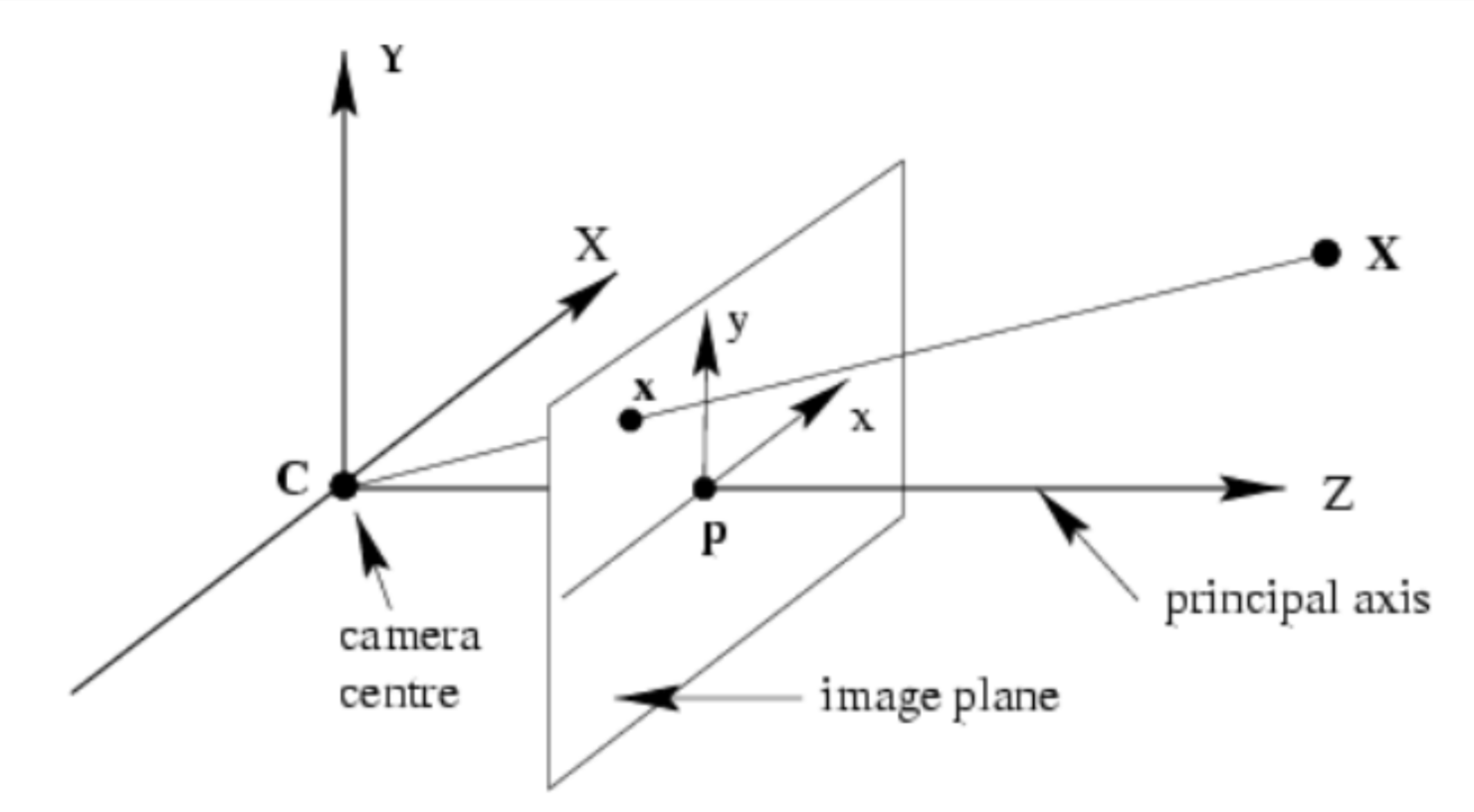
$$\Delta \equiv Ground\ Distance\ [ft]$$

$$\phi \equiv Bank\ Uncertainty\ [\text{deg}]$$

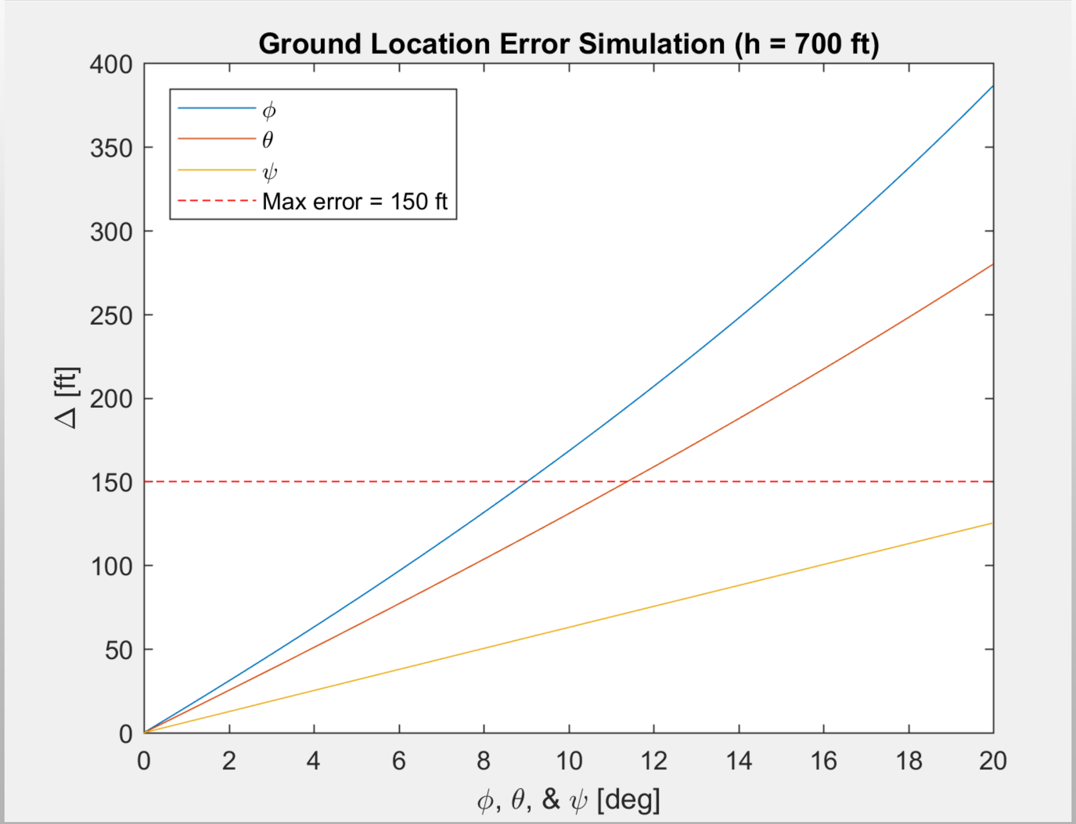
$$\alpha \equiv True\ Bank\ Angle\ [\text{deg}]$$

$$\text{L} \equiv \text{Target Location in image (left } = 0, \text{right} = 1)$$

Pixel Mapping Diagram



Attitude Error with Payload & Algorithm Simulation



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

Structures Backup

Structural Requirements

Derived Requirements	Description
DR 1.4	The vehicle shall withstand the forces of the launch and glide phases.

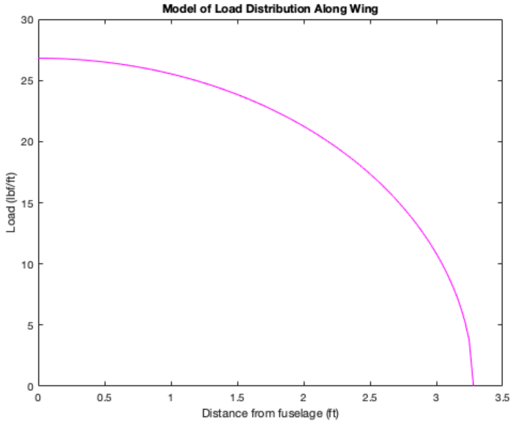
A Matlab model of shear force and bending moment along the wing.

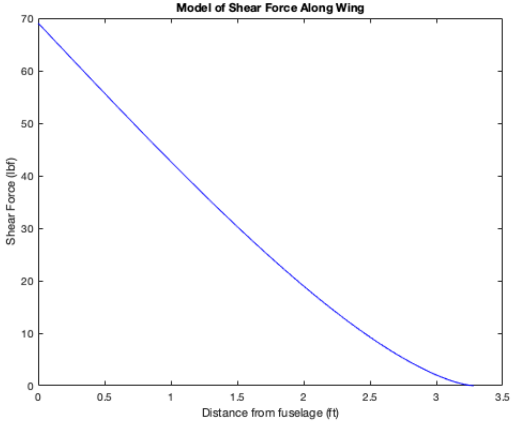
Flexure Formula for 0.25” diameter rod → slight climb σ_{max} = 12,457 psi → worst case σ_{max} = 376,232 psi

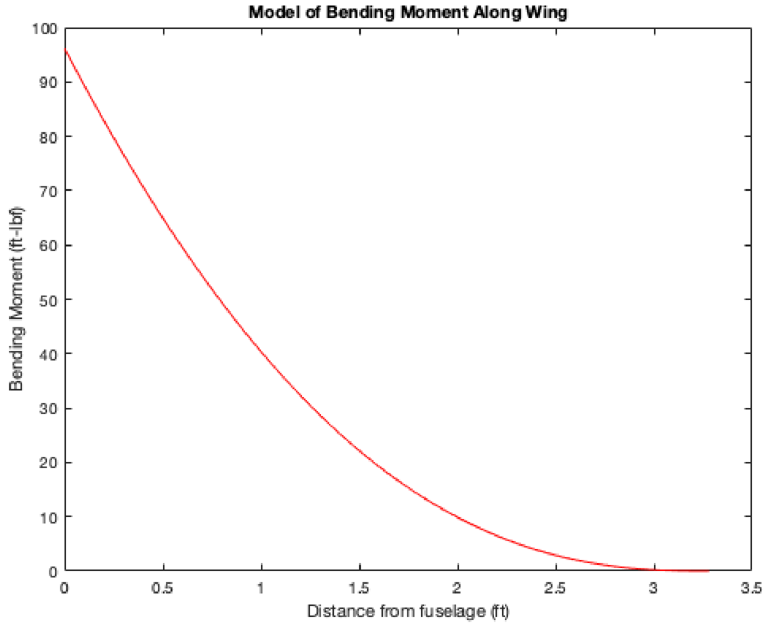
Material	**σ_y [psi]**	**FOS (slight climb)**	**FOS (worst case)**
Balsa	2,828	0.276	0.007
Al-6061	40,000	3.916	0.106
Steel	53,700	5.257	0.142
Carbon Fiber	82,762	8.102	0.219

Structural Requirements

Worst Case





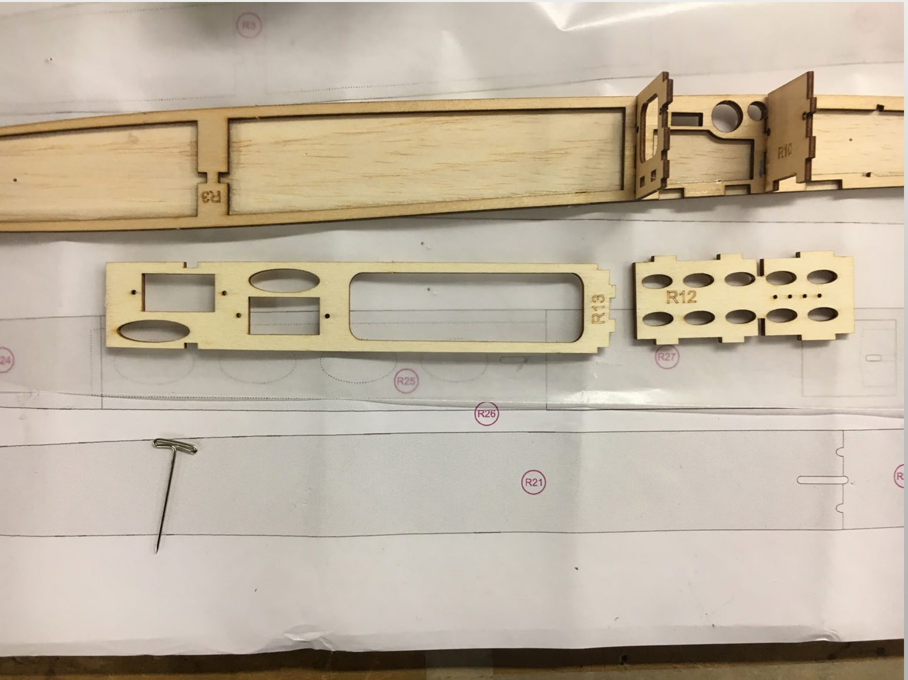


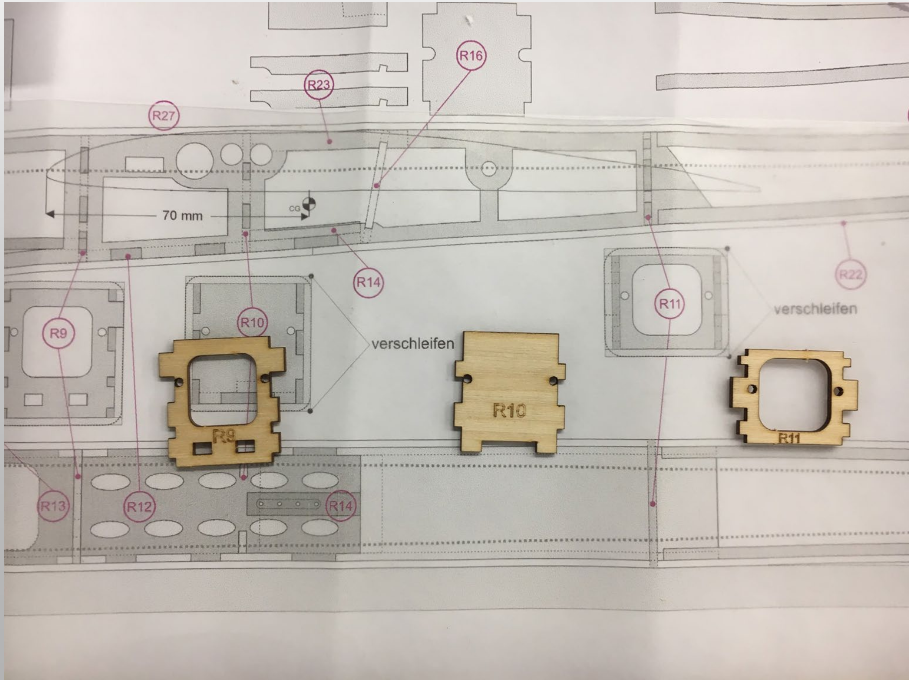
Structural Integrity

(DR 1.4) ✓

Fuselage Modification

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





Fuselage Modification

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

Wing Loading Test

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

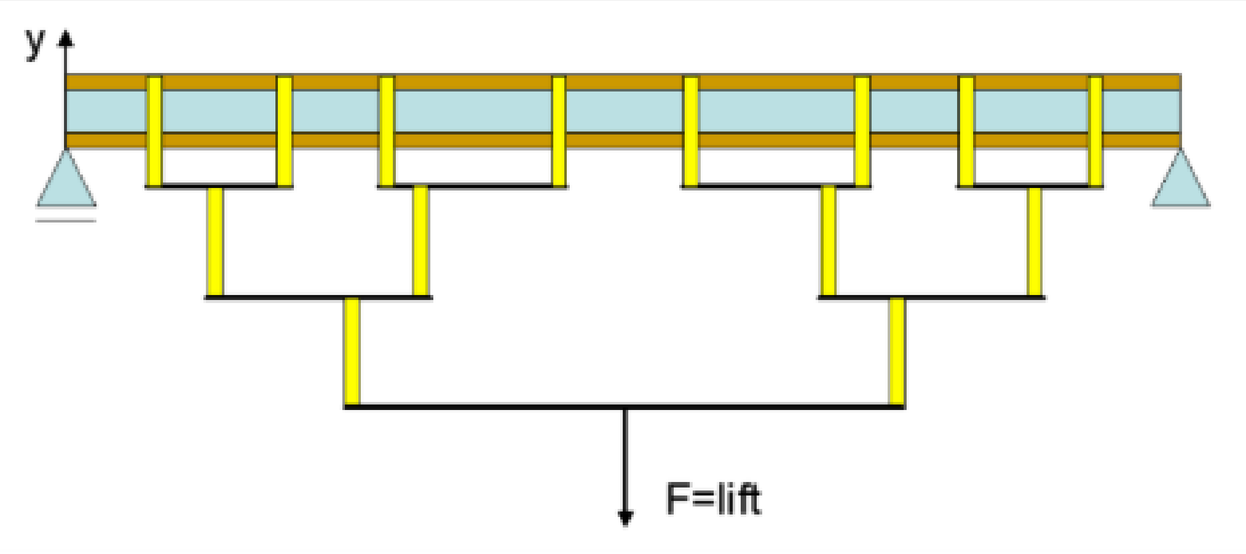
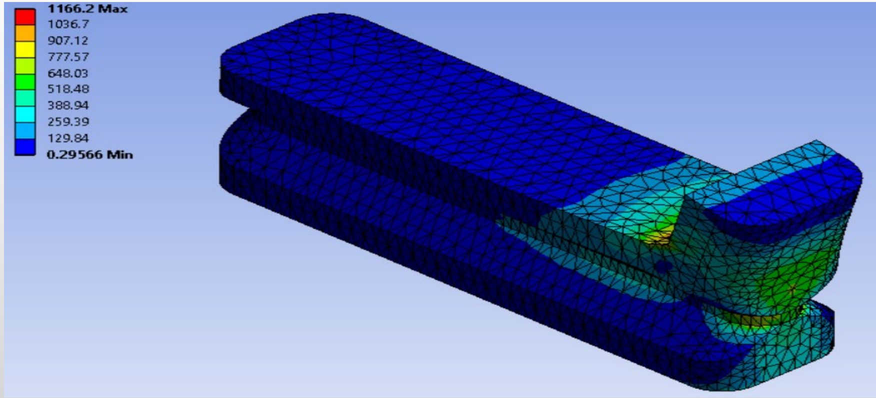


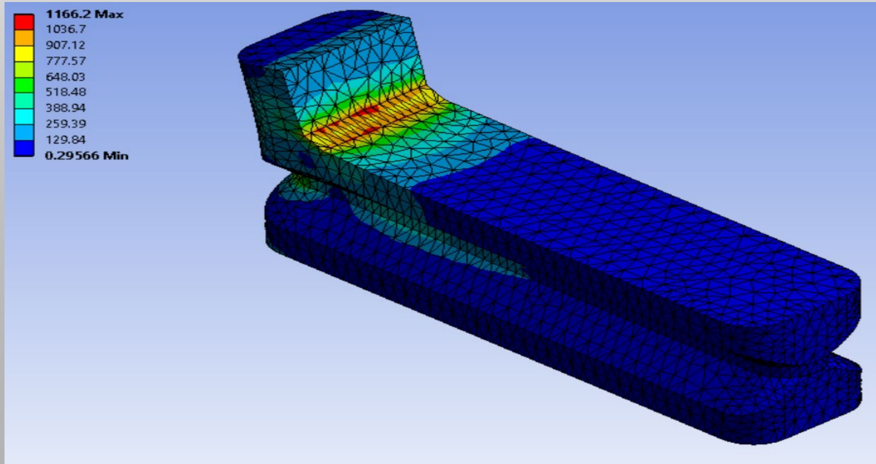
Image courtesy of Dr. Wingate

Motor Mount Ansys Analysis

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

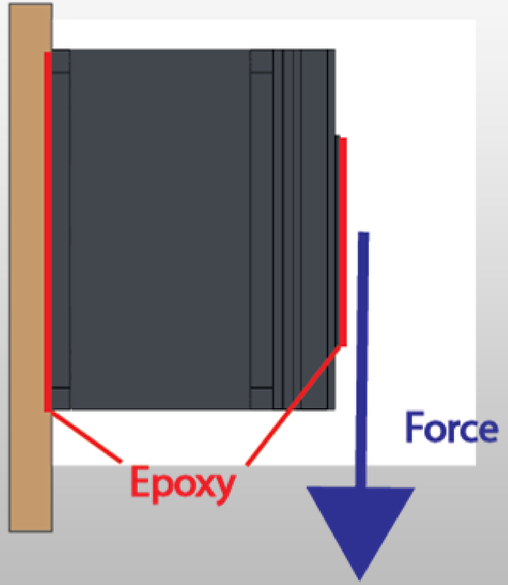
Material	Tensile Strength [psi]
PLA	6066.23
ABS	5656.47
Onyx with Carbon FIber	101526





Structural Requirements

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



Structural Requirements

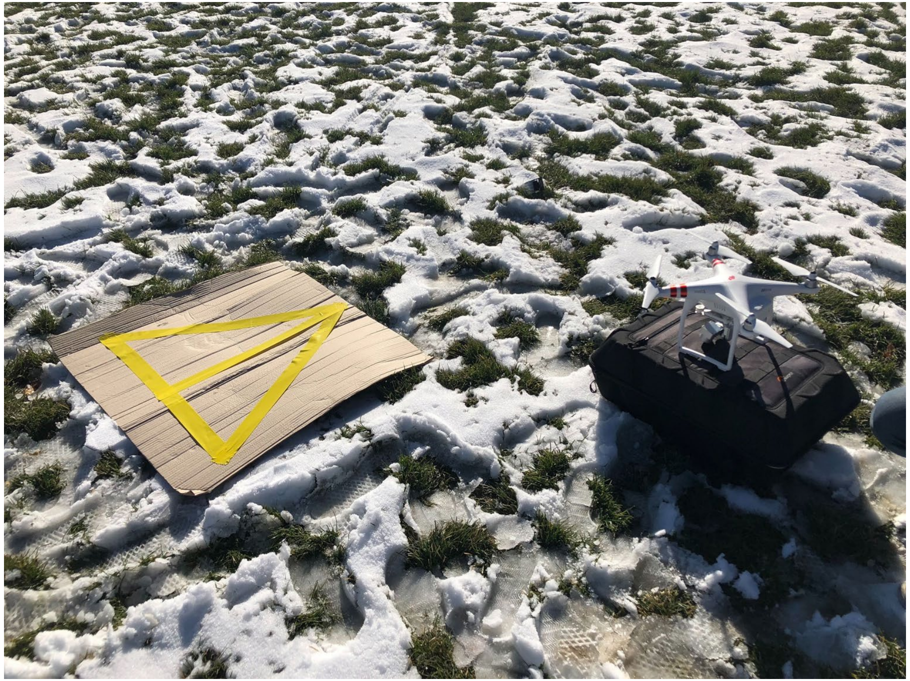
Item(s)	Mass [g]	Mass [lb]
Airframe	518	1.1419
Motor and Mount	680.29	1.4998
Electronics	218.09	0.4808
Payload	498.95	1.1000
Total	**1,915.33**	**4.2225**

Test Backup

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

Software

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



Structures

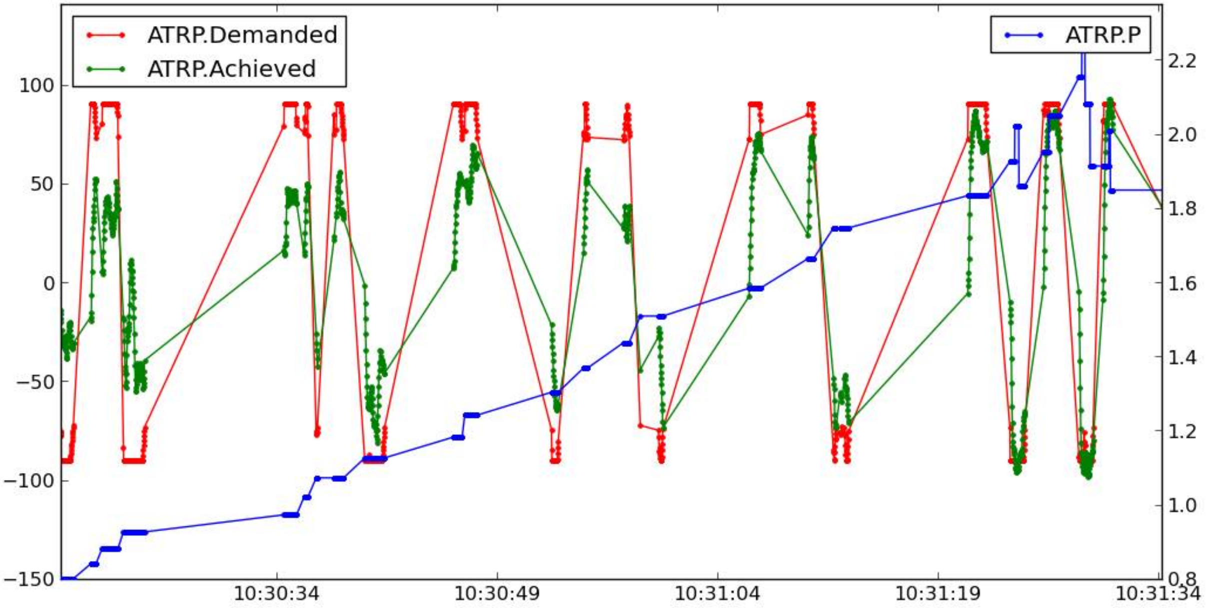
- **Purpose:** Verify structural integrity of wing/motor mount **(FR 1)**
- **Location:** Outside of ITLL
- **Equipment:**
  - AndREaS Glider
  - Eye Hook
  - 5 Gallon Bucket
  - Epoxy
  - 3D Printed Motor Mount
  - Vice Grips
- **Measurements:**
  - Failure of Wings/Motor Mount
- **Methods:**
  - Insert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

Picture coming soon

Aerodynamics

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

Controls/PixHawk



Test Regulations

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

Test Regulations

§ 101.25 Operating limitations for Class 2-High Power Rockets and Class 3-Advanced High Power Rockets.

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

(a) At any altitude where clouds or obscuring phenomena of more than five-tenths coverage prevails;

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

(c) Into any cloud;

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

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

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

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

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

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

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

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

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