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Collins Aerospace

Project S.U.N.S.E.T

Supersonic **U**nmanned **N**ovel **S**ensor **E**quipment **T**estbed

Critical Design Review

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Alex Peik, Nathan Gall, Pranav Kartha, and Quentin Saylor

Team Members


Mykhail Sandacz (Team Lead)


Rory Conway (Systems Engineer)


Nathan Gall (Controls Lead)


Alex Peik (External Systems Lead)


Sam Fortin (Recovery Lead)


Pranav Kartha (Embedded Systems)


Liam Normand (CAD Lead)


Quentin Saylor (Aerodynamics Lead)

Agenda

- Overview
- Requirements
- Approach
- Detailed Design Walkthrough
- Project Plan
- FMEA and Safety
- Conclusions
- Appendix
- Individual Reports

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Overview

System Overview

Customer: Collins Aerospace

Purpose: Test sensors in transonic and supersonic conditions

Mission: Create a vehicle for these flight conditions driven solely by gravity

Product: Gravity driven, supersonic, unmanned, novel sensor equipment testbed

System Overview

Needs:

- Collins Aerospace requires a supersonic test vehicle to replace traditional wind tunnel and flight tests for air data sensors

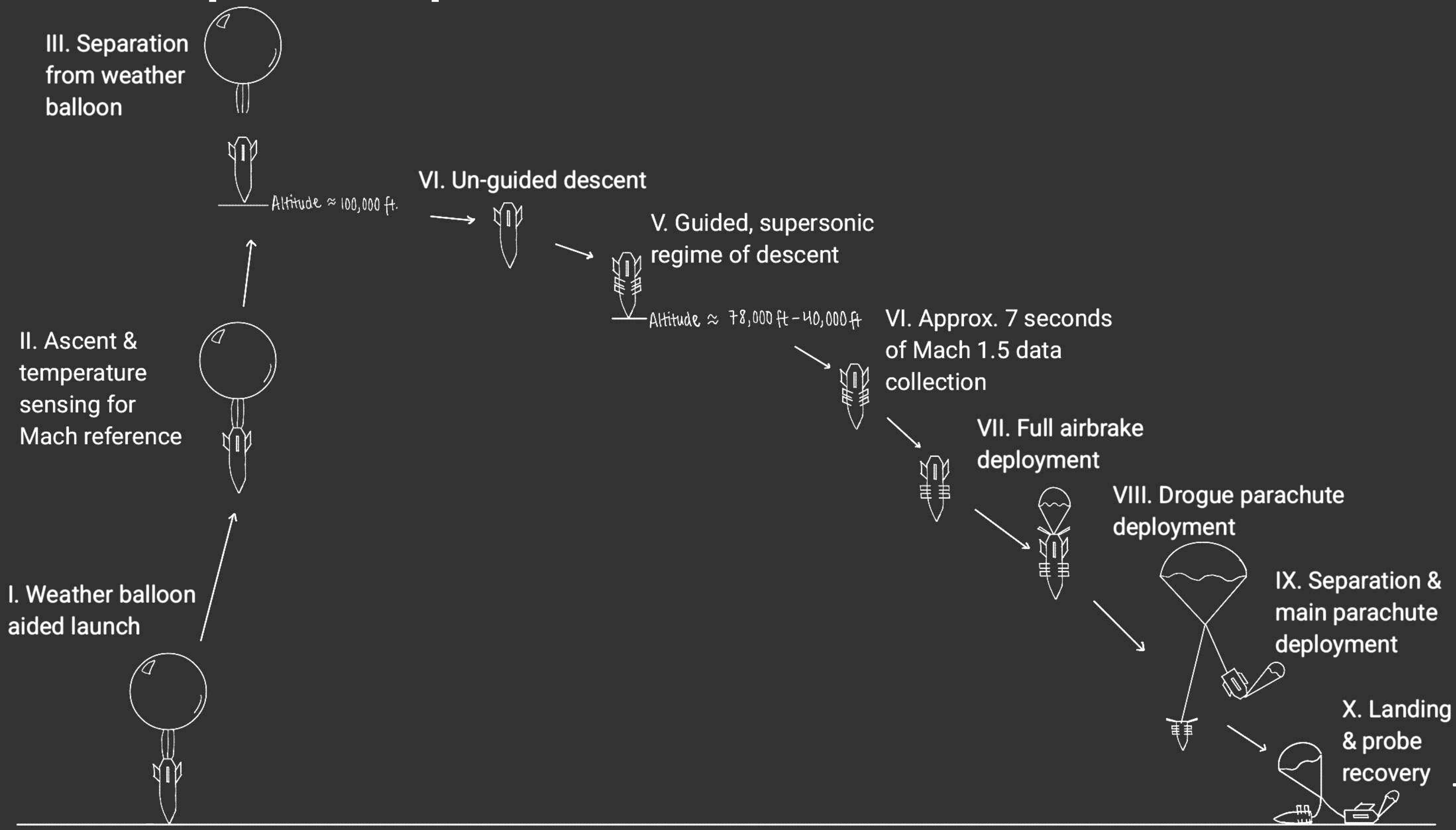
Goals:

- Develop a vehicle capable of characterizing transonic regimes with a pitot static probe
- Maintain competitive operational cost relative to alternative testing methods

Objectives:

- Achieve a minimum of Mach 1.2 and maintain for a minimum of 10 seconds
- Log and store all collected air data in flight
- Recover intact and without damage to Air Data Computer (ADC)

Concept of Operation



Requirements

Requirements and Standards

FAA 14 CFR Part 101D

- Federal regulations for unmanned balloons
- Requirements on test environment, conditions
- Requires redundant cutdown and flight termination systems
- Requires ATC notification, visibility and radar cross section enhancement
- Requires dispersion and trajectory analysis, location tracking in flight
- FAA waiver and approval will be required for each flight

MIL-STD 210C

- Provides atmospheric data for a range of operational conditions
- Requirement: operation at up to 10% extremes in test environment

RVTM – Sponsor Requirements

Source	Keyword	Description	Criteria	Status	Solution Rating (1-10)	Notes / Future Plans
Collins	Shall	Achieve a minimum of Mach 1.2 and maintain for a minimum of 10 seconds	Confirm requirement satisfaction in flight simulations	Vehicle simulating to Mach 1.2 for 26 seconds and Mach 1.7 for 10 seconds	8	Validate simulation vs reality in subscale flights, improve ballistic coefficient to achieve higher Mach number
Collins	Shall	Recover intact and without damage to Air Data Computer (ADC)	Confirm that max simulated deceleration in flight is lower than rated value (8 G's)	Max simulated deceleration in flight is 20 G's	4	Changing drogue chute dimensions or implementing a sliding ring to reduce shock load on system
Collins	Shall	Maintain ±0.02 Mach reference accuracy	Demonstrate capability under nonlinear simulation	current controller shows roughly 6 seconds of ±0.02 mach reference trajectory	6	Revisit other controller options, redesign air brakes to increase control authority and track Mach more accurately
Collins	Shall	Log and store all collected air data in flight	Custom avionics shall store all flight data and not overwrite while vehicle awaits recovery	Commercial units onboard storage is sufficient for flight time, ensure that checklist between flights verifies that prior flight data has been saved and cleared to ensure no loss of data	9	Perform lifetime testing to ensure full length data collection and battery life
Collins	Will	Ascend to drop altitude by a standard weather balloon or balloon cluster	Ensure that balloon selection has specification to raise vehicle mass (167.5 lb) to target apogee (100k ft)	Each of 12 balloons has the ability to lift a max of 18 lb at the rate of 320 m/min. Total lift capacity = 216 lb = 1.28x Vehicle weight. Burst altitude = 118k - 130k ft	10	Must have a flight test to ensure criteria is met

RVTM – Derived Requirements (1/2)

Source	Keyword	Description	Criteria	Status	Solution Rating (1-10)	Notes / Future Plans
Team	Shall	Deploy recovery hardware in all flight scenarios	Determine whether our separation method is sufficient to separate vehicle at apogee and in side loading cases, and that vehicle is not passively stable if parachutes do not deploy	Developed deployment methods meant for high dynamic pressure conditions, and vehicle is passively unstable after main separation point	9	Do ground testing of deployment methods for validation
Team	Shall	Maintain structural integrity through course of operation	Determine SF under both max dynamic pressure as well as max recovery deployment forces	FEA simuations preformed for ciritial structural components, results indicate acceptable saftey margin to failure	10	Stress test flight critical components to ensure strength when manufactured
Team	Shall	Ensure onboard batteries & electronics do not overheat or fall below operating temperatures	Batteries and electronics stay within operational temperature ranges specified by manufacturer in stratospheric conditions	Heating systems designed for batteries, avionics, and other temperature-sensitive systems	7	Environmental testing required to verify the ability of the heaters to maintain temperatures in an accaptable range throughout the flight envelope
Team	Shall	Transmit its location to a ground station for recovery	Vehicle shall have redundant GPS trackers on board	Vehicle has two commercial GPS flight computers and GPS on our custom avionics suite	10	Confirm GPS reacquisition after recovery deployment
Team	Will	Stabilize to a vertical orientation without offset	Veichle shall implent Robust Feedback Control	3x3 attitude regulator designed using Mu-Synthesis maintains vertical orientation	10	Validate controller performance through flight testing
Team	Will	Maintain robust stability in attitude tracking	Closed loop system maintains stability under expected density variation and to unstructured uncertainty of 20%	Robust stability demonstrated by wost case disk margins	10	Validate controller performance through flight testing

RVTM – Derived Requirements (2/2)

Source	Keyword	Description	Criteria	Status	Solution Rating (1-10)	Notes / Future Plans
Team	Will	Provide heating to the boom probe to allow for proper functionality	In stratospheric conditions, ensure that the probe can be heated from ambient temperature to above 0 C within 2.5 minutes of activating the heating element	Heaing system integrated into test payload, power electronics for the payload designed to accomadate max current load imposed by heating system and other electronics with saftey margin	4	Testing required to verify ability to sustain max loads under flight conitions for an acceptable time window
Team	Will	Have onsite flight reset capability	Vehicle systems shall be rapidly replaceable and utilize minimal single-use components, minimize inspection requirments between flights	Single use components are separation charges and boom probe, parachutes will need to be repacked and control systems tested to validate continued functionality	8	Multiple vehicles on site that have the capability of being fitted with the ADC and new boom probe, charges, and parachutes seems more viable for multiple flights in a given day
Team	Should	Maintain robust performance in attitude tracking	Structured singular value < 1 for uncertain perturbation >25% at all freqeuncies	Mu-Synthesis achieves closed loop performance of 0.343	10	Validate controller performance through flight testing
Team	Should	Achieve speeds of up to Mach 1.5 and maintain for 10 seconds during flight	Determine time above Mach 1.5 without controller input and then determine if the controller can hold selected Mach number	At current design, airbrakes can afford 7 seconds of mach 1.5	7	increasing size of airbrakes will allow longer time in flight regime

Approach

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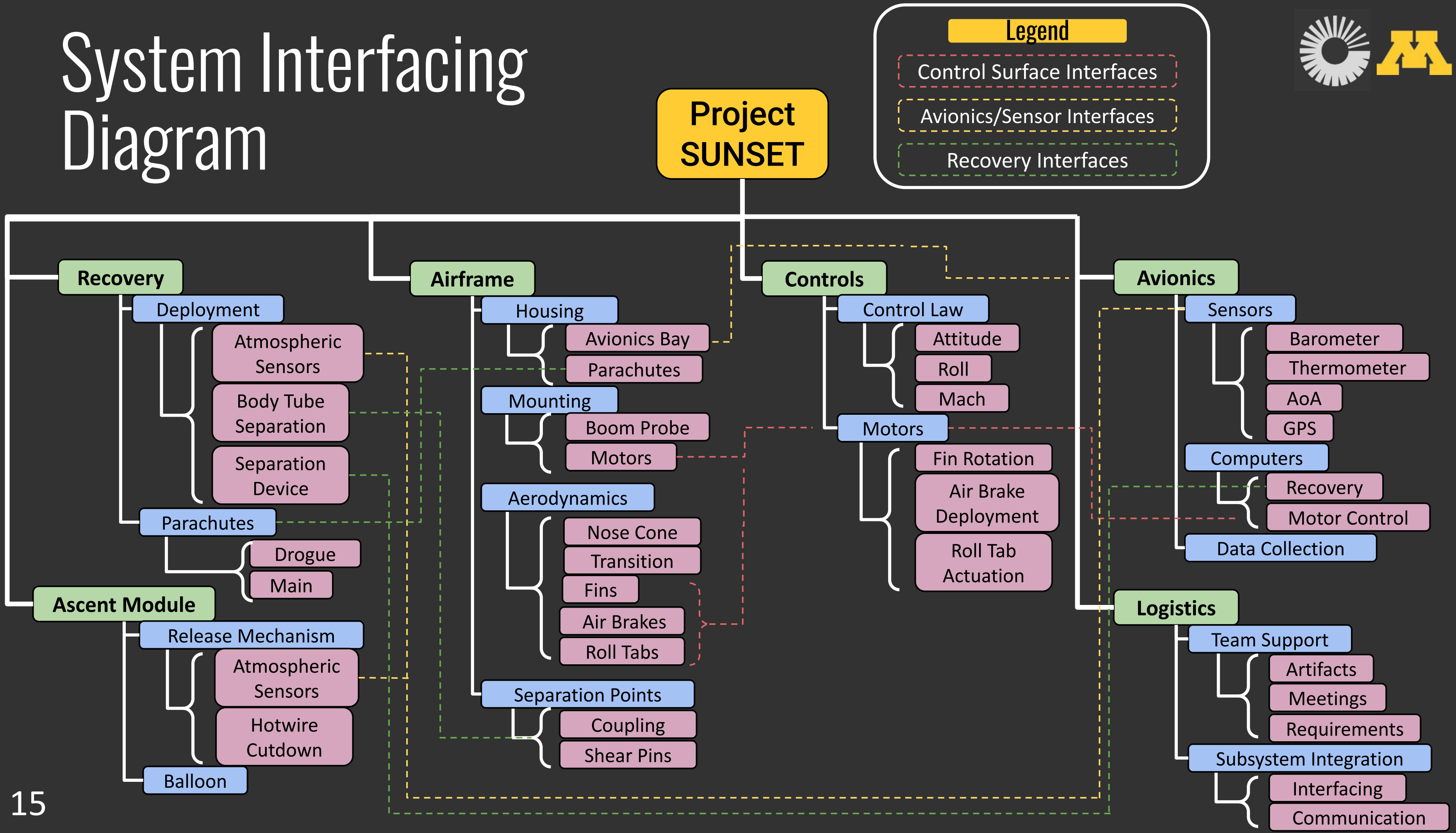
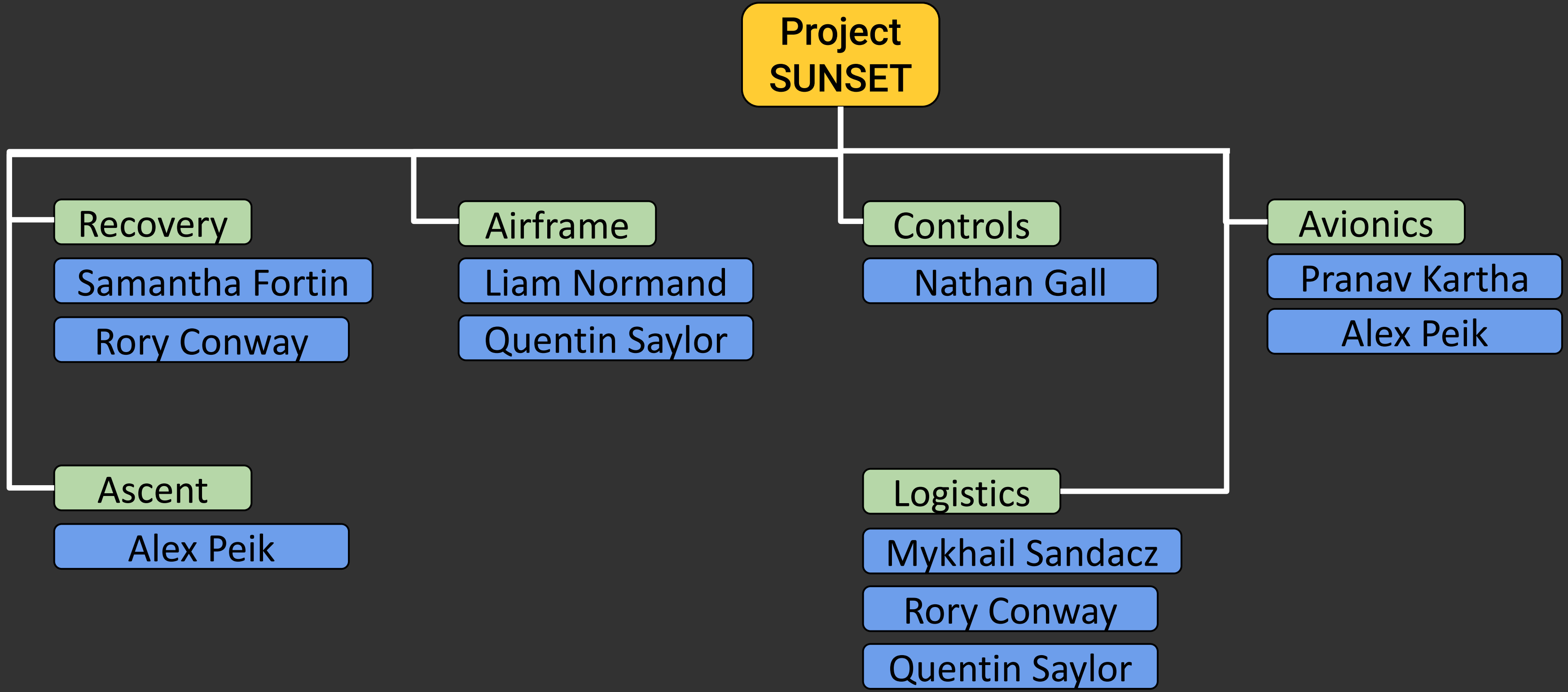
Technical Approach

- Preliminary research
  - Reading of documentation and academic papers and conducting trade studies
- Design work conducted through CAD
- Analysis performed primarily via flight and structural simulation
- Communication and collaboration within team
  - Weekly integration meetings to discuss progress and keep everybody up to date
  - Full team worktimes as needed for ease of collaboration

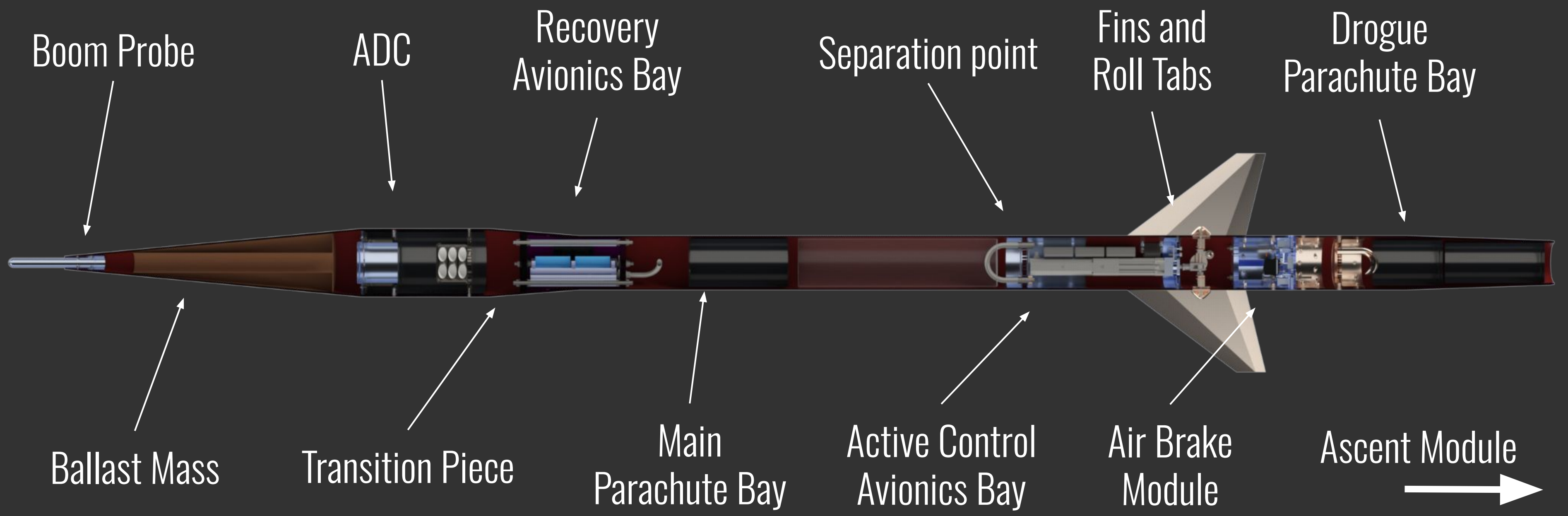
System Interfacing Diagram



Team Organization



Subsystem Overview



Detailed Design Walkthrough

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Ascent Module

- 12 x 18 lb Lift helium weather balloons
  - FOS = 1.28 for 216 lb available lift
  - Model: Kaymont HAB-4000 Latex
- ¼" Nylon rope external to vehicle
- ¼" Dyneema rope inside vehicle
  - Cable raceway → Parachute anchor
- Ascent time = 95.25 minutes
  - 320 m/min

Ascent Module: Dispersion

Simple Dispersion Estimate:

- Estimated balloon drift = 114 km (West)
- Drift before release ~ 45 km (West)

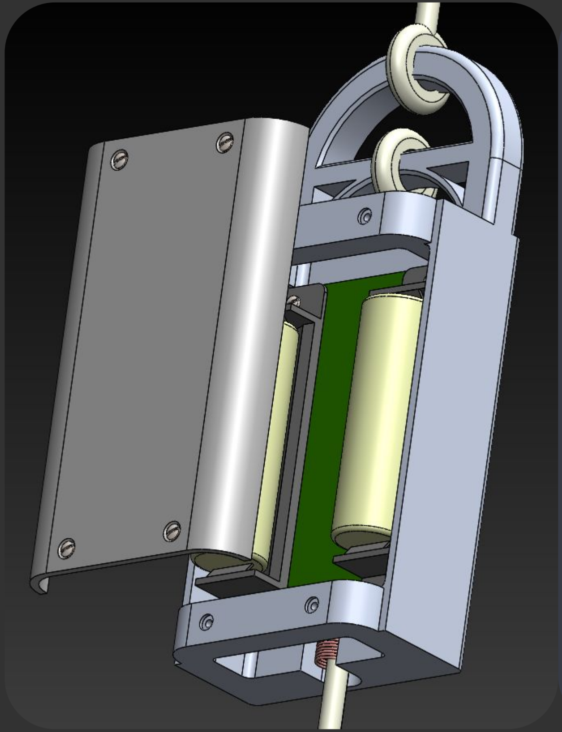
Launch Site: Black Rock NV (41 lon. , -119 lat.)

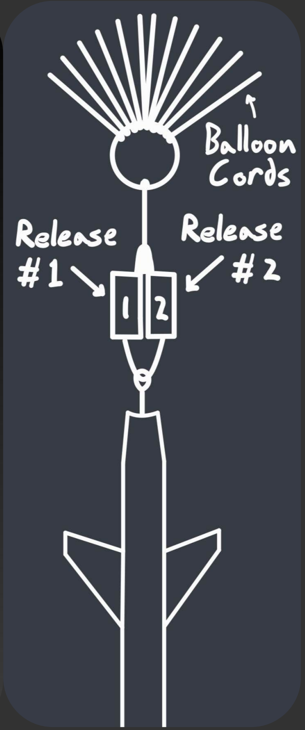
Launch Date: 12/11/2024

Estimate software credit: Stratoflights

Release System

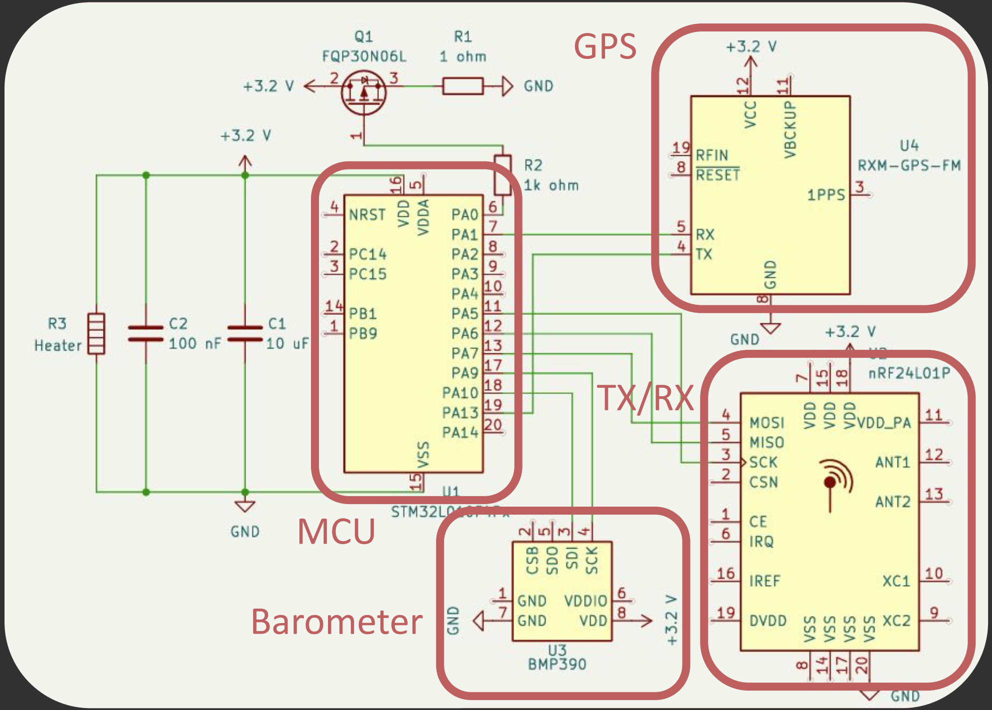
- Tied to O-ring which joins balloons (top rung)
- Rope joining 2 redundant units (lower rung)
  - Led through nichrome wire
- Drop altitude = 100,000 ft
- Wire heated to 250 °C to melt joining loop
- Loop approx. 2” from vehicle tail
- Vehicle & release system weight = 168.9 lbs



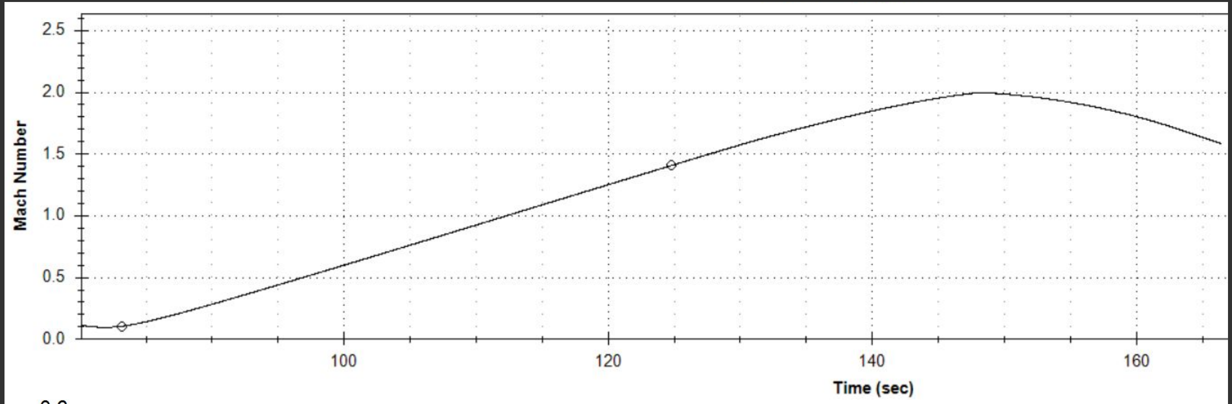


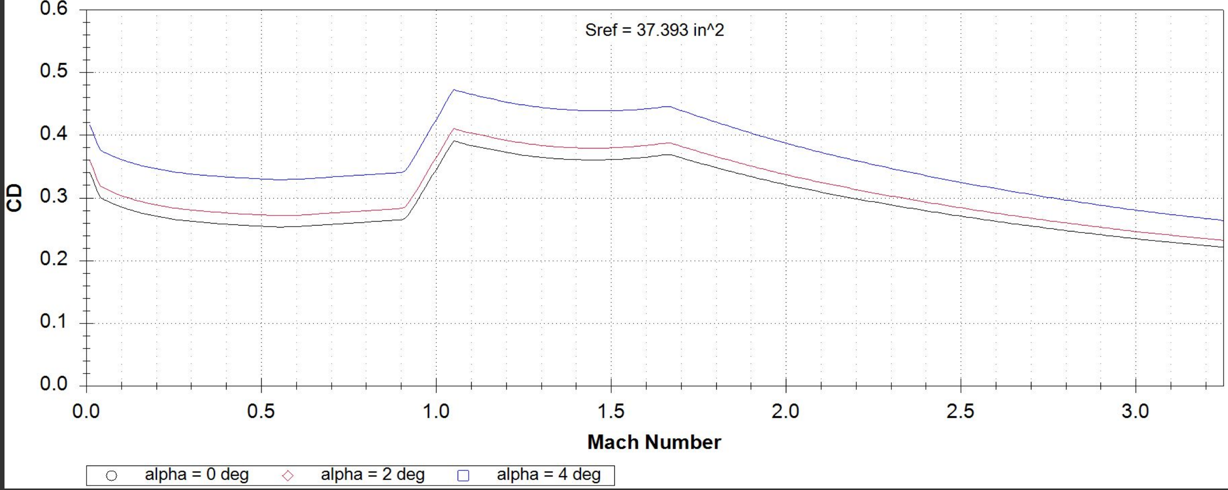
Release System: Avionics

- GPS Module
- Barometer
- Microcontroller
- 2x 3.2V Lithium battery
- Resistive Heater
- Wireless Transceiver
    - Redundancy

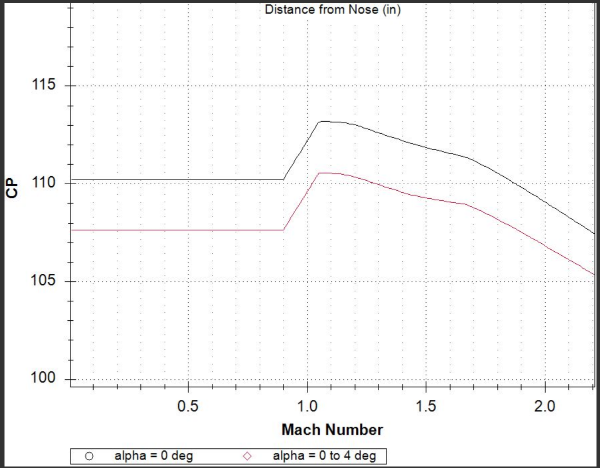


Ballistic Simulation in RasAero





	Minimum Static Margin (Caliber)	Minimum Static Margin (Percentage)
RasAero Result	3.99	17.9%
OpenRocket Result	3.40	15.3%



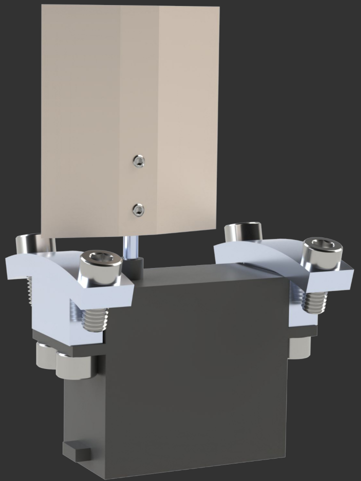
Airframe: Structural Design

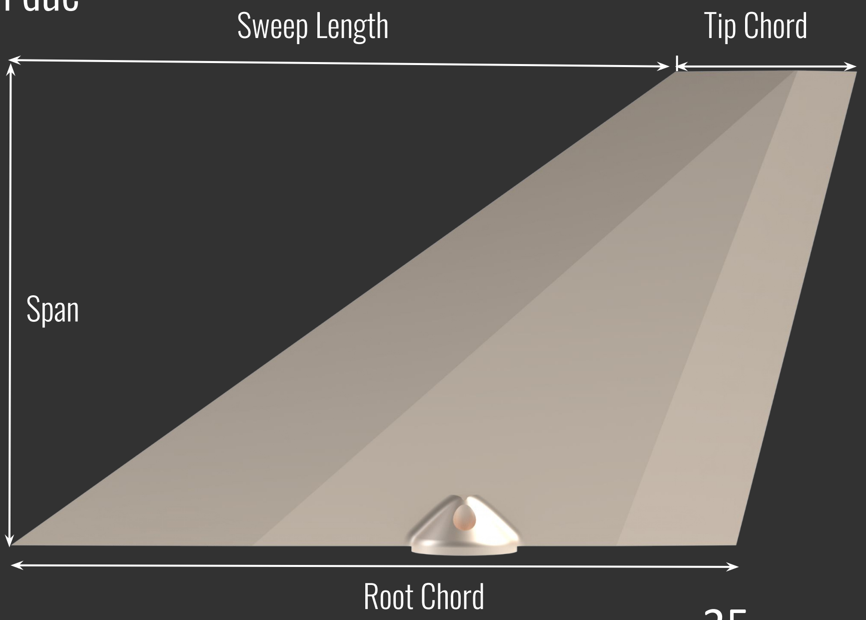
- Fiberglass composite airframe with 4:1 conical nose cone
- Bolted connections for body tube section coupling
- Extended tail cone for drag reduction
- Steel fins with hexagonal profile
- Aft-end airbrakes

Control Surface Design

- Fins sized and positioned to provide passive stability to vehicle
- Roll tabs have small impact on static stability margin due to smaller size

	Fins	Roll Tabs
Root Chord	12 in.	1.5 in.
Tip Chord	3 in.	1.5 in.
Span	8.25 in.	2 in.
Sweep Length	11 in.	0 in.
Thickness	0.25 in.	0.25 in.



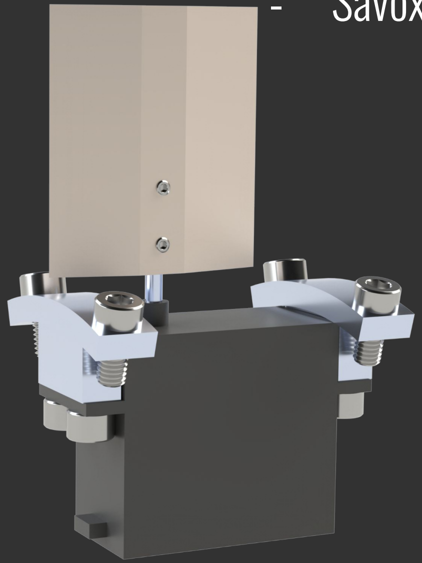


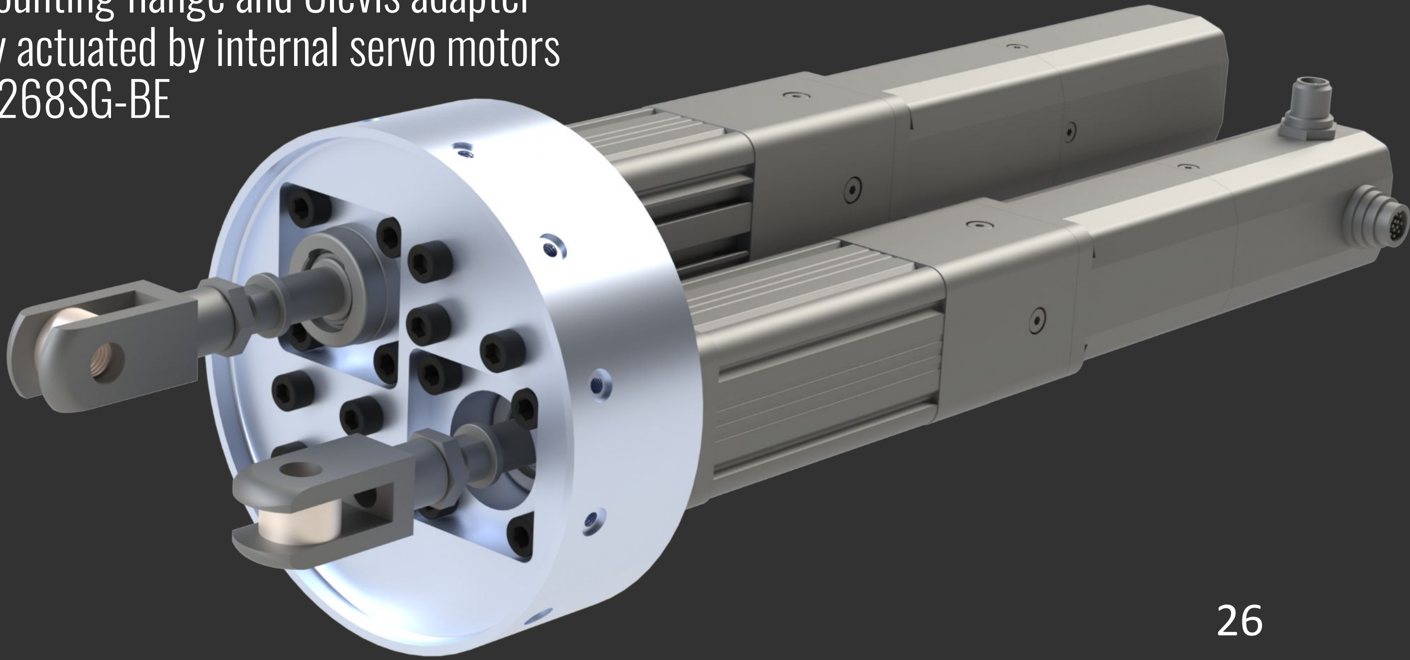
Full-Fin Actuators

- Ewellix CASM-32-BS Linear Actuators chosen for high speed operation of mechanically coupled pitch and yaw fin sets
  - Custom mounting flange and Clevis adapter
- Roll tabs directly actuated by internal servo motors
  - Savox SC1268SG-BE

Company	Ewellix
Description	CASM linear units
Part No.	CASM-32-BS-0020AA-0000 BG45X30PI ZBE-375570 ZBE-375510-32-E
Type	CASM
Size[mm]	32
Motor shape	Standard
Screw Type	Ball screw
Speed	Slow
Stroke (S)[mm]	20

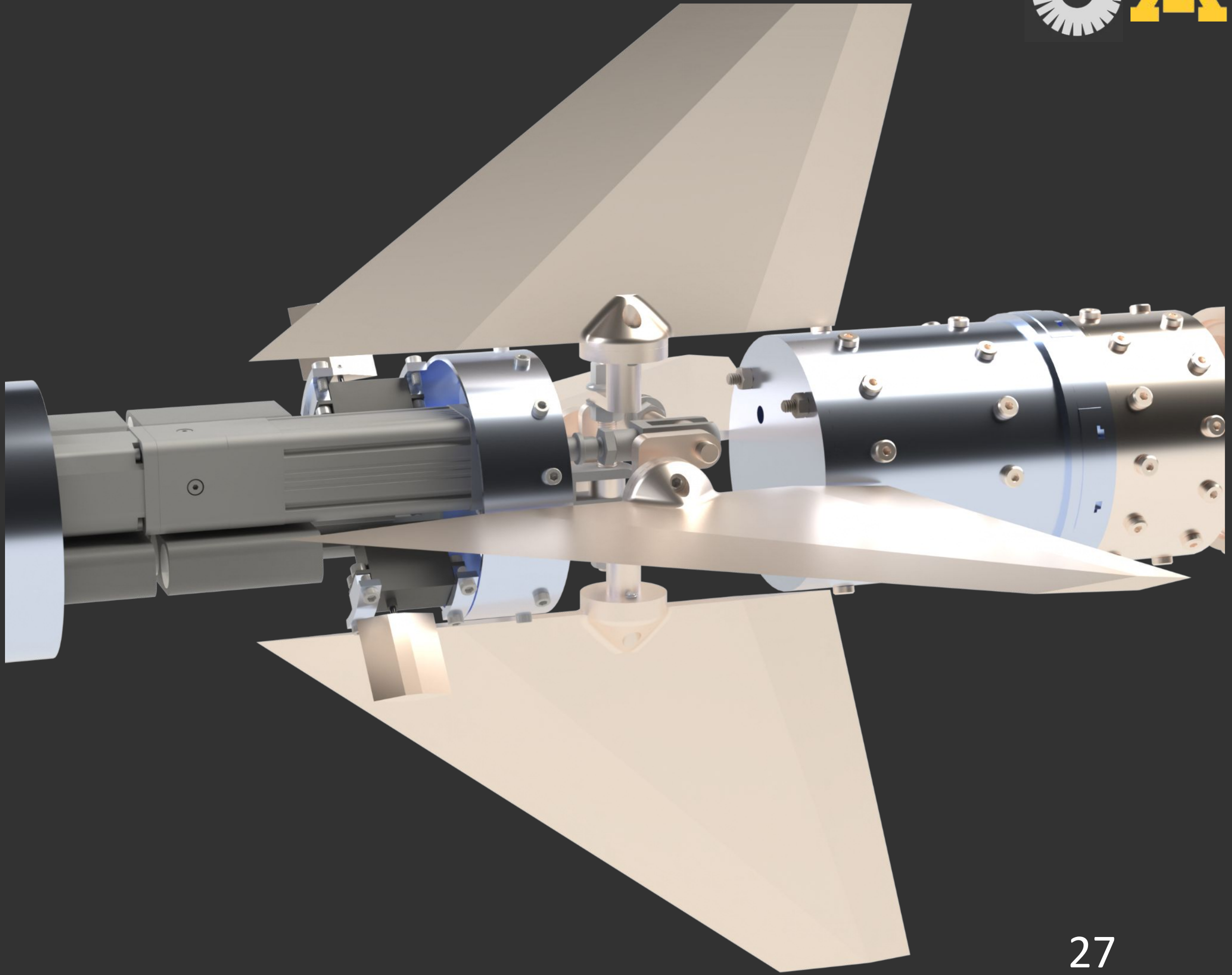
Specifications from Ewellix Catalog





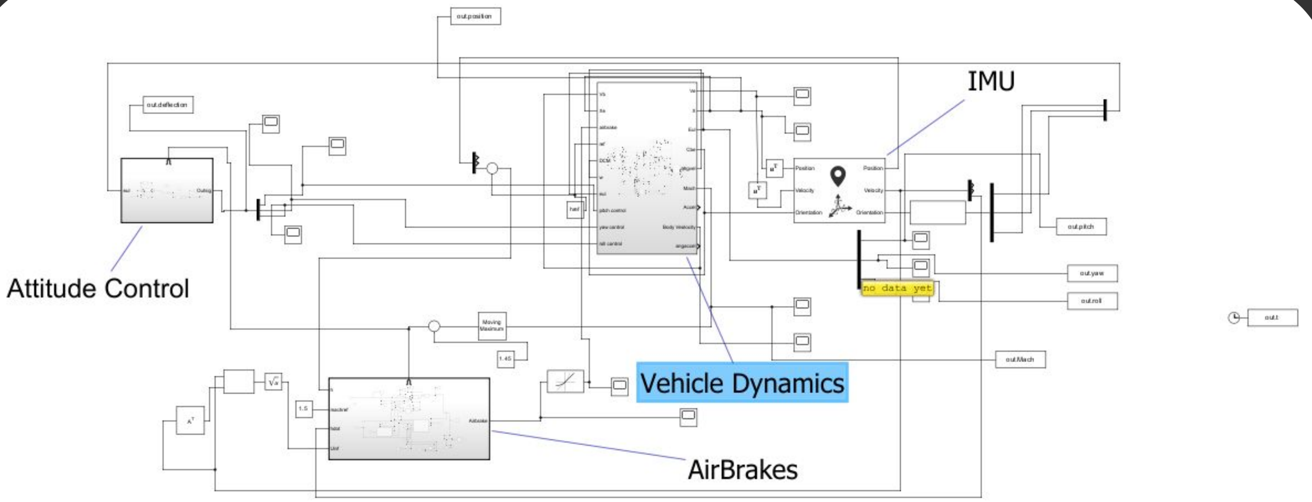
Control Bay

- Fully steel linkages
  - Reduces risk of binding or loosening from thermal expansion
- Batteries located parallel to servos for volume efficiency
- Motor controllers and wiring not shown in this render



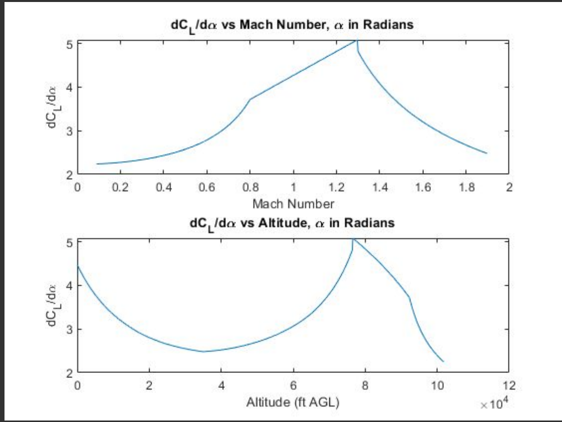
Dynamic Simulation

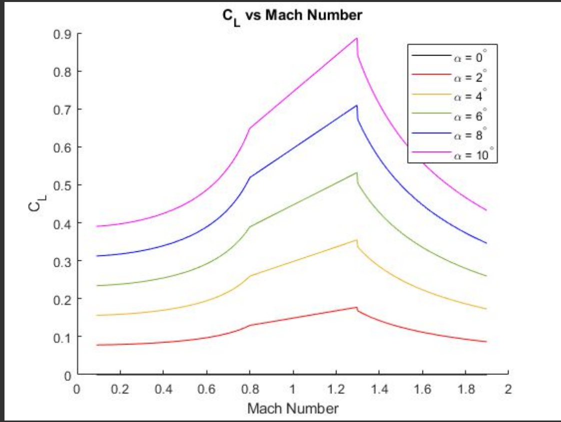
- 6 DOF rigid body
- Aerodynamics from RasAero
- Turbulence and Wind
- Control Loops

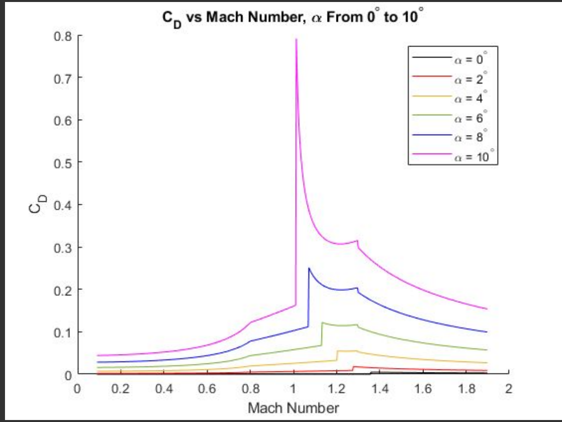


Attitude Control: Force Predictions

- MATLAB: C_L and C_D for fins and roll tabs
  - Inviscid, compressible aerodynamic model
- Model is limited, but capable of providing results sufficient for initial design
- Values used to determine parameters for control design and loads for structural analysis

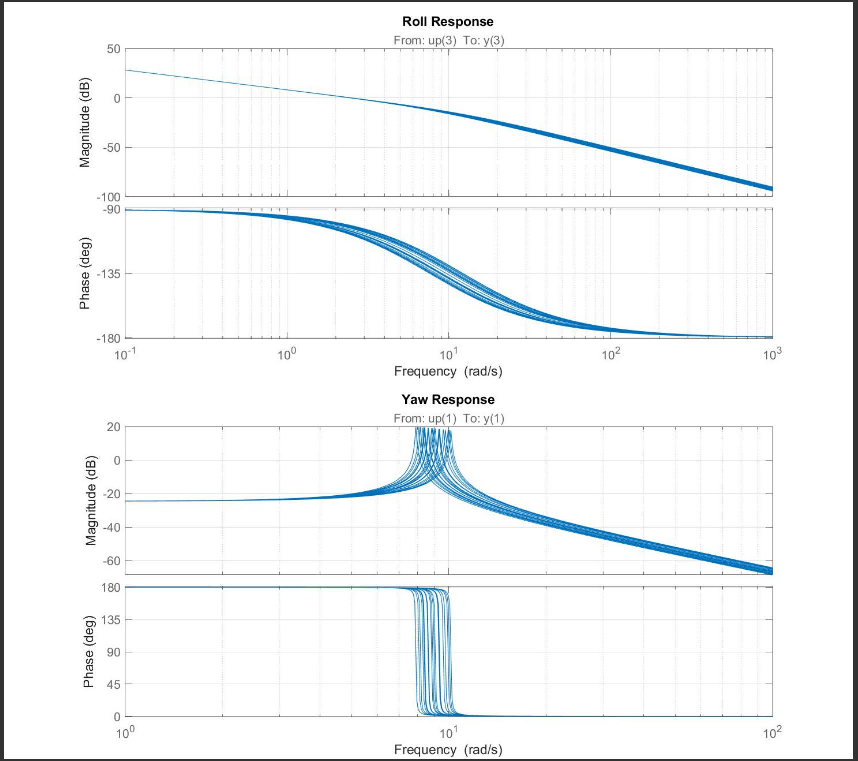






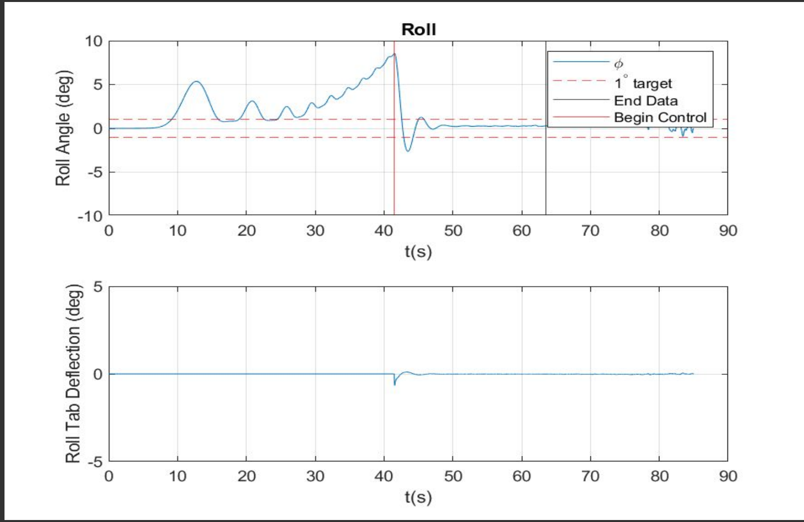
Attitude Control: Linearized Model

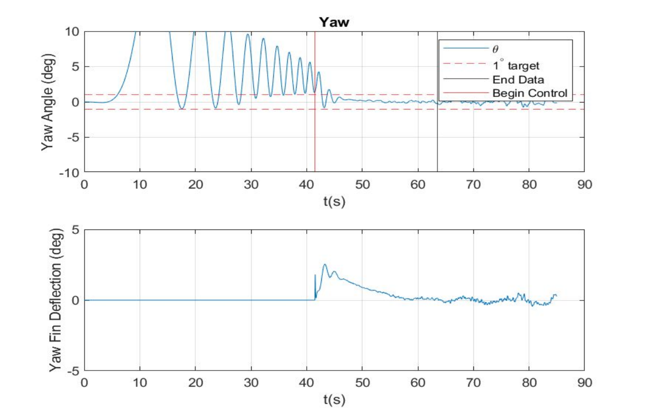
- Second order linear model
- Subject to unstructured perturbation
    - 25% at low frequencies to 40% at high frequencies
    - Bounds effect of density variation and unmodeled coupling
- Disturbances assumed low frequency from Kolmogorov spectrum
- Closed-Loop system achieved robust stability margins

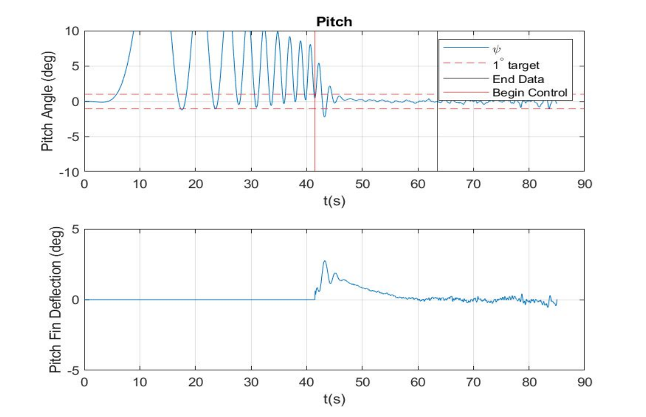


Attitude Control: Performance Under Moderate Turbulence

Control Initiated at Mach 1.45



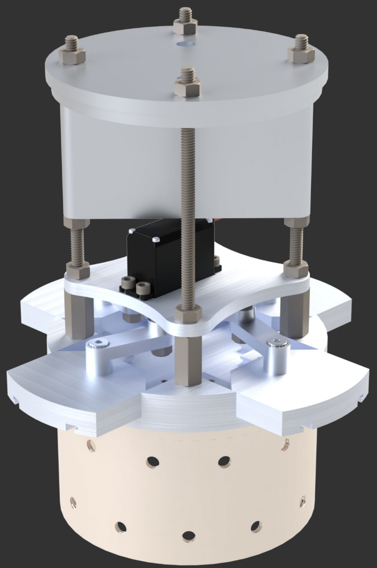




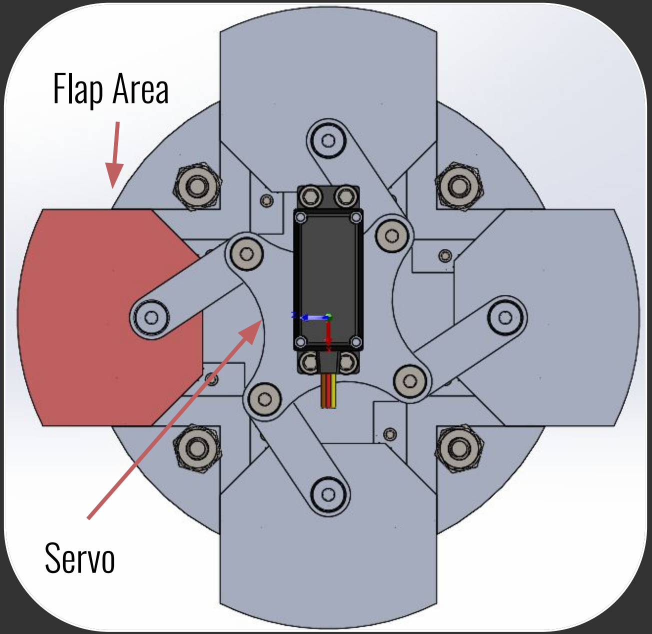
Air brakes: Overview

- Located aft of fins
- Utilizes same servos as as roll tabs
- 12 in^2 total
    - 3.075 in^2 per flap
- Threaded rods transfer loads through airframe

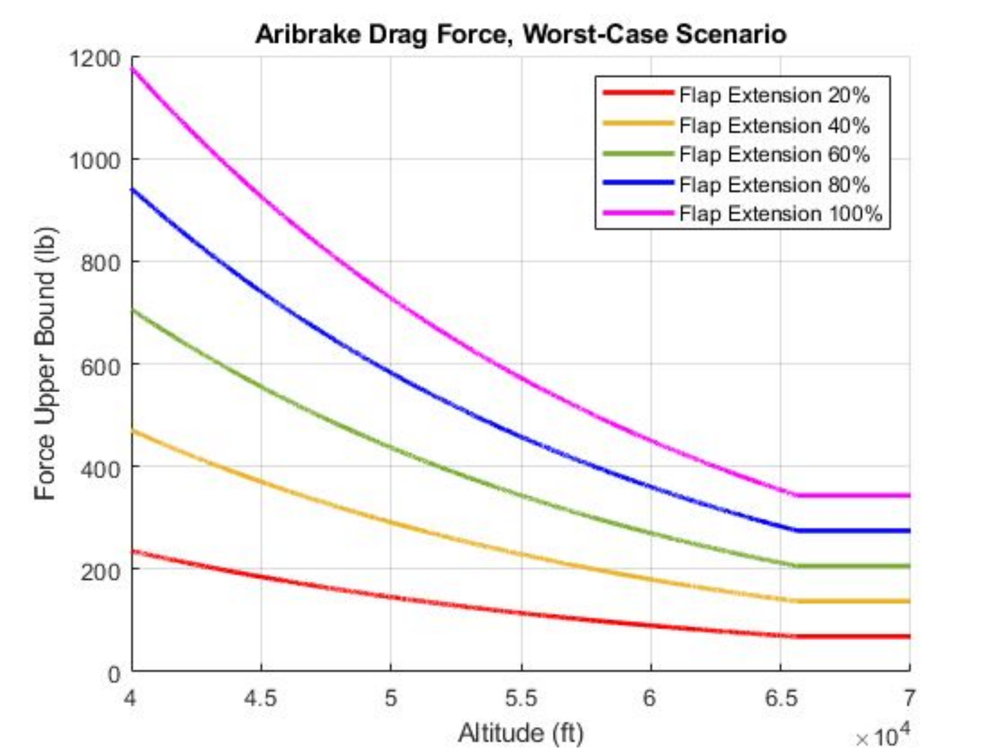
Air Brake Module



Mechanism Top Down View



Air brakes: Aerodynamic Forces

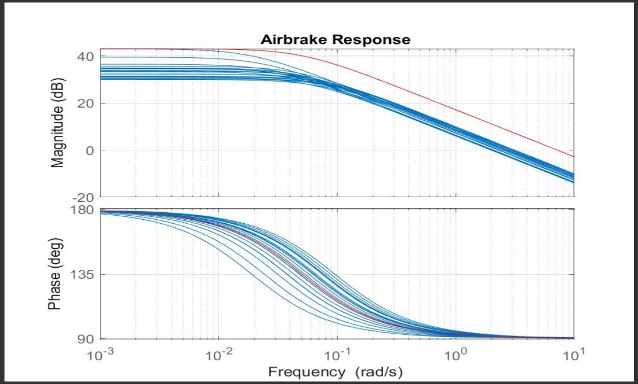


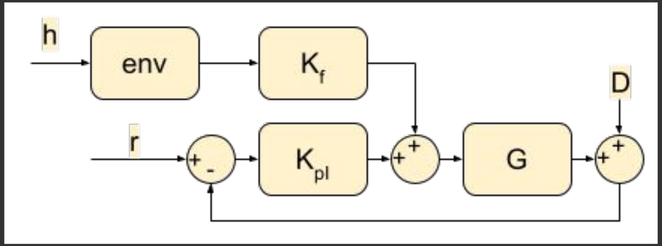
*Forces corrected based on consultation with Joseph Hoang

- Component C_D of 1.28
- 1177 lbs max force per flap
    - Overestimate for structural analysis
    - Worst-case scenario forces
    - May not be as precise as attitude control predictions

Air Brakes: Mach Tracking Controller

- 2 DOF design (FeedForward + Feedback)
- Linearizing about desired mach number
- Feedforward
  - Input altitude to ISA model
  - Solves for air brake actuation to cancel out nominal offset at Mach 1.5
- Feedback
  - Proportional Integral controller
  - Designed around largest possible gain across nominal flight conditions
  - Use Internal Model Control tuning rules for first-order time delay systems in Postlethwaite & Skogestad (2005)



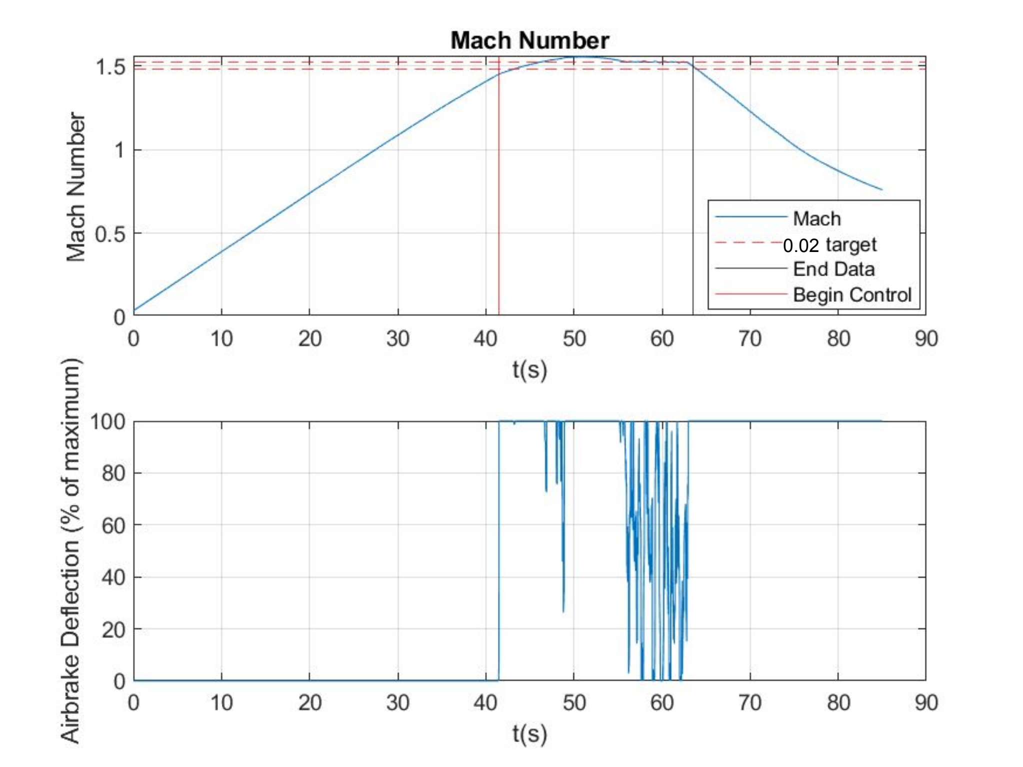


Air Brakes: Mach Tracking Controller

Proportional Gain: -2.2944

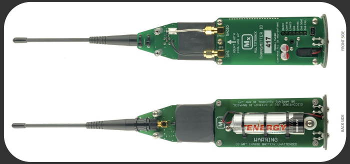
Integral Gain: -0.4780

- Design over gain bound promotes robustness
- Tested using rigid body simulation
  - Sensor Noise
  - Output Noise
  - Control signal delay 0.2s
- Control turned on at mach 1.45 (feedforward) and 1.48 (feedback)

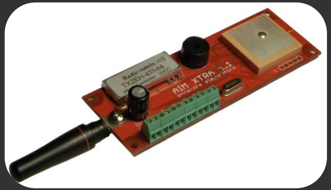


Avionics: Overview

Recovery and Location Transmission



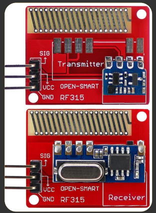
Kate-3



AIM XTRA GPS

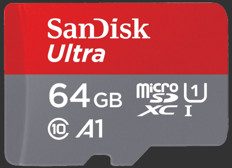
Data Logging and Telemetry

GNSS/INS



RF Transmitter

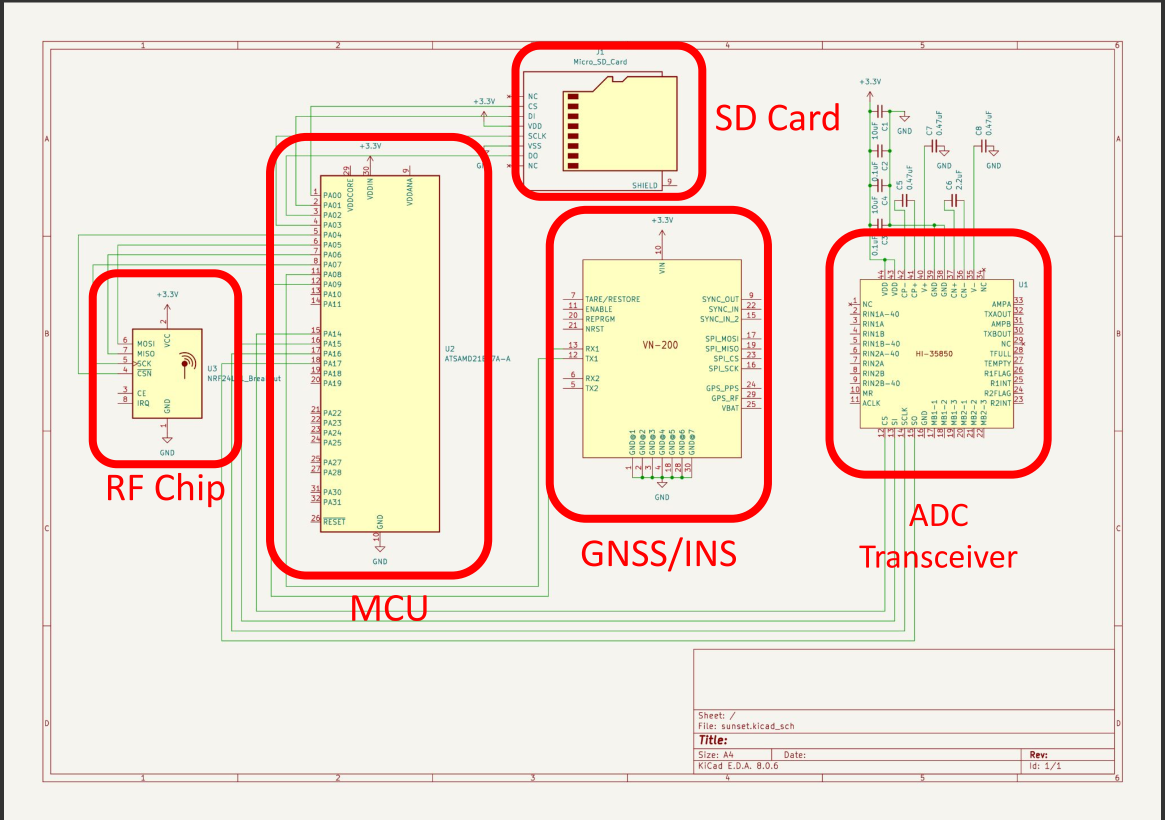
Microcontroller



MicroSD card

ADC

Avionics: Wiring



Avionics: Microcontroller/Interface

Microchip SAMD21RT

- Radiation tolerant MCU
- 48 MHz maximum clock speed
- Serial communication
- Operating temps: -40º C to 85º C

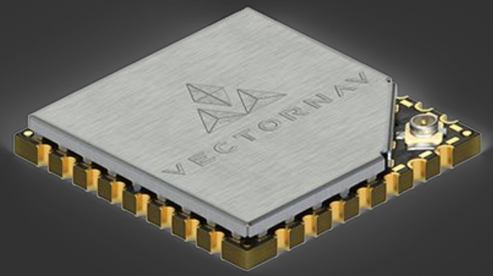
Holt IC HI-35930

- ARINC 429 transceiver for ADC
- SPI interface
- Operating temps: -40º C to 85º C

Avionics: Mach Reference/Controls Sensor

VectorNav VN-200

- GNSS/INS
  - External antenna
- 400 Hz data rate
- Operating temps: -40° C to 85° C
- Dynamic pitch/roll accuracy: 0.03°
- Dynamic heading accuracy: 0.2°
- **Velocity accuracy: 0.05 m/s**
  - **Calculated Mach accuracy: 0.005**



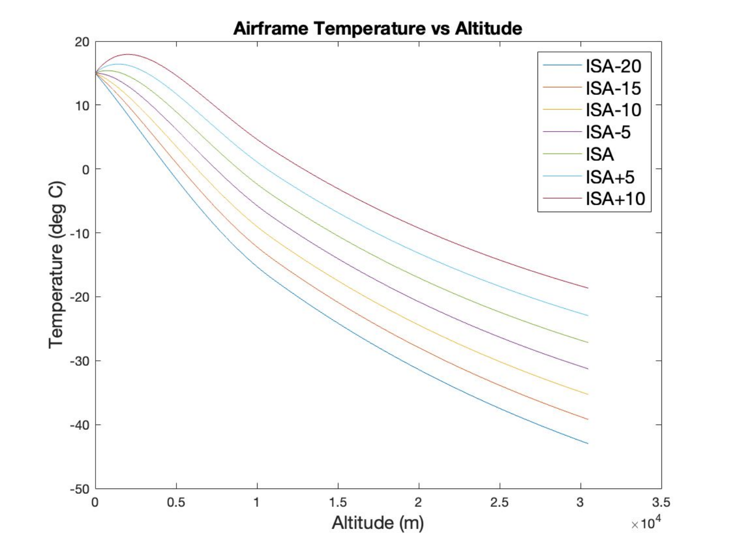
Thermal Analysis

Results

- Minimum airframe temperature reached at ISA-20: **-43º C**
  - Heating or insulation required
- Peak stagnation temperature achieved at maximum Mach number in ISA+15: **77º C**
  - Held for a few seconds

Assumptions/approximations:

- Constant ascent rate of 5 m/s
- Stagnation point temperature at maximum Mach number used as conservative upper bound for temperature



Ascent temperature vs time for various ISA deviations

Thermal Analysis: Insulation and Heating

Low emissivity coating: LO/MIT II

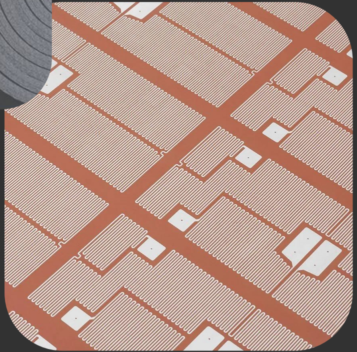
- Minimize radiative cooling
- Emissivity: 0.160-0.190
- Reflectivity: 82-86%

Aerofoam XLPE Polyolefin Insulation

- Conductive insulation
- Conductivity: 0.035 W/mK

CHR Custom Flexible Rubber Heaters

- Silicone heaters that can be adhesively attached to low-temp sensitive electrical components
- 15W at 12V



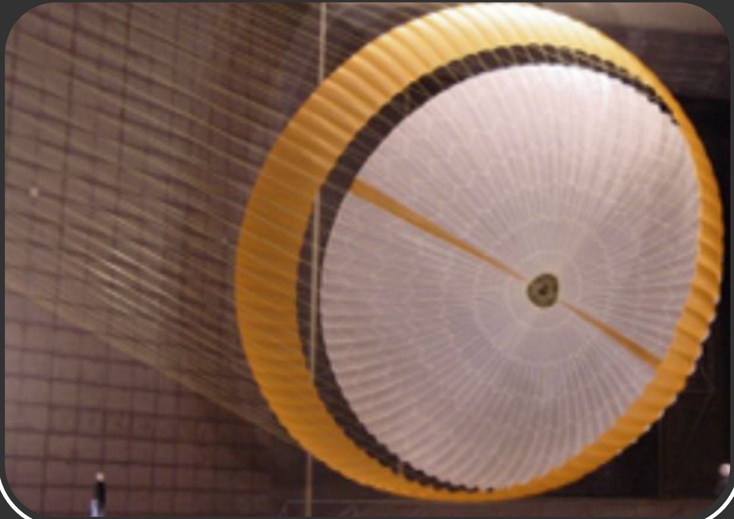
Recovery Systems: Overview

Drogue

- Conical Ribbon
- Deploys out of tail cone
- Made for supersonic deployment
- Limits shock loading

Main

- Disk-Gap-Band
- Deploys after airframe separation
- Final recovery system



Source: https://blog.gridpro.com/supersonic-parachutes-for-reentry-vehicles/

Recovery Systems: Deployment

Drogue: Drogue "slug" gun deployment

- Compressed gas to release dense slug that ejects parachute
- High ejection velocity
- Medium reaction force upon ejection
- High system weight

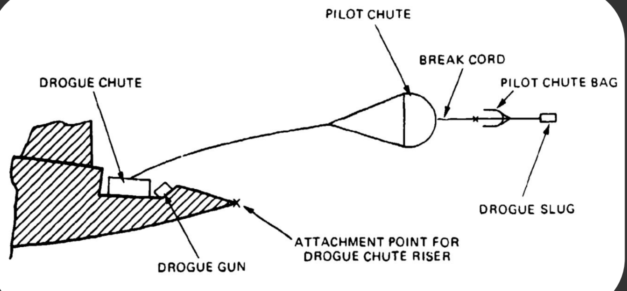


FIGURE 6-6. Drogue Gun Deployment.

Source: T.W. Knacke. (1991). Parachute Recovery Systems Design Manual.

Main: Mortar system deployment

- Effective at quickly moving parachute into positive airflow
- High ejection velocity
- High system weight
- Large reaction force upon ejection
- Reliable

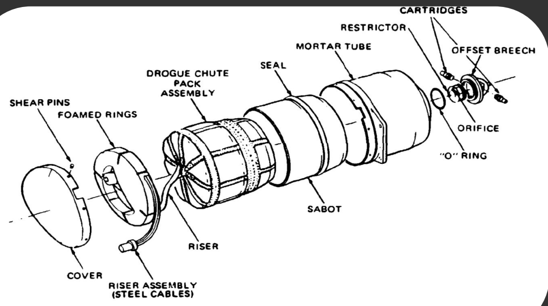


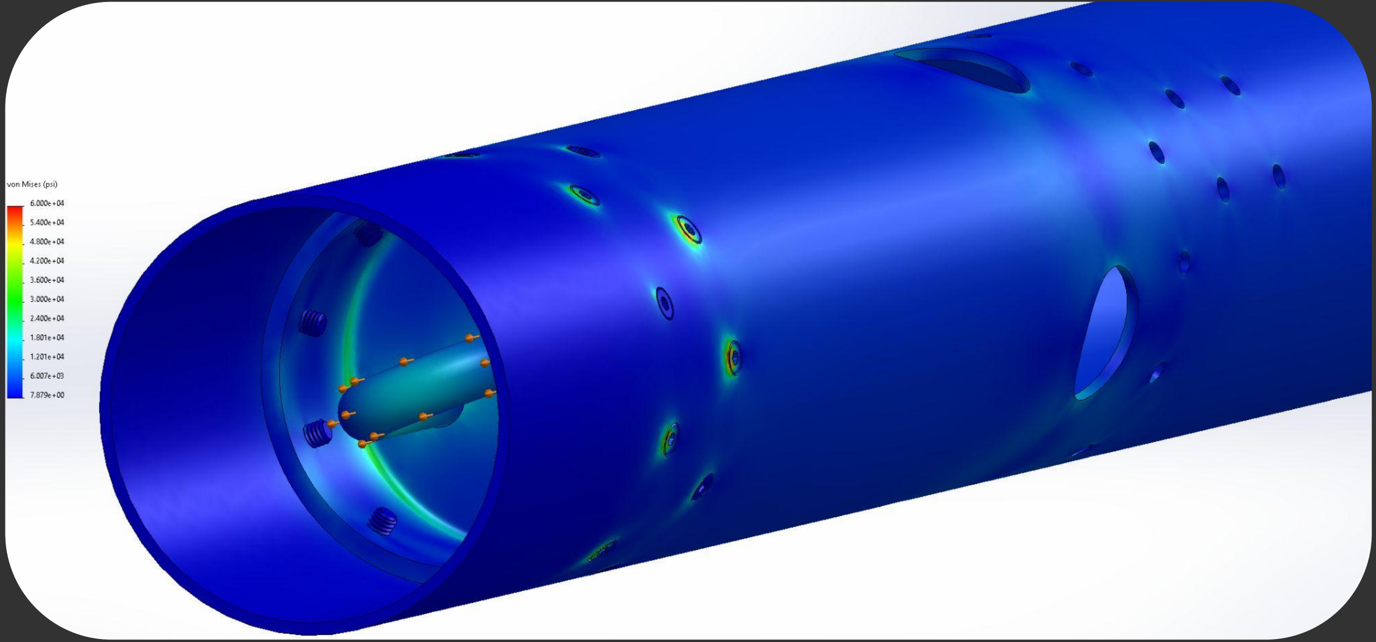
FIGURE 6-8. Mortar Assembly of the Apollo Drogue Chutes.

Source: T.W. Knacke. (1991). Parachute Recovery Systems Design Manual.

Airframe Structure: Drogue Attachment

Drogue Deployment Shock Force– 10,000 lbf simulated load for 3 factor of safety

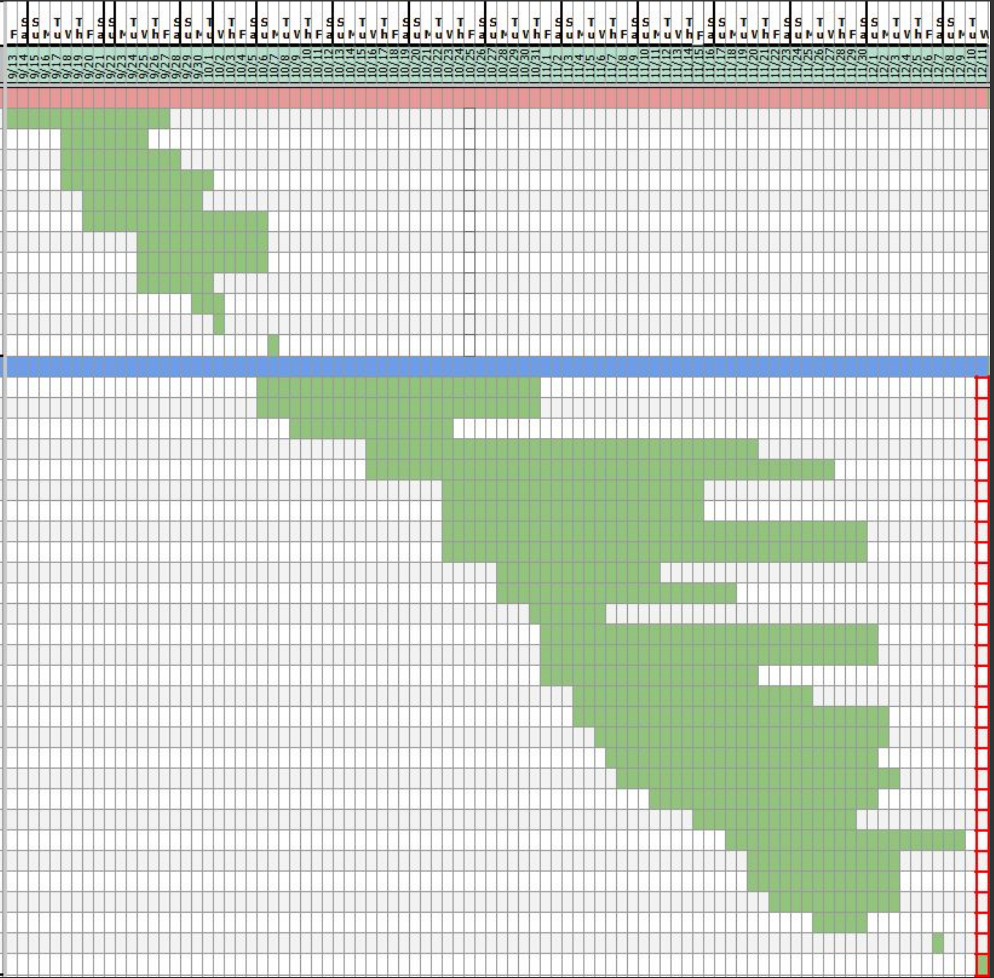
- Looking for effect on body tube, stress around aft fin cutouts, and bolt bearing



Project Plan

Project Schedule

Task name	Start date	End date	Assigned
Phase 1			
Preliminary Research	9/12	9/27	All
Establish Subsystems	9/18	9/25	All
Determine System Interfaces	9/18	9/28	Rory
Balloon sep Mechanism	9/18	10/1	Alex
Trade Studies	9/20	9/30	All
CAD Modelling	9/20	10/6	Liam
PDR Slides	9/25	10/6	All
CONOPS	9/25	10/6	Sam
Parachute Parameters	9/25	10/1	Sam
Mounting Mechanism	9/30	10/2	Liam
Instructor PDR	10/2	10/2	All
PDR	10/7	10/7	All
Phase 2			
Mechanism: Attitude Control	10/6	10/31	Quentin
Mechanism: Airbrakes	10/6	10/31	Myki
Integration of Avionics systems	10/9	10/23	Pranav
Integrated CAD	10/16	11/20	Liam
Trajectory Simulations	10/16	11/27	Nathan
Structural Sims Airframe	10/23	11/15	Liam
Finalize Airframe Design	10/23	11/15	Liam
Control Software: Velocity	10/23	11/20	Nathan
Control Software: Attitude	10/23	11/20	Nathan
Staging of Drogue and Main	10/28	11/11	Sam
Wiring diagrams for components	10/28	11/18	All
Structural Sims Airbrakes	10/31	11/6	Myki
Vehicle Aerodynamic Analysis	11/1	12/1	Quentin
Control Surfaces Aerodynamic Analysis	11/1	12/1	Quentin
Thermal Analysis for Batteries	11/1	11/20	Pranav
Detailed system diagram	11/4	11/25	Rory
Finalize Main and Drogue Params	11/4	12/2	Sam
Expected data accuracy	11/6	12/2	Pranav
Power usage analysis	11/7	12/1	Pranav
Calculate Parachute Opening Forces	11/8	12/3	Sam
Finalize Ascent & Release Design & CAD	11/11	12/1	Alex
Characterize Airbrakes for control	11/15	11/29	
CDR Slides	11/18	12/9	All
Prototype vs actual breakdown	11/20	12/3	Liam
Bill of Materials	11/20	12/3	Myki
Parachute Materials & Costs	11/22	12/3	Sam
Release Avionics Circuit Diagram	11/26	11/30	Alex
Parachute Deployment Avionics	12/7	12/7	Sam
CDR	12/11	12/11	All



Project schedule breakdown

Weeks 1-2
- Preliminary research, trade studies

Weeks 3-4
- CONOPS, initial design, initial CAD models, probe mounting

Weeks 5-6
- **PDR**
- Trajectory simulations, begin integrated CAD

Weeks 7-8
- Finalizing airframe, structural sims, begin control software, avionics design

Weeks 9-10
- Aerodynamic analysis, recovery staging, detailed system diagram

Weeks 11-12
- Calculate parachute forces, finalize parachute parameters, finalize ascent and release mechanism

Weeks 13-14
- Characterize control surfaces, wiring diagrams, finalize integration and control software
- **CDR**

FMEA and Safety

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Risk Assessment Severity Criteria

- Risk assessment updated from PDR to add more granularity to criteria scales
- Severity criteria value doubled in analysis tables in following slides

Numeric Scale	Severity of Event	Likelihood of Occurance	Ability to Detect
1	No effect	Extremely unlikely to occur	Certain detection
2	Loss of redundancy in non flight critical systems	Highly unlikely to occur	Easily detected
3	Loss of redundancy in flight critical systems	Unlikley to occur	Moderate chace of detection
4	Loss of function of non flight critical systems, adverse effect on mission completion	Moderatly likely to occur	Difficult to detect
5	Loss of function in flight critical systems and/or damage to vehicle or payload, loss of mission, remote risk of danger to ground crew	Likely to occur	Very difficult to detect
6	Loss of vehicle, risk of injury of ground crew or damage to ground equipment	Very likely to occur	Extremely difficult to detect
7	Catastrophic loss of vehicle, immeadete potential for death or severe injury to ground crew, or serious damage to ground objects	Almost certian to occur	Impossible to detect

Risk Assessment: FMEA Evaluation 1

Subsystem	Event	Severity	Liklehood of Occurance	Liklehood of Detection	Total Risk
Recovery	Drogue parachute failure to deploy	7	4	7	25
Recovery	Drogue parachute fails to inflate	7	3	6	23
Recovery	Main parachute fails to deploy	6	4	7	23
Recovery	Main parachute fails to inflate	5	3	6	19
Recovery	Secondary recovery telemetry and flight computer failure	3	4	5	15
Recovery	Complete telemetry system loss	6	2	4	18
Recovery	Deployment event during integration	7	1	2	17
Recovery	Premature deployment on ascent	5	3	6	19
Recovery	Premature deployment on descent, main parachute	5	3	5	18
Aerostructure	Inflight vehicle breakup	7	2	3	19
Aerostructure	Inflight aerostructure failure not leasding to a breakup	6	2	3	17
Aerostructure	Overstress event without failure	3	4	3	13
Aerostructure	Failiure of control fin retention	6	3	3	18
Aerostructure	Failure of roll tab retention	6	3	3	18
Aerostructure	Failure of airbrake flap retention	6	3	3	18

*extended analysis in appendix

Risk Assessment: FMEA Evaluation 2

Subsystem	Event	Severity	Liklehood of Occurance	Liklehood of Detection	Total Risk
Control Hardware	Failure of fin actuators in neutral position	4	3	2	13
Control Hardware	Failure of fin actuators in deflected positoin	5	4	2	16
Control Hardware	Failure of roll tabs in neutral position	4	3	2	13
Control Hardware	Failure of roll tabs in deflected position	5	4	2	16
Control Hardware	Failure of airbrake actuators	5	3	3	16
Control Hardware	Inability of fins/roll tabs to comply with controller actuation commands	4	3	4	15
Control Hardware	Inability of airbrakes to comply with controller commands	5	3	4	17
Control Software	Inability of controller to restore attitude reference	4	2	2	12
Control Software	Inability of controller to restore attitude reference	5	2	2	14
Control Software	Controller sends incorrect commands to attitudfe control surfaces	5	1	2	13
Control Software	Controller sends incorrect commands to airbrakes	5	1	2	13
Data Recording and Payload Avionics	Failure to record reference data	5	3	3	16

*extended analysis in appendix

Risk Assessment: FMEA Evaluation 3

Subsystem	Event	Severity	Liklehood of Occurance	Liklehood of Detection	Total Risk
Data Recording and Payload Avionics	Failure to record air data from ADC	5	3	3	16
Data Recording and Payload Avionics	Failurre of ADC or boom probe inflight	5	3	3	16
Power Systems	Loss of power to recovery avionics, telemetry	7	3	2	19
Power Systems	Loss of power to control systems	5	3	2	15
Power Systems	Loss of power to data collection and logging systems	5	3	2	15
Power Systems	Loss of battery heating	5	2	6	18
Launch Balloon	Failure of cutdown to release vehicle	6	3	4	19
Launch Balloon	Premature cutdown system activation	5	2	5	17
Launch Balloon	Premature balloon pop	5	2	3	15
Launch Balloon	Loss of secondary telemetry, control computers	3	2	4	12
Launch Balloon	Loss of all telemetry	5	1	4	15
Launch Balloon	Loss of all telemetry and control computers	6	2	4	18

*extended analysis in appendix

Primary Flight Risks & Mitigation

Risk	**Mitigation**
Failed Parachute Deployment	Extensive Ground and Drop Testing
- Vehicle loss & Personnel danger	- Highly reliable deployment system
In-Flight Structural Failure	Simulation, Testing, and Inspection
- Vehicle loss, falling debris	- High FOS, known structural integrity
Loss of Attitude Control; Mach Tracking	Simulation and Bench Testing, Inspection
- Loss of mission, data accuracy	- Robust controller, capability of hardware
Loss of Telemetry Datalink	Redundancy and Testing of Datalink
- Tracking loss, no vehicle recovery	- Robust to failure, minimal chance of LOS

Conclusions

- Successfully designed a Mach sensor test vehicle
  - Is capable of maintaining Mach 1.5 ±0.02 for 7 seconds
  - Can hold lower Mach values for longer
  - Total of ~35 seconds of greater than Mach 1.2
- Vehicle mostly satisfies customer requirements
  - ADC experiences ~20 Gs
    - Further design must be done to reduce G loading to 8
  - Maintains attitude during data collection
- Failure modes and safety issues were addressed, and the vehicle could move to build and test phase

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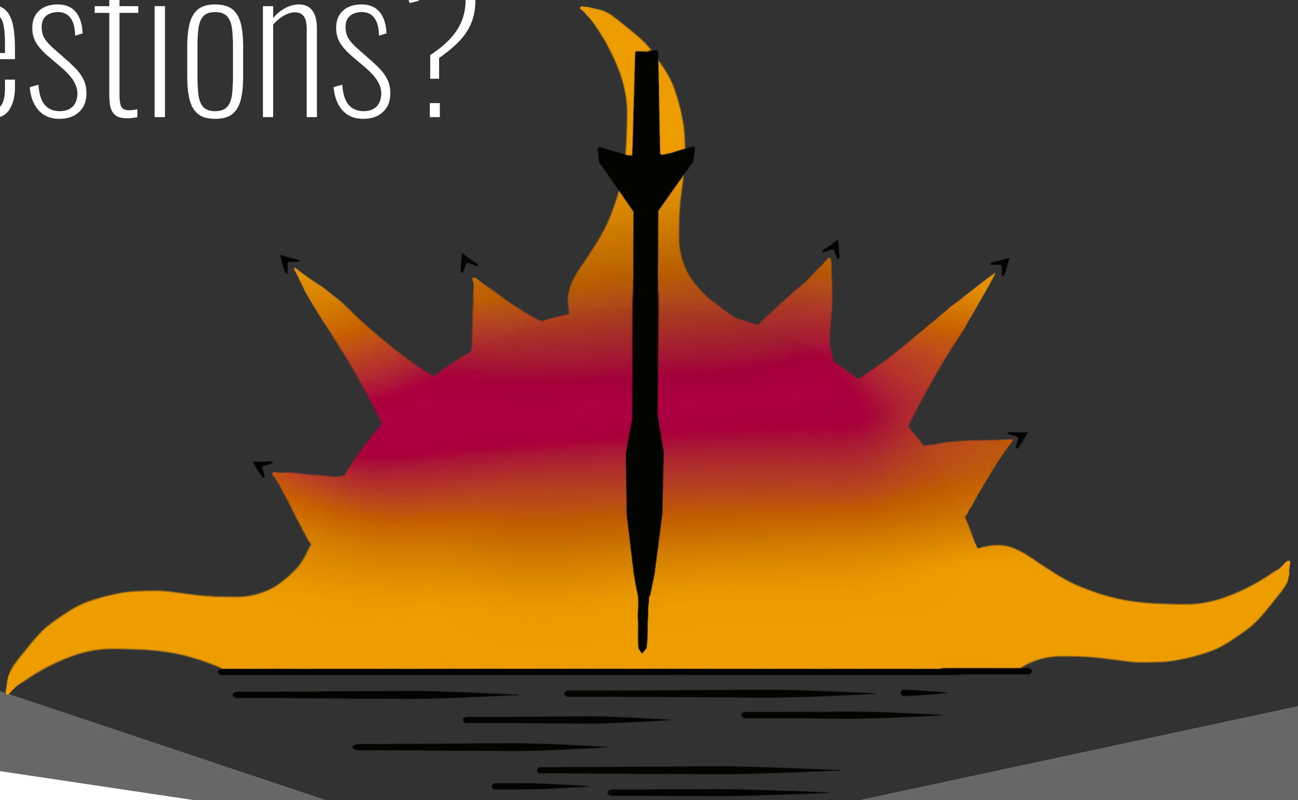
Questions?



Appendix

- Build and Test Campaign
- Extended FMEA
- Bill of Materials
- Backup Slides

Build and Test Campaign

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Preliminary Build Schedule: Gantt Chart

- Includes build and test phases, BRR, FRR, flight test
- Preliminary schedule, subject to change as needed

Task name	Start date	End date
Phase 3		
Complete Detatiled Structural Design	1/27/25	1/31/25
Complete Aerodynamic Simulations	1/27/25	2/4/25
Complete Bill of Materials	2/1/25	2/7/25
Verify Manufacturbility of Vehicle	2/1/25	2/7/25
Complete BRR Deliverables	2/6/25	2/11/25
Build Readiness Review	2/12/25	2/12/25
Implement BRR Design Feedback	2/13/25	2/16/25
Procure, Recieve Requires Materials	2/17/25	2/26/25
Implement Control Software	2/24/25	3/24/25
Manufacture Parachutes	3/1/25	3/21/25
Manufacture Structural Components	3/1/25	4/4/25
Manufacture Avionics	3/1/25	3/21/25
Test Avionics Systems	3/24/25	3/28/25
Test Recovery Systems	4/1/25	4/9/25
Test Aerodynamic Control Systems	4/7/25	4/11/25
Test Vehicle Integration	4/10/25	4/16/25
Complete FRR Deliverables	4/16/25	4/20/25
Flight Readiness Review	4/21/25	4/21/25
Implement FRR Feedback as Needed	4/22/25	4/28/25
Final Vehicle Integration	4/28/25	4/30/25
First Test Flight	5/1/25	5/1/25

Test Campaign: Ground Testing

Focus on subsystem validation

- Recovery systems
  - Ground deployment testing, drop testing from platforms or aircraft
- Aerostructure
  - Shock loading tests, material and bolt strength testing, thermal expansion testing
- Control hardware
  - Simulation, wind tunnel testing, bench testing of actuation force and freeplay
- Avionics, power systems
  - Runtime and load testing, independent tests of all avionics subsystems
- Ascent system
  - Ground testing of cutdown, telemetry avionics

Test Campaign: Flight Testing

Progressive ramp in scope and scale of flight tests

- Subscale testing: reduced altitudes and speeds
  - Open-loop test; passive stability, verification of recovery and sensing
  - Attitude control active, verification of tracking attitude reference
  - All control systems active, verification of tracking attitude and mach reference
- Full scale testing: operational altitudes and speeds
  - Similar progression to subscale testing, elimination of open-loop flights
  - Data collection test flight with known probe to verify data logging and data quality

Emphasis on verification of safe operation and ability to complete design mission

Extended FMEA

FMEA Criteria Scale

Numeric Scale	Severity of Event	Likelihood of Occurance	Ability to Detect
1	No effect	Extremely unlikely to occur	Certain detection
2	Loss of redundancy in non flight critical systems	Highly unlikely to occur	Easily detected
3	Loss of redundancy in flight critical systems	Unlikley to occur	Moderate chace of detection
4	Loss of function of non flight critical systems, adverse effect on mission completion	Moderatly likely to occur	Difficult to detect
5	Loss of function in flight critical systems and/or damage to vehicle or payload, loss of mission, remote risk of danger to ground crew	Likely to occur	Very difficult to detect
6	Loss of vehicle, risk of injury of ground crew or damage to ground equipment	Very likely to occur	Extremely difficult to detect
7	Catastrophic loss of vehicle, immeadete potential for death or severe injury to ground crew, or serious damage to ground objects	Almost certian to occur	Impossible to detect

Extended FMEA – 1

Subsystem	Event	Severity	Potenial Effects	Liklehood of Occurance	Potential Causes	Liklehood of Detection	Detection Methods	Mitigation Strategy
Recovery	Drouge parachute failure to deploy	7	Vehicle returns on ballistic trajectory, impacts gound at ~M 1.2, lethal hazard to personell near impact site	4	Improper chute packing, failure of ejection system, failure of recovery avionics, premature deployment on descent	7	Impossible to detect some failure modes, others possible with rigourous preflight inspection	Extensive ground and drop testing of deployment sequence, preflight inspection of system, keep-out zone around impact site
Recovery	Drouge parachute fails to inflate	7	Vehicle returns on ballistic trajectory, impacts gound at ~M 1.2, lethal hazard to personell near impact site	3	Improper manufacture of drouge parachute, subpar material quality, fatigue failure of chute, tangled suspension lines, premature deployment	6	Detection possible but unlikely with preflight inspection, nondestructive testing methods	High design saftey factors, preflight inspection, material testing of parachute, conservative service life limits
Recovery	Main parachute fails to deploy	6	Vehicle recovery at high speeds under drouge, vehicle shell severly damaged or destroyed	4	Improper chute packing, failure of ejection system, failure of recovery avionics	7	Impossible to detect some failure modes, others possible with rigourous preflight inspection	Extensive ground and drop testing of deployment sequence, preflight inspection of system, keep-out zone around impact site
Recovery	Main parachute fails to inflate	5	Vehicle seperates and tumble recovers, severe damage to vehicle shell	3	Improper manufacture of drouge parachute, subpar material quality, fatigue failure of chute, tangled suspension lines, premature deployment	6	Detection possible but unlikely with preflight inspection, nondestructive testing methods	High design saftey factors, preflight inspection, material testing of parachute, conservative service life limits
Recovery	Secondary recovery telemetry and flight computer failure	3	Loss of redundancy in vehicle tracking and parachute deployment	4	Power loss to flight computer, improper porgramming or setup, loss of radio contact, failure of computer electronics	5	Programming can be verified, computers can be inspected for damage	Ground testing, factor of saftey on battery sizing, preflight inspection of computers and verification of programming
Recovery	Complete telemetry system loss	6	Failure to recover vehicle due to loss of location data, possibiliy of vehile landing too close to personell	2	Multiple independent failures in the modes listed above affecting bopth telemetry systems	4	Programming can be verified, computers can be inspected for damage	Multiple indfependent redundant telemetry computers in addition to above methods
Recovery	Ground deployment event	7	Activation of charges on the ground seperates vehicle, charge gases and vehicle components injure integration workers	1	Stray currents through charge leads, premature activation of recovery avionics	2	Moniter recovery aviionics for unexpected power on, check to ensure static charges have not built up near or on the vehicle	Power reecovery avionics on only immeadetly before takeoff, ground launch integratio personell and vehicle during launch integration
Recovery	Premature deployment on ascent	5	Mission abort without drop due to lack of ability to recover	3	Incorrect flight computer setup, error in flight computer event detection in flight	6	Verify programming completed successfully	Preflight checks of flight computer programming, sensors on computers
Recovery	Premature deployment on descent, main parachute	5	Loss of mission due to early vehicle seperation, damage to vehicle due to descent under tangled or shreddded main parachute	3	Incorrect flight computer setup, error in flight computer event detection in flight, issues relating to density fluctuation s in transonic regieme	5	Verify programming completed successfully, altimeters are safe to operate in transonic, supersonic regiemes	Preflight checks of flight computer programming, sensors on computers, enauring mach delay saftey measures are implemented
Aerostructure	Inflight vehicle breakup	7	Catastrophic structural results in loss of vehicle, falling debris present a serious hazard on the ground	2	Damage or fatigue from previous flights weakening structure, manufacturing or assembly errors	3	Nondestructive testing of components between flights, rigorous QA on all components and integration	High design saftey factor for aerostructure, rigorous and standardized QA procedures for manufacture and assembly of all critical structural components
Aerostructure	Inflight aerostructure failure not leasding to a breakup	6	Vehicle damaged beyone repair by failure, but recovered without inflight disintegration	2	Damage or fatigue from previous flights weakening structure, manufacturing or assembly errors, unanticipated harsh fliight conditions	3	Nondestructive testing of components between flights, rigorous QA and preflight on all components and integration	High design saftey factor for aerostructure, rigorous and standardized QA procedures for manufacture and assembly of all critical structural components

Extended FMEA – 2

Subsystem	Event	Severity	Potenial Effects	Liklehood of Occurance	Potential Causes	Liklehood of Detection	Detection Methods	Mitigation Strategy
Aerostructure	Overstress event without failure	3	Saftey factor of flight reduced due to overstress, without causing structural failure	4	Damage or fatigue from previous flights weakening structure, manufacturing or assembly errors, unanticipated harsh fliight conditions	3	Nondestructive testing of components between flights, rigorous QA and preflight on all components and integration	High design saftey factor for aerostructure, rigorous and standardized QA procedures for manufacture and assembly of all critical structural components
Aerostructure	Failiure of control fin retention	6	Loss of mision due to compromised attitude control, potential falling debris poses risk risk to ground personell	3	Failure of control fin due to overstress or fatigue, failure at connection due to bolts shearing or backing out	3	Nondestructive testing of fin between flights, QA and preslight inspections of components	High design factor of saftey, QA and prefligth inspection procedures for all aerodynamic surfaces
Aerostructure	Failure of roll tab retention	6	Loss of mision due to compromised attitude control, potential falling debris poses risk risk to ground personell	3	Failure of roll tab due to overstress or fatigue, failure at connection due to bolts shearing or backing out	3	Nondestructive testing of fin between flights, QA and preslight inspections of components	High design factor of saftey, QA and prefligth inspection procedures for all aerodynamic surfaces
Aerostructure	Failure of airbrake flap retention	6	Loss of mision due to compromised attitude control, potential falling debris poses risk risk to ground personell	3	Failure of airbrake flap due to overstress or fatigue, failure at connection due to bolts shearing or backing out	3	Nondestructive testing of fin between flights, QA and preslight inspections of components	High design factor of saftey, QA and prefligth inspection procedures for all aerodynamic surfaces
Control Hardware	Failure of fin actuators in neutral position	4	Reduced mission capability due to partial loss of attitude control	3	Failure of control surface actuators, failure of connecting mechanisms, damage to connection wires to control computer or power	2	Inspection for damage to actuators, control and power wires, and actuation mechanism	Simulation and testing to verify forces and prevent actuaor overload, preflight inspection of actuators, mechansims, and connections
Control Hardware	Failure of fin actuators in deflected positoin	5	Loss of mission due to partial loss of attitude control, deviation form planned flight trajectory due to constant pitch/yaw input	4	Failure of control surface actuators, failure of connecting mechanisms, damage to connection wires to control computer or power	2	Inspection for damage to actuators, control and power wires, and actuation mechanism	Simulation and testing to verify forces and prevent actuaor overload, preflight inspection of actuators, mechansims, and connections
Control Hardware	Failure of roll tabs in neutral position	4	Reduced mission capability due to partial loss of attitude control	3	Failure of roll tab actuators, failure of connecting mechanisms, damage to connection wires to control computer or power	2	Inspection for damage to actuators, control and power wires, and actuation mechanism	Simulation and testing to verify forces and prevent actuaor overload, preflight inspection of actuators, mechansims, and connections
Control Hardware	Failure of roll tabs in deflected position	5	Loss of mission due to partial loss of attitude control, excessive roll rate sue to deflection causing pitxh/roll coupling and deviation from flight trajectory	4	Failure of roll tab actuators, failure of connecting mechanisms, damage to connection wires to control computer or power	2	Inspection for damage to actuators, control and power wires, and actuation mechanism	Simulation and testing to verify forces and prevent actuaor overload, preflight inspection of actuators, mechansims, and connections
Control Hardware	Failure of airbrake actuators	5	Inability to complete mission due to lack of ability to track a reference mach number	3	Failure of driving servo, failure of actuation mechansim, jamming of mechanism due to overloading, failure of conrol or power connections	3	Inspection for damage to actuators, control and power wires, and actuation mechanism	Testing to verify forces and prevent overload or mehcanical binding, preflight inspection of servo, actuation mechansim, and control and power wires
Control Hardware	Inability of fins/roll tabs to comply with controller actuation commands	4	Adverse impact ondata quailty due to degraded ability to maintain attitude reference	3	Degraded actuation speed due to voltage sag or damage/binding in actuation mechanism	4	Inspection for damage before flight, verification of battery state of charge before flight	Testing to verify voltaage ag under load does not excessivly impact actuator operation, preflight inspection of actuation system
Control Hardware	Inability of airbrakes to comply with controller commands	5	Inability to gather data effectivly due to lack of ability to track mach reference effectivly	3	Degraded actuation speed due to voltage sag or damage/binding in actuation mechanism	4	Inspection for damage before flight, verification of battery state of charge before flight	Testing to verify voltaage ag under load does not excessivly impact actuator operation, preflight inspection of actuation system

Extended FMEA – 3

Subsystem	Event	Severity	Potenial Effects	Liklehood of Occurance	Potential Causes	Liklehood of Detection	Detection Methods	Mitigation Strategy
Control Hardware	Inability of airbrakes to comply with controller commands	5	Inability to gather data effectivly due to lack of ability to track mach reference effectivly	3	Degraded actuation speed due to voltage sag or damage/binding in actuation mechanism	4	Inspection for damage before flight, verification of battery state of charge before flight	Testing to verify voltaage ag under load does not excessivly impact actuator operation, preflight inspection of actuation system
Control Software	Inability of controller to restore attitude reference	4	Adverse impact ondata quailty due to degraded ability to maintain attitude reference	2	Inadequatly robust controller design, unexpectdly large inflight perturbations from reference	2	Verification of controller deisgn, prediction of expected perturbations in flight	Simulation and flight testing to verify controler dfesign, use of meterological data to fetermine expected perturbations to vehicle
Control Software	Inability of controller to restore attitude reference	5	Inability to gather data effectivly due to lack of ability to track mach reference effectivly	2	Inadequatly robust controller design, unexpectdly large inflight perturbations from reference	2	Verification of controller deisgn, prediction of expected perturbations in flight	Simulation and flight testing to verify controler dfesign, use of meterological data to fetermine expected perturbations to vehicle
Control Software	Controller sends incorrect commands to attitudfe control surfaces	5	Loss of mission and deviation from planned trajectory due to loss of attitude control	1	Bugs in the implementation of the controller on the vehicle	2	Validation testing of control software prior to flight testing	Tersting and simulation of controller implementation to verify expected behavior occurs
Control Software	Controller sends incorrect commands to airbrakes	5	Inability to gather data effectivly due to lack of ability to track mach reference effectivly	1	Bugs in the implementation of the controller on the vehicle	2	Validation testing of control software prior to flight testing	Tersting and simulation of controller implementation to verify expected behavior occurs
Data Recording and Payload Avionics	Failure to record reference data	5	Loss of mission data	3	Loss of power to measurment and data logging electronics, faliure of measurmetn sensors, failure or corruption of written data	3	Testing and inspection of power and data collection systems	Testing of electronics, preflight inspection of sensors, betteries, and data collection system
Data Recording and Payload Avionics	Failure to record air data from ADC	5	Loss of mission data	3	Loss of power to measurment and data logging electronics, failure of connection to ADC, failure or corruption of data storage	3	Testing and inspection of power and data collection systems	Testing of electronics, preflight inspection of sensors, betteries, and data collection system
Data Recording and Payload Avionics	Failurre of ADC or boom probe inflight	5	Loss of mission data and ADC	3	Loss of power to ADC, failure of ADC or boom probe electronics	3	Testing of boom probe and ADC in flight environment	Validation of ADC's ability to function in test environment, protection for the boom probe during launch preperration
Power Systems	Loss of power to recovery avionics, telemetry	7	Vehicle returns on ballistic trajectory, impacts gound at ~M 1.2, lethal hazard to personell near impact site	3	Overcurrent protection triggering, failure of battery cells or control electronics, inadequate battery state of charge	2	Load testing of batteries, inspection of cells, control eelctronics	Testing of batteries and power electronics to verify expected loads can be sustained, preflight inspection of power systems
Power Systems	Loss of power to control systems	5	Loss of mission due to inability to hold attitude and mach reference during test envelope	3	Overcurrent protection triggering, failure of battery cells or control electronics, inadequate battery state of charge	2	Load testing of batteries, inspection of cells, control eelctronics	Testing of batteries and power electronics to verify expected loads can be sustained, preflight inspection of power systems
Power Systems	Loss of power to data collection and logging systems	5	Loss of mission due to loss of data collection	3	Overcurrent protection triggering, failure of battery cells or control electronics, inadequate battery state of charge	2	Load testing of batteries, inspection of cells, control eelctronics	Testing of batteries and power electronics to verify expected loads can be sustained, preflight inspection of power systems
Power Systems	Loss of battery heating	4	Severe degredation of avaliable power to systems, pootential for loss of function on some systems	2	Failure of battery heating electronics	2	Inspection of heating system prior to flight	Environmental testing of heating system, preflight inspection of heating electronics
Launch Balloon	Failure of cutdown to release vehicle	6	Vehicle and ballon descend together at a high rate, vehicle severly damaged or destroyed on impact with ground	3	Damage to hotwire mechanism,loss of power to release control electronics	4	Preflight inspection of hotwire cutdown and control electronics	Dual redundant cutdown system, testing of howire and electronics, preflight inspection of system

Extended FMEA – 4

Subsystem	Event	Severity	Potenial Effects	Liklehood of Occurance	Potential Causes	Liklehood of Detection	Detection Methods	Mitigation Strategy
Launch Balloon	Failure of cutdown to release vehicle	6	Vehicle and ballon descend together at a high rate, vehicle severly damaged or destroyed on impact with ground	3	Damage to hotwire mechanism,loss of power to release control electronics	4	Preflight inspection of hotwire cutdown and control electronics	Dual redundant cutdown system, testing of howire and electronics, preflight inspection of system
Launch Balloon	Premature cutdown system activation	5	Vehicle released before target drop height, unable to carry out mission	2	Premature activation of release conrol electronics	5	Preflight inspection of hotwire cutdown and control electronics	Testing of howire and electronics, preflight inspection of system, validation of computer setup, programming
Launch Balloon	Premature balloon pop	5	Vehicle released before target drop height, unable to carry out mission	2	Manufacturing defect or damage to balloon	3	Preflight inspection of balloon	Preflight inspection to ensure balloon conforms to standards, select manufacturer capable of reliable quality
Launch Balloon	Loss of secondary telemetry, control computers	3	Loss of redundancy on telemetry and tracking of balloon	3	Failure of one telemetry and flight computer on ascent stage, limited loss of radio contact	4	Testing and inspection of ascent stage flight computers, testing of radio connection quality	Environmental testing of radio telemetry and tracking, preflight inspection of computers
Launch Balloon	Loss of all telemetry	5	Loss of balloon tracking vehicle releases and executes flight	1	Failure of telemetry systems on both indfependent telemetry computers on ascent stage, total loss of radio contact	4	Testing and inspection of ascent stage flight computers, testing of radio connection quality	Environmental testing of radio telemetry and tracking, preflight inspection of computers
Launch Balloon	Loss of all telemetry and control computers	6	Loss of balloon tracking vehicle fails to release and descends with balloon	2	Failure of both independent telemetry and fligth computers on ascent stage	4	Testing and inspection of ascent stage flight computers, testing of radio connection quality	Environmental testing of radio telemetry and tracking, preflight inspection of computers

Primary Flight Risks

- Failed parachute deployment
  - Leads to vehicle loss, danger to ground personnel
  - Impossible to be certain of deployment before flight
- In Flight structural failure
  - Loss of vehicle, falling debris
  - Easier to detect than recovery failures
- Loss of attitude control, mach tracking
  - Multiple possible failure modes across subsystems
  - Loss of mission; inability to gather useful data
- Loss of telemetry datalink
  - Unable to track location of vehicle for recovery
  - Redundancy and proven systems reduce risks

Risk Mitigation

- Parachute Deployment and inflation:
  - Redundant deployment charges and avionics, ground and drop tests before launch
  - High design safety factor, slip ring to extend chute inflation time, preflight inspections
- Telemetry/Tracking Loss:
  - RF Transparent Midframe, high power transmitters, independent redundant trackers
- Structural Failure:
  - High design safety factor, structural simulations with off-nominal loading, nondestructive testing and inspection throughout vehicle life cycle
- Control System Failure
  - High design safety factor, aerodynamic simulation with off-nominal loading
  - Robust controller design, verification of controller function by simulation
  - Testing and inspection of control hardware throughout vehicle life cycle

Bill of Materials

Collins Aerospace

University of Minnesota
Driven to Discover℠

Bill of Materials

Item	Purpose	Source	Link (if applicable)
Recovery			
Kevlar (MIL-C-87129A, Type 9) Suspension Cords	Suspension cords for drogue and main parachutes	5Col Survival Supply	https://5col.com/products/mil-spec-braided-
Kevlar Para-Aramid (Kevlar 49, 1420 HM Denier)	Drogue parachute fabric	Rocket-Fibers, LLC	https://www.rocket-fibers.com/products/kev
64" Ultra-Lo Porosity Nylon Ripstop Fabric (MIL-C-44378, Type IV)	Main parachute fabric	Para Gear Equipment Company	https://www.paragear.com/skydiving/10000
1/2" Kevlar Tape (MIL-T-87130)	Radial tape for drogue and main parachutes	Para Gear Equipment Company	https://www.paragear.com/skydiving/10000
Ascent Module			
Latex Helium Meteorlogical Balloons	Lifting vehicle to drop altitude	Kaymont Consolidated	https://www.kaymont.com/product-page/ha
Aluminum	To be machined into the release module shell	Metals Depot	https://www.metalsdepot.com/aluminum-pr
Nylon Rope	Connects Balloons to Release Module & Vehicle for ascent	Rope.com	https://www.rope.com/products/1-4-double-
Dyneema Rope	Anchors nylon rope from release module to the Parachute anchor	Rope.com	https://www.rope.com/products/endura-brai
Soft Shackle	Attaches the exterior nylon release rope to the interior dyneema anchor rope	West Marine	https://www.westmarine.com/west-marine-c

- Custom machined hardware not included due to difficulty constraints
- Price not included due to budget not being a concern from the sponsor

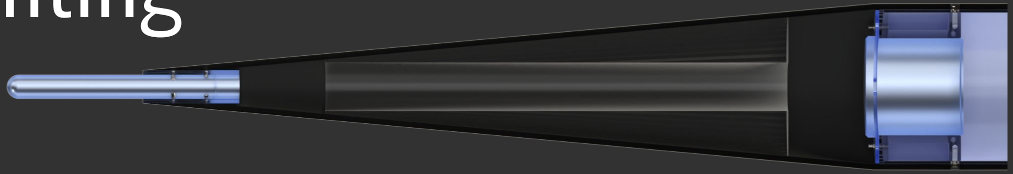
Bill of Materials

Control Hardware			
SC1268SG-BE	Savox high torque servo for roll control tab actuation	Savox USA	https://www.savoxusa.com/products/savsc
CASM-32-BS-0020AA-0000 BG45X30P	Linear Actuator for pitch and yaw control surfaces with DC motor	Ewellix	https://www.ewellix.com/en/products/high-p
Avionics			
SAMD21RT Microcontroller	Microcontroller for custom avionics	Microchip	https://www.microchip.com/en-us/product/s
VN-200 GNSS/INS	GNSS/INS sensor for controls and Mach reference validation	VectorNav	https://www.vectornav.com/products/detail/
HI-35930 ARINC-429 Transceiver	ADC interface	Holt Integrated Circuits	https://www.holtic.com/products/3136-lightr
nRF21L01+	RF communication between release avionics and custom avionics	Nordic Semiconductor	https://www.nordicsemi.com/Products/nRF
Industrial microSD Memory Card	Data storage	Kingston	https://shop.kingston.com/products/industri
Kate-3 Mx-230 Transmitter & Pyro Board	GPS Tracking, primary recovery device separation responsibility	Multitronix	https://www.multitronix.com/buy.html
Kate-3 Mx-220 Receiver	Ground Receiver for Kate-3 Transmitter	Multitronix	https://www.multitronix.com/buy.html
AIM XTRA 4.1 GPS Flight Computer & Receiver	GPS Tracking, secondary recovery device separation responsibility	Entacore	https://entacore.com/electronics/aimxtra
Insulation/Heating			
LO/MIT II	Low emissivity coating	SOLEC	https://solec.org/lomit-radiant-barrier-coatin
Aerofoam XLPE	Conductive insulation	Aerofoam	https://aerofoamusa.com/polyolefin-therma
Custom Flexible Silicone Rubber Heaters	Heating for electrical components	CHR	https://customheatersandresearch.com/ind

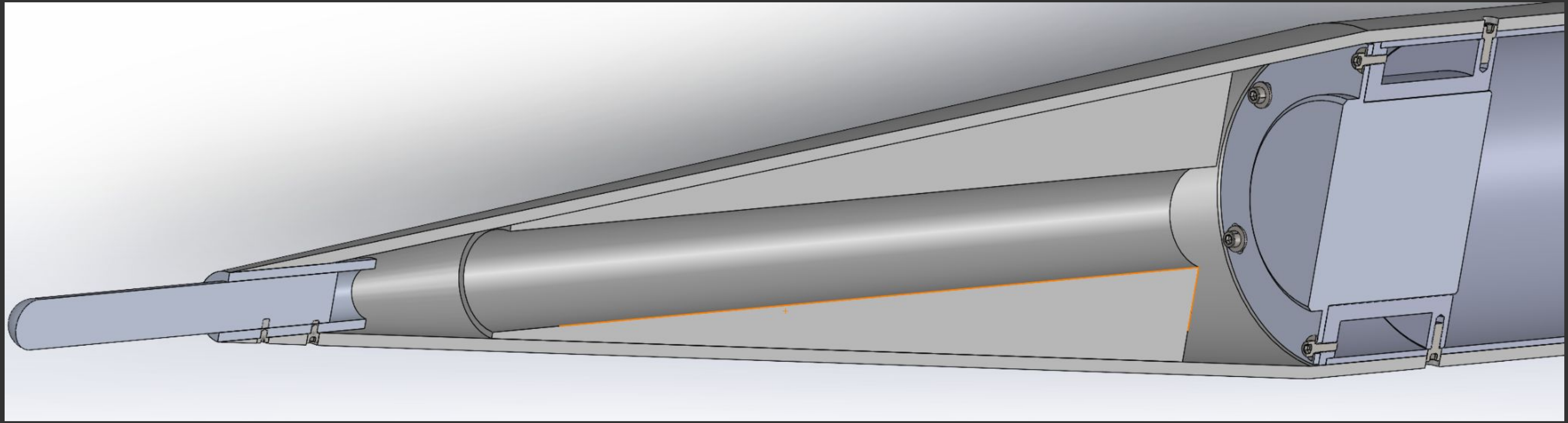
- Custom machined hardware not included due to difficulty constraints
- Price not included due to budget not being a concern from the sponsor

Backup Slides

Airframe: Boom Mounting

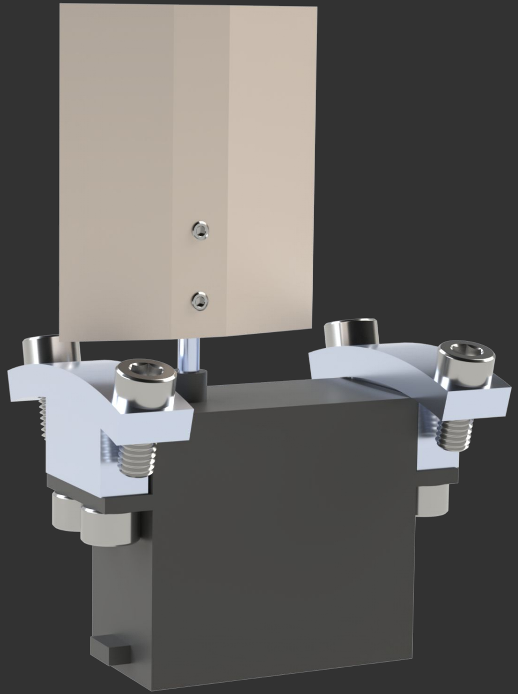


- Focus on standard COTS hardware
    - 10-32 socket heads for the boom, low profile for the forward set
        - These require simple modifications on a lathe
    - ¼-28 socket for the ADC mount connection to the airframe
    - 10-32 socket heads for the ADC mounting flange



Roll Actuators Technical Specifications

Direction	Clockwise
Output Shaft Style	H25T Spline
Voltage Range	4.8V ~ 7.4
No-Load Speed (6.0V)	0.13 sec/60°
No-Load Speed (7.4V)	0.11 sec/60°
Stall Torque (6.0V)	208.3 oz-in (15.0 kg.cm)
Stall Torque (7.4V)	347.2oz-in (25.0 kg.cm)
Max PWM Signal Range	800-2200μsec
Pulse Amplitude	3-5V
Operating Temperature	-10°C to 50°C
Current Drain - idle (4.8V)	5mA
Current Drain - idle (6.0V)	5mA
Current Drain - idle (7.4V)	5mA
Current Drain - no-load (4.8V)	100mA
Current Drain - no-load (6V)	120mA
Current Drain - no-load (7.4V)	150mA
Current Drain - stall (4.8V)	2500mA (2.5A)
Current Drain - stall (6V)	3000mA (3.0A)
Current Drain - stall (7.4V)	3500mA (3.5A)
Motor Type	Coreless
Output Shaft Support	Dual Ball Bearings
Gear Material	Steel
Wire Length	7.0" (177.8mm)
Weight	2.19oz (62g)
Wire Gauge	22 AWG
Servo Size	Standard
Max Rotation	160°
Travel per μs	0.114°/μsec



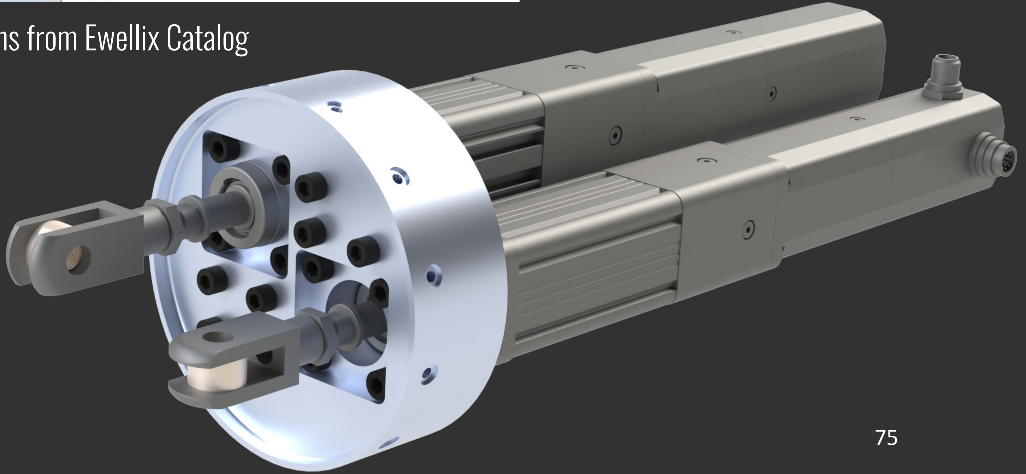
Fin Actuators Technical Specifications

Technical data

Designation	Symbol	Unit	BLDC motor BG45
Performance Data			
Continuous force @ zero speed	F_{c0}	kN	0,393
Continuous force @ max. speed	F_c	kN	0,393
Peak force @ zero speed	F_{p0}	kN	0,700
Peak force @ max. speed	F_p	kN	0,603
Dynamic load capacity	C	kN	2,8
Holding force (motorbrake option)	F_{Hold}	kN	0,558
Max. linear speed	v_{max}	mm/s	150
Max. acceleration	a_{max}	m/s²	6
Duty cycle	D	%	100
Mechanical Data			
Screw type	–	–	Ball screw
Screw diameter	d_{screw}	mm	10
Screw lead	p_{screw}	mm	3
Lead accuracy	–	–	G7
Stroke	s	mm	50...400
Internal overstroke each side	s_0	mm	1
Backlash	$s_{backlash}$	mm	0,06
Gear reduction	i	–	1
Efficiency	η	%	58
Inertia @ 0 mm stroke	J	10^{-4} kgm²	0,0920
Δ Inertia per 100 mm stroke	ΔJ	10^{-4} kgm²	0,0047
Inertia of optional brake	J_{brake}	10^{-4} kgm²	0
Weight @ 0 mm stroke	m	kg	1,61
Δ weight per 100 mm stroke	Δm	kg	0,34
Weight of optional brake	m_{brake}	kg	0,12
Electrical Data			
Motor type	–	–	Brushless DC
Nominal voltage	U	V DC	24
Nominal current	I	A	4,9
Peak current	I_{peak}	A	15,0
Nominal power	P	kW	0,091
Environment and Standards			
Ambient temperature	$T_{ambient}$	°C	0...+50
Degree of protection	IP	–	54S
Standards	–	–	ISO 15552

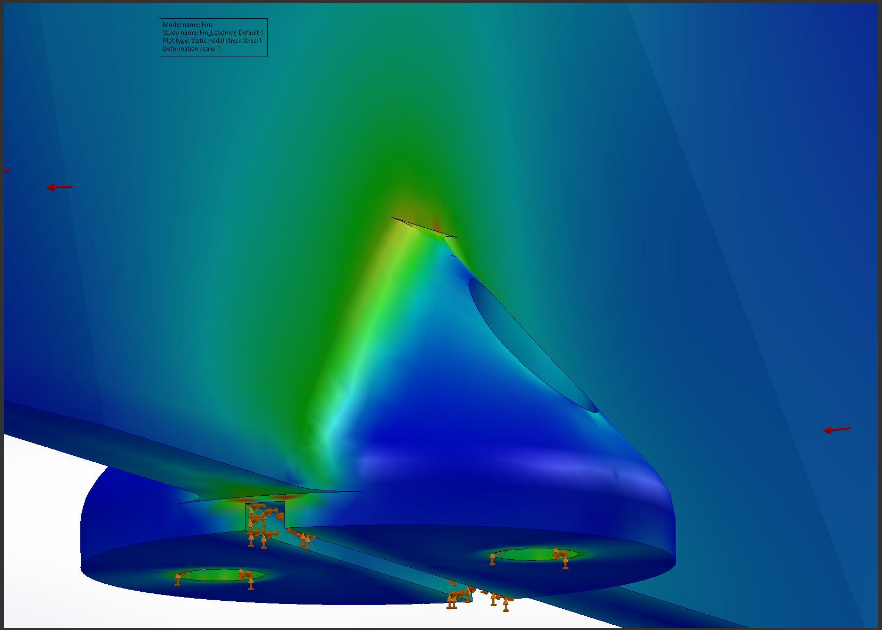
Company	Ewellix
Description	CASM linear units
Part No.	CASM-32-BS-0020AA-0000 BG45X30PI ZBE-375570 ZBE-375510-32-E
Type	CASM
Size[mm]	32
Motor shape	Standard
Screw Type	Ball screw
Speed	Slow
Stroke (S)[mm]	20
Option	Motor, adapter and accessories separately delivered - contact Ewellix for more information
Adapter kit	Adapter kit for BG45x30 (ZBE-375570)
Motor type	BG45x30PI motor
Accessories - Front attachment	Rod clevis
Accessories - Mounting kits	No mounting device
Accessories - Sensor	without Proximity sensor
Accessories - Parallel adapter	No mounting device
Trunnion position	0.0
Position	Extended

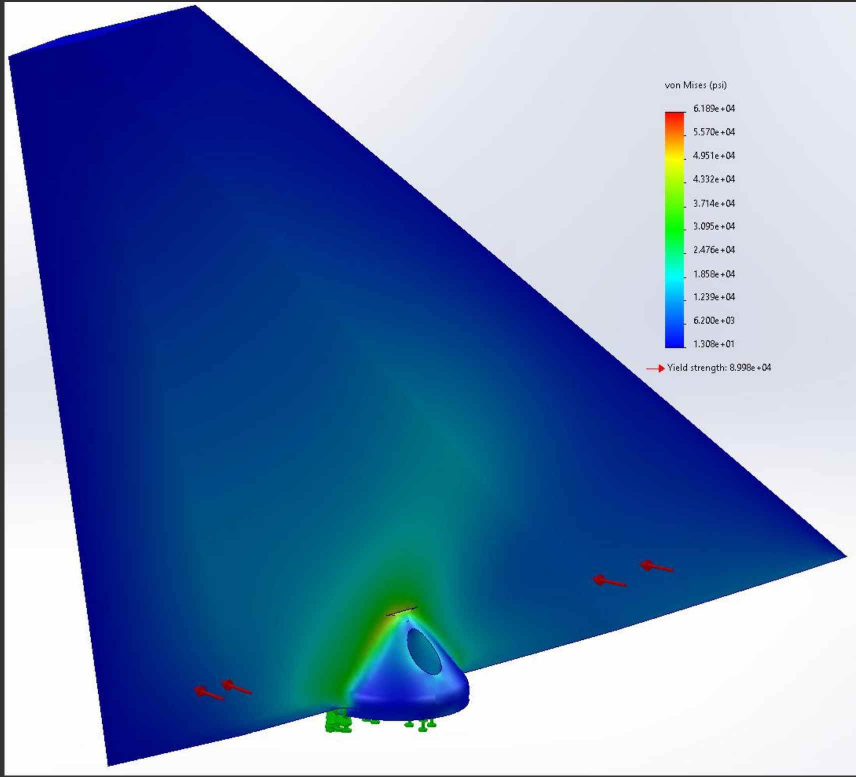
Specifications from Ewellix Catalog



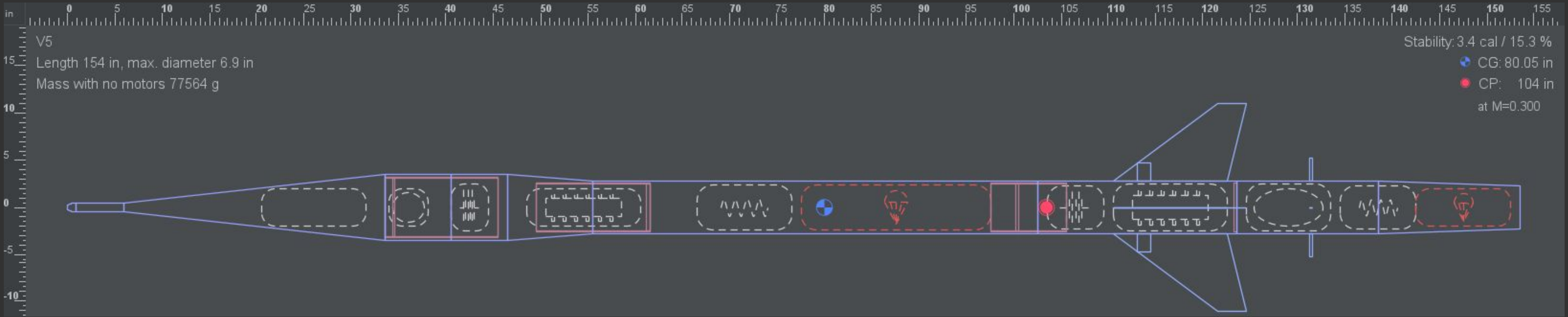
Airframe Structure: Fin Attachment

Fin Actuation – Simulated 20psi normal along leading edge and 8psi normal along trailing edge



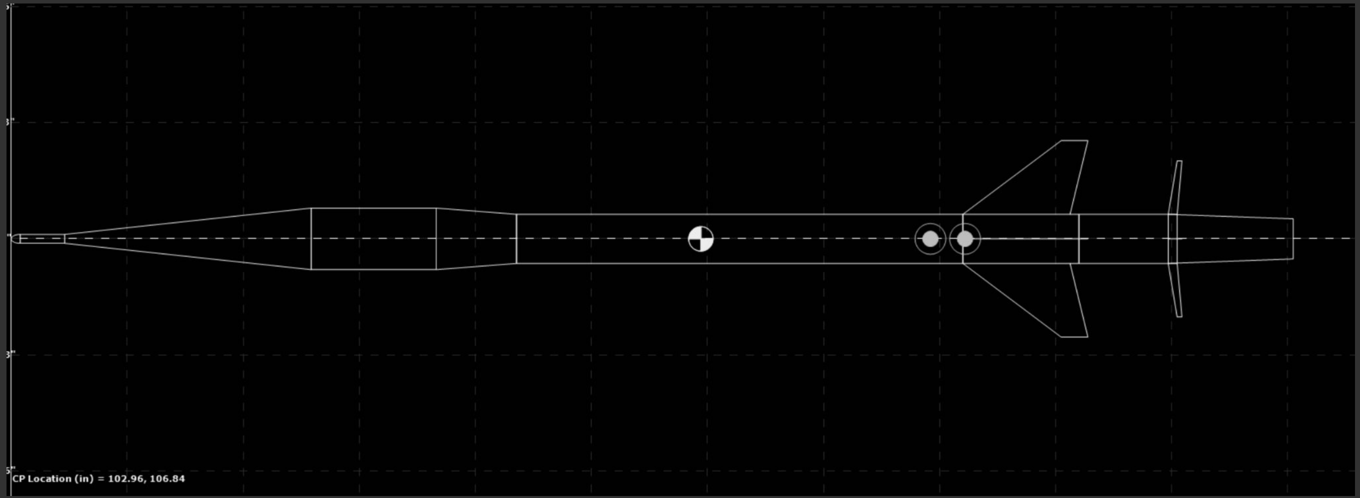


OpenRocket Vehicle Layout/Dimensions



Airframe: Aerodynamic Design

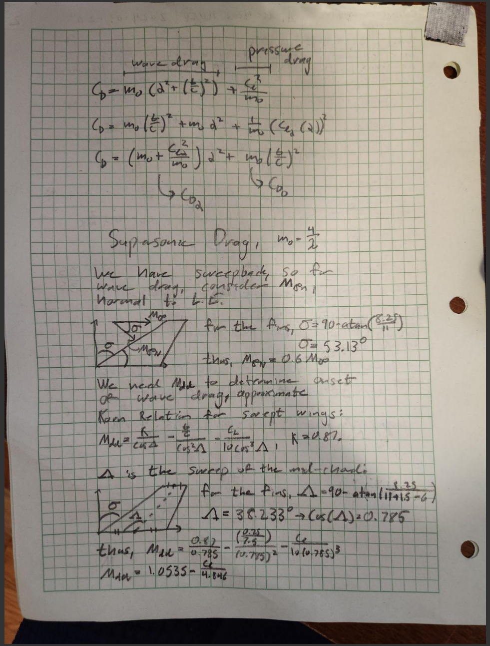
- Fixed Aerodynamic Surfaces
  - Fins are sized to ensure aerodynamic stability across our desired Mach regime
  - The integrated fin set use a clipped delta planform for optimal control surface integration while maintaining good supersonic drag and aeroelastic properties
  - Hexagonal profile used for good structural, aerodynamic, and manufacturing properties

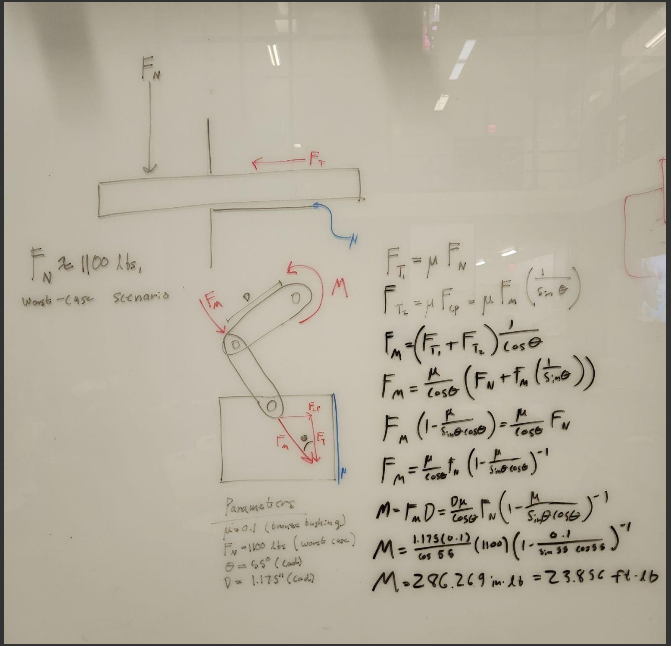


Aerodynamic Computations

Hand Calcs Used

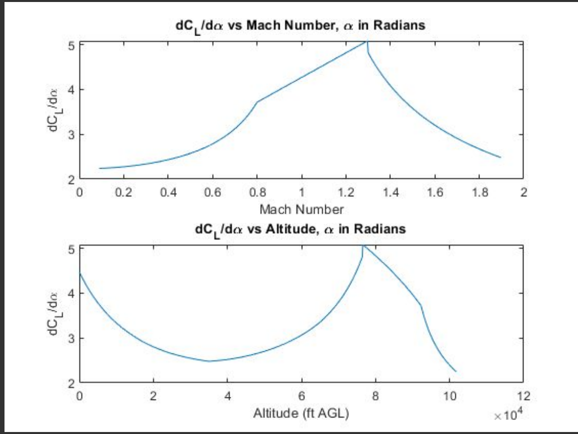
- Used to determine mathematical steps to compute drag divergence mach number, wave drag
- Used to determine expected torque from airbrake actuator based on drag force

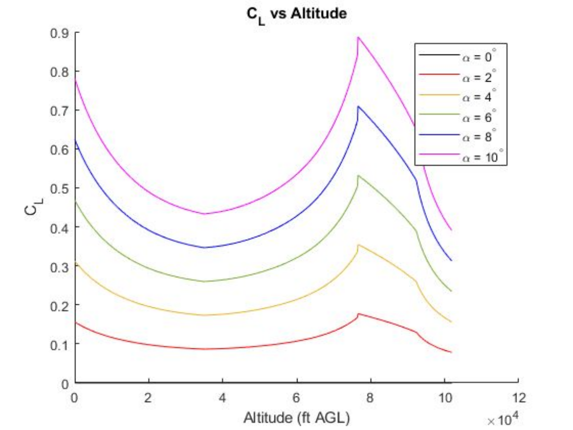


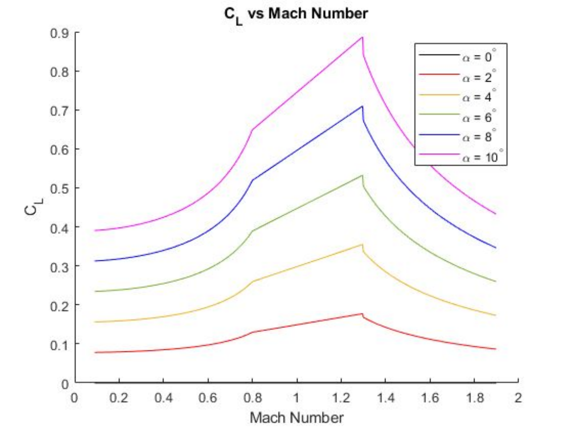


Attitude Control: Force Prediction Plots, C_L

- C_L computed for symmetric airfoil, output $dC_L/d\alpha$ constant for each timestep
- C_L and $dC_L/d\alpha$ potted vs altitude and mach number for each timestep on descent from apogee

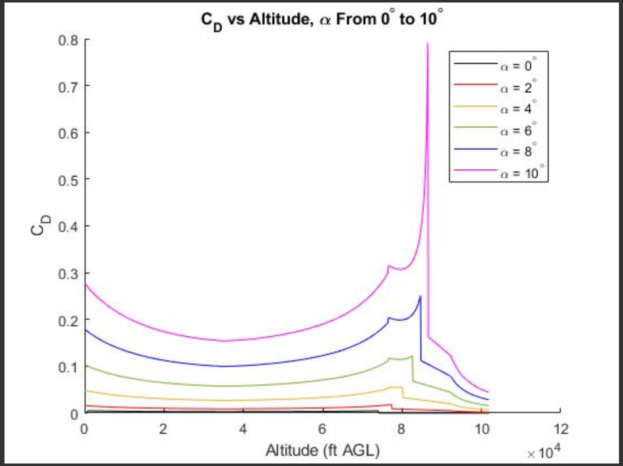


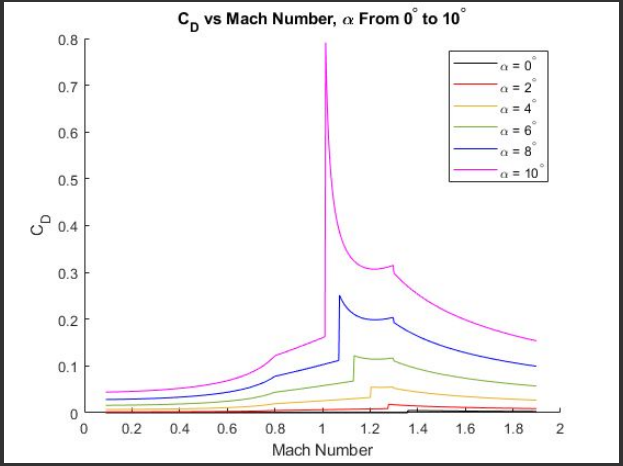




Attitude Control: Force Prediction Plots, C_D

- C_D computed for biconvex airfoil in compressible flow, including wave drag
- Korn's relation applied to LE sweep to find M_{dd}, onset of wave drag term
    - Proximity of M_{dd} to unity causes peak for α = 10 due to error
- C_D plotted on descent vs altitude and mach number





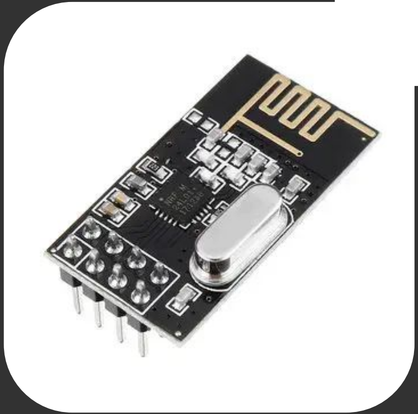
Avionics: Storage/Telemetry

Kingston Industrial microSD Card

- Stores ADC data
- Storage: 64 GB
- 20 MB/s write
- Operating temps: -40° C to 85° C

Radio transceiver: NRF24L01+

- Collects temperature data from release mechanism temperature sensor
- 2.4 GHz band
- 2 MB/s data rate
- Operating temps: -40° C to 85° C



GNSS/INS Uncertainty Calculation

- Operating regime:
  - M = 1.5
  - c = 294.9 m/s
  - v = 442.4 m/s

Mach uncertainty: ± 0.005

$$M = c\frac{v}{\sqrt{T}} \qquad \frac{\partial v}{\partial M} = \frac{c}{\sqrt{T}} \qquad \frac{\partial T}{\partial M} = -\frac{c}{2}\frac{v}{T^{\frac{3}{2}}}$$

Expected minimum M = 1. , c = 294.9 m/s @ 12,000 m

$\Rightarrow v = 1.5 \cdot 294.9$ m/s = 442.4 m/s

$$\sigma_M^2 = \sigma_v^2\left(\frac{\partial v}{\partial M}\right)^2 + \sigma_T^2\left(\frac{\partial T}{\partial M}\right)^2$$

$$= \sigma_v^2\frac{c^2}{T} + \sigma_T^2\frac{c^2}{4}\frac{v^2}{T^3}$$

$$\frac{\sigma_M^2}{M^2} = \frac{T}{c^2v^2}\left(\sigma_v^2\frac{c^2}{T} + \sigma_T^2\frac{c^2}{4}\frac{v^2}{T^3}\right)$$

$$= \frac{\sigma_v^2}{v^2} + \frac{1}{4}\frac{\sigma_T^2}{T^2}$$

$$= \frac{0.05^2}{442.4^2} + \frac{1}{4}\frac{2^2}{294.9^2}$$

$$= 1.151 \times 10^{-5}$$

$$\frac{\sigma_M}{M} = 0.003392$$

@ anticipated Mach of 1.5:

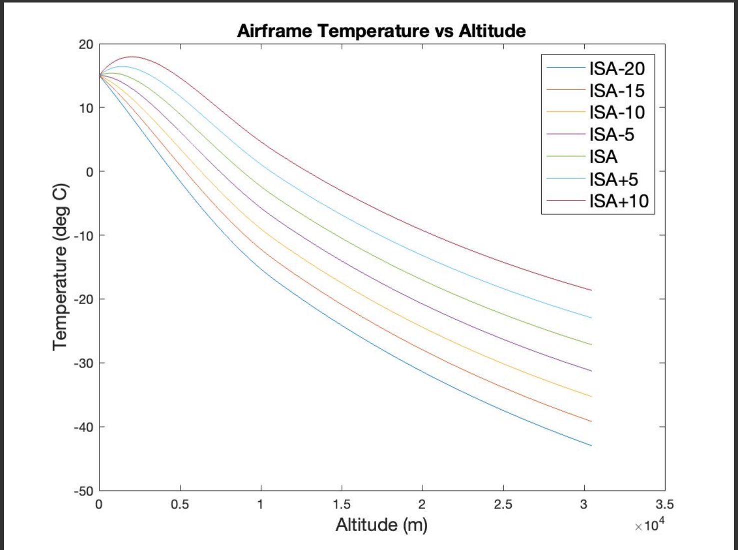
$$\sigma_M = 1.5(0.003392)$$

$$= 0.005089 \approx \boxed{0.005}$$

Thermal Analysis: Ascent

Assumptions/approximations:

- Constant ascent rate of 5 m/s
- Lumped capacitance airframe temperature used as lower bound
- Initial temperature: 15º C
  - ISA model with -plus and -minus deviations
- Forced convection
  - Body approximated as a flat plate in parallel flow
- Radiation
  - Radiative heat loss to sky



Ascent temperature vs time for various ISA deviations

Thermal Analysis: Descent

Assumptions/approximations:

- Stagnation point temperature at maximum Mach number used as **conservative** upper bound for temperature
- Isentropic compressible flow relation:

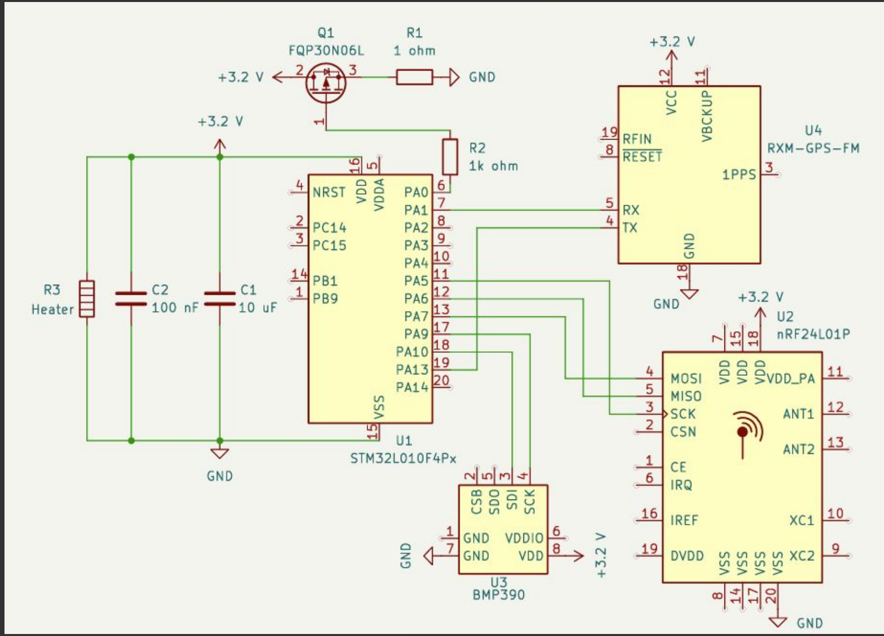
$$T_0 = T(1 + M^2 (\gamma - 1)/2)$$

Results

- Peak stagnation temperature achieved at maximum Mach number in ISA+15: **34º C**
    - Well within limits for electronics

Release System: Avionics Parts

- Battery: Lithium Werks 18650 1100mAh LiFePO4;
- GPS Module: RXN-GPS-FM
- Barometer: BMP390
- Microcontroller: STM32L010F4Px
- Wireless Receiver: nRF24L01
- Relay (switch) FQP30N-6L
- 1x 1 ohm & 1x 1k ohm resistors
- 2x 100 nF capacitors



Recovery Systems: Dimensions

Drogue

Nominal Surface Area	69.94 ft^2
Nominal Diameter	9.44 ft
Weight	5.36 lb
Coefficient of Drag	0.56
Suspension Line Length	14.15 ft
Gores	20
Canopy Fill Time	0.17 sec

Main

Nominal Surface Area	590.59 ft^2
Nominal Diameter	27.42 ft
Weight	21.21 lb
Coefficient of Drag	0.45
Suspension Line Length	46.62 ft
Gores	12
Canopy Fill Time	0.91 sec

Recovery Systems: Opening Forces

Drogue	
G Force	19.80 G's
Average Opening Force	3,118.50 lbf
Opening Force Lower Limit	2,970.00 lbf
Opening Force Upper Limit	3,267.00 lbf
Drag Force	294.64 lbf

Main	
G Force	1.61 G's
Average Opening Force	247.10 lbf
Opening Force Lower Limit	228.10 lbf
Opening Force Upper Limit	266.11 lbf
Drag Force	366.67 lbf

Recovery Systems: Dimensions (cont.)

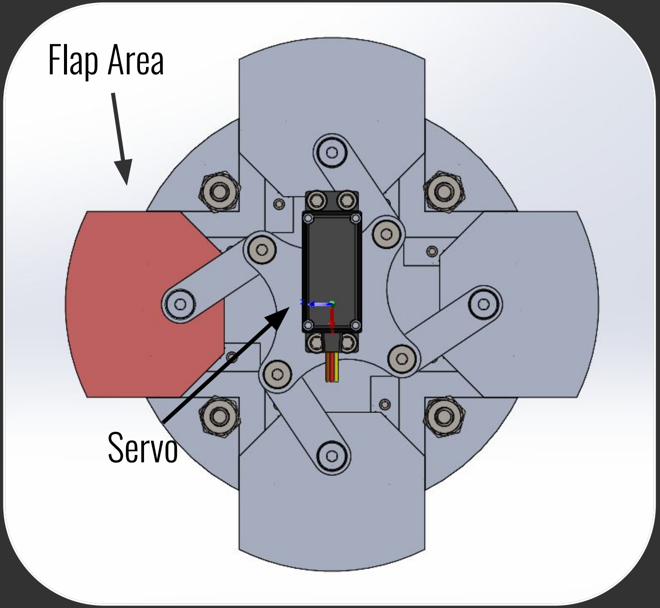
Drogue	
Constructed Diameter	9.06 ft
Projected Diameter	6.61 ft
Projected Surface Area	34.27 ft^2
Gore Area	52.68 ft^2
Gore Width	3.73 ft
Gore Height	28.22 ft
Vent Diameter	0.78 ft
Vent Height	7.62 ft

Main	
Constructed Diameter	20.02 ft
Projected Diameter	17.82 ft
Disk Diameter	14.41 ft
Gap Height	0.84 ft
Band Height	2.42 ft
Band Length	62.89 ft
Vent Diameter	1.40 ft

Air brakes: Parameters

Max surface area per flap	3.075 in^2
Total surface area	12 in^2
Max force per flap	1177.3 lbs
Torque needed for motor	286.3 in·lbs
Torque provided for actuation	433.9 in·lbs

Top Down Module View



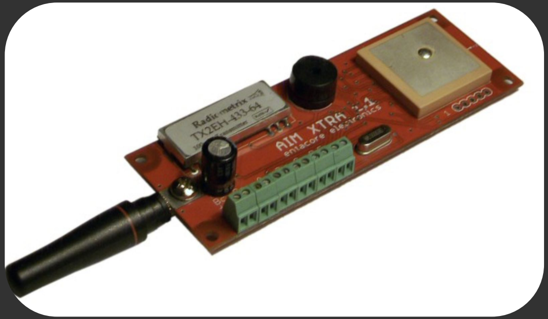
Recovery Systems: Avionics

AIM XTRA GPS Flight Computer

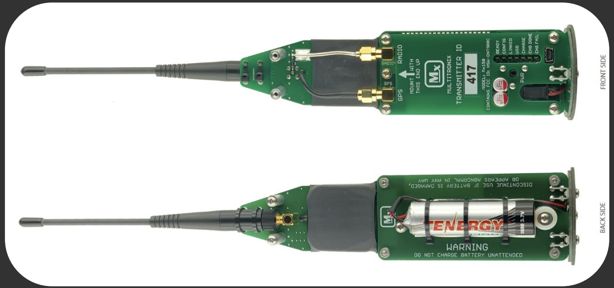
- RF transmitter
- Complete telemetry system
- Accelerometer
- Charge ignition for parachute deployment

Kate-3 Unlimited Altitude GPS Tracking System

- Mx 210 transmitter
- Lithium ion battery with built-in charging
- Flexible mounting



Source: https://entacore.com/electronics/aimxtra



Source: https://www.multitronix.com/kate-3-transmitter.html

Recovery Systems: Materials

- **Suspension Lines:** Kevlar MIL-C-87129A
  - Type 9: 2000 lb break strength
- **Drogue:** Kevlar Para-Aramid (Kevlar 49)
  - 1420 HM Denier: 70 lb break strength (per gore)
  - ~ 2.5% elongation
  - Strong and lightweight, high porosity
- **Main:** 64” Ultra-Lo Porosity Nylon Ripstop
  - MIL_C-44378 Type IV
  - Low air permeability, high tenacity, relatively lightweight
- **Radial Tape:** ½” Kevlar MIL-T-87120, Type 1, Class 2
  - Tensile strength: 550 lbs

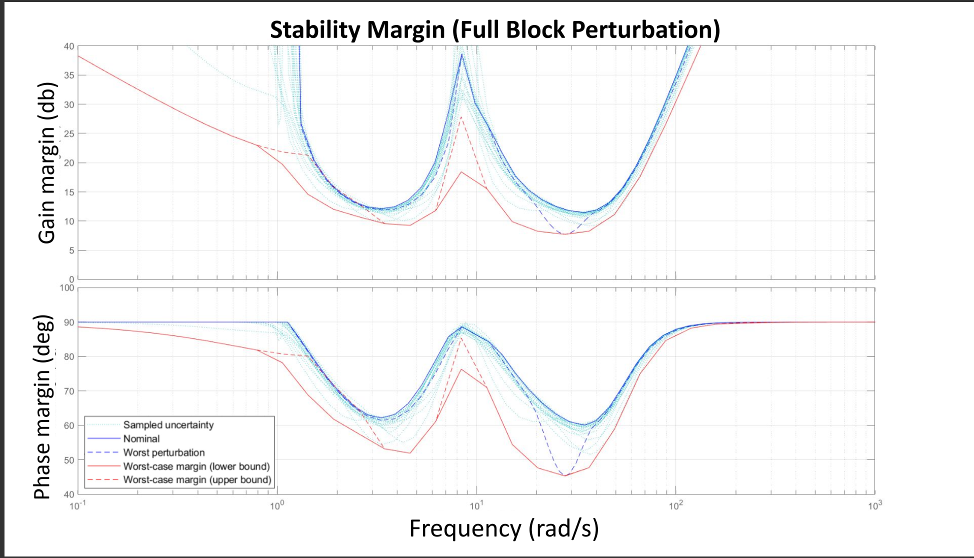
Source: https://www.rocket-fibers.com/products/kevlar%C2%AE-fiber?variant=49689665339712

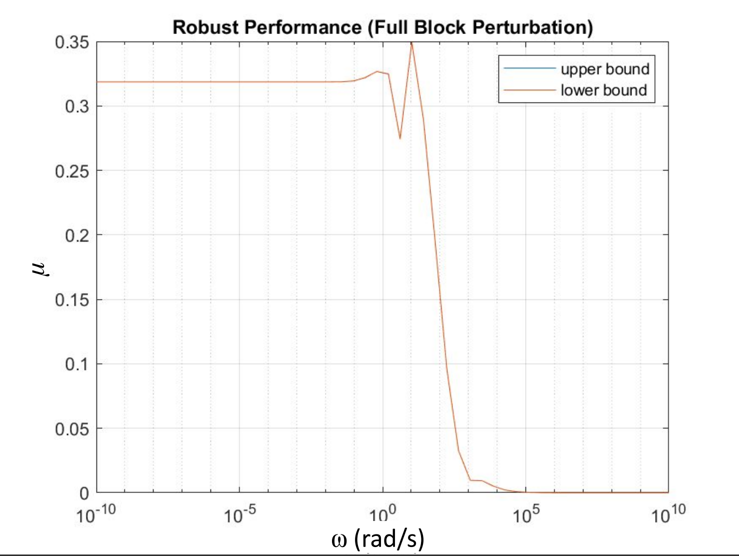
Source: https://www.paragear.com/skydiving/10000042/W9110W/

Attitude Control: Control Synthesis

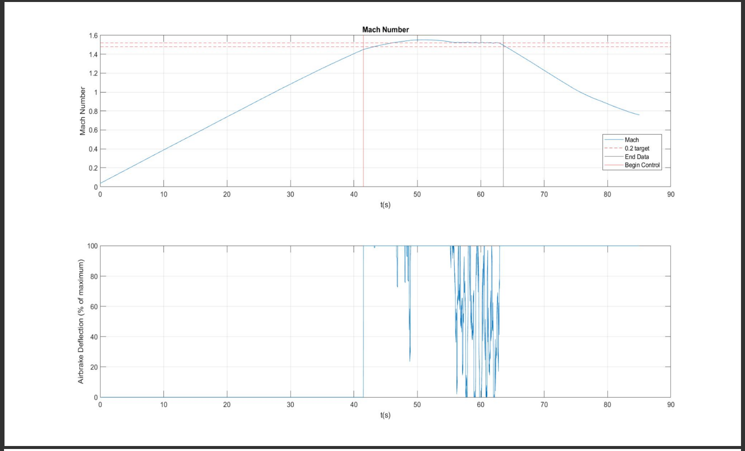
μ-Synthesis to achieve robust performance

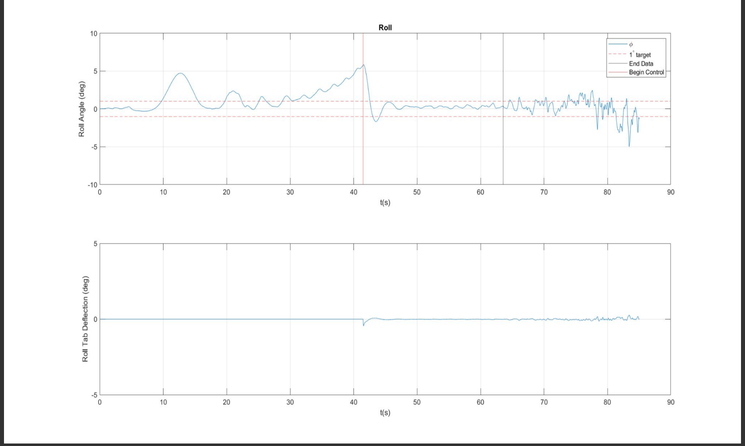
- Minimize worst case amplification of disturbance while reducing conservativeness

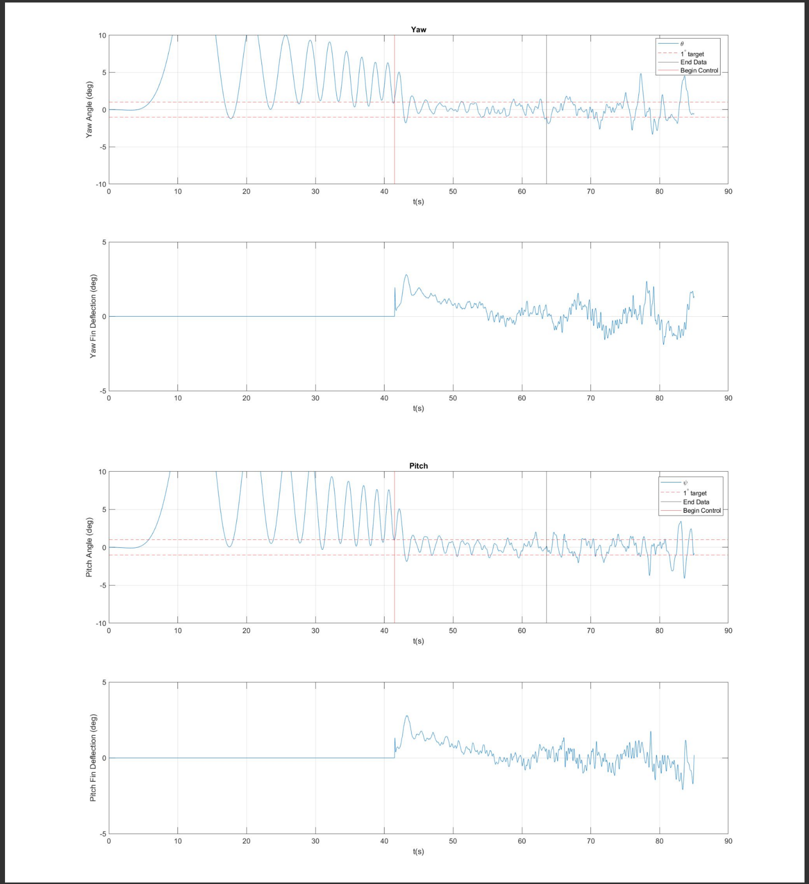




Control Under Severe Turbulence







References Used

- Foundations of Aerodynamics, Kuethe & Chow, 1998
- Commercial Airplane Design Principles, Sforza, 2014
- Parachute Recovery Systems Design Manual, Knacke, 1991

Technical Approach (cont.)

- Collaboration with outside sources
  - Consulted Mackenzie Steiner (Rocket Team Recovery Lead) and Gaven House (Cirrus Parachute Testing Engineer) to design recovery systems
  - Collaborated with Drew Miller (Rocket Team) to design Air Brakes
  - Collaborated with Joseph Hoang from other Collins design group for CFD consultation
  - Consulting with other Collins team
  - Consulted with Prof. James Flaten regarding ascension system

Individual Presentations

Mykhail Sandacz

Team Lead – Individual Report

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Mykhail Sandacz – Lifelong Learning

- Leadership
  - Delegation, conflict resolution, and promoting team collaboration.
- Time management
  - Juggling many tasks at once while meeting outside deadlines
- Project planning
  - Adaptability to manage evolving project requirements and expectations
  - Process for research and development of a project
- Communication
  - Ensuring open communication between group members
  - Summarize progress for instructors and industry leaders for clear communication
  - Distributing knowledge on updates and requirements given by instructors and industry leaders to team
- Problem solving
  - Deepened technical knowledge through research and hands-on problem-solving.

Mykhail Sandacz – Team Contribution

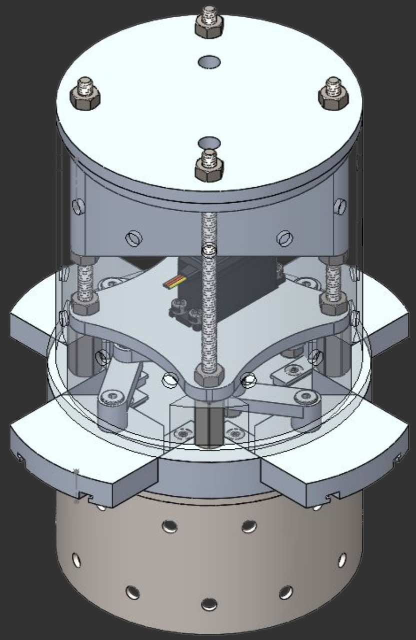
Team lead

- Point of contact for instructors and industry leaders
- Aided in definition of project requirements
- Delegated tasks effectively based on individual strengths
- Lead weekly/biweekly calls with Collins
- Organized and lead integration meetings to allow for open communication
- Communicated with individuals to ensure progress
- Organized worktimes as needed to hit deadlines
- Maintained project timelines through planning and progress reviews
- Ensured high quality of design and presentations

Mykhail Sandacz – Secondary Tasks

- Air Brake Mechanical Design
  - Iterated through multiple different designs
  - Maximizing surface area while maintaining low complexity
  - Keep the profile minimal to reduce footprint in the airframe
  - Transfer load through structurally sound components

- Led test campaign to prototype in wind tunnels
  - Data was used to make decisions regarding initial design
  - Unable to run further wind tunnel tests in given time



Rory Conway

Individual Report

UNIVERSITY OF MINNESOTA
Driven to Discover[SM]

Rory Conway - Lifelong Learning

- Schedule Management
  - Consolidating workload between long-term design project with other workload and personal time factors
- Communication
  - Having multiple minds contributing to the design and implementation of a novel system and working through different design processes and methods
  - Collaborating with project sponsor / customer on ideas and approaches to arrive at the solution best determined by the team for the problem the customer is facing
- Drawing Board Design
  - Having to think of solutions for a design problem that hasn’t really been solved (without a security clearance)

Rory Conway - Team Contribution

- Systems Engineering
  - Made system diagram detailing interfaces between system components
  - Determined FMEA risk and severity criterion to track and quantify system risks
  - Developed RVTM to assess design's fulfillment of system requirements
  - Looked at vehicle design with Liam to determine location of system components within the airframe. Considerations were to minimize vehicle integration and controller interface complexity and ensure structural integrity, recovery deployment, and vehicle tracking

Rory Conway - Team Contribution

- Recovery
  - Coordinated and worked with Recovery Lead Sam meetings with former and current UMN Rocket Team members to discuss recovery system solutions
  - Analyzed different solutions to mitigating maximum shock loading due to recovery deployment, including parachute design and novel methods such as sliding rings and parachute reefing
  - Utilized past recovery experience with UMN Rocket Team to aid in determining material selection, parachute retention methods, and providing resources to aid in designing the recovery system

Alex Peik

External Systems Lead - Individual Report

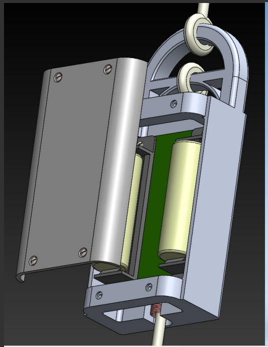
Alex Peik - Lifelong Learning

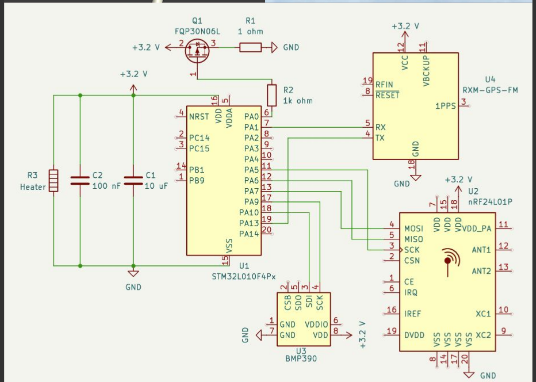
- Team Communication
- Consulting outside of design team.
  - Professional communication & information sharing.
- Research methods & design by constraints.
  - Modifying pre-existing concepts to fit project needs.
- Design Processes
  - Iteration & consultation
- Practical experience with CAD Structure Modelling.
- Practical experience with circuit design & modelling.

Alex Peik - Design Contributions

External Systems Lead

- Ascent Method Research & Design
- Release Method Research & Design
    - Hotwire Research
    - CAD Model
- Release Avionics Design & Modeling
    - Assisted by Pranav
        - Parts selection
        - KiCAD training





Alex Peik - Primary Tasks

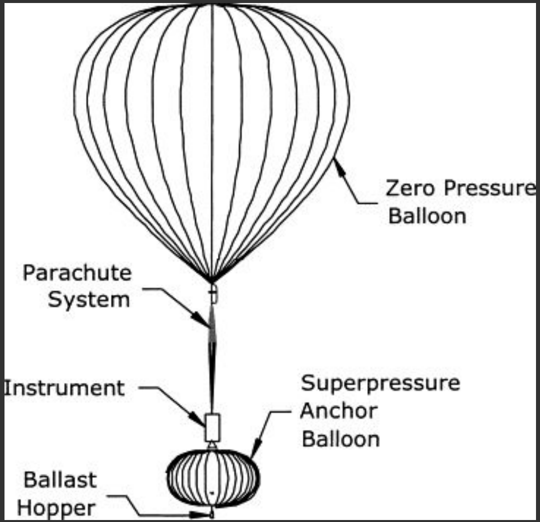
Ascent Design Process

1st Iteration: Theoretical Balloon (PDR).

- Scaled NASA estimate up to vehicle weight.

2nd Iteration: Commercial Balloon Sourcing.

- Consulted with Prof. Flatten.
    - No existing balloon meets needs by itself.
- Resulting decision to use multiple existing balloons.



Alternative Super-pressure Balloon Method:
M.S. Smith; Optimum designs for superpressure balloons.

Alex Peik - Primary Tasks

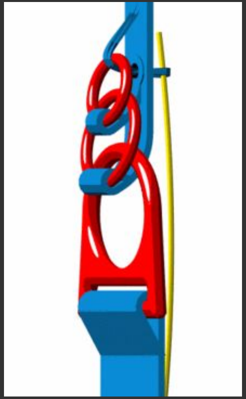
Release Design

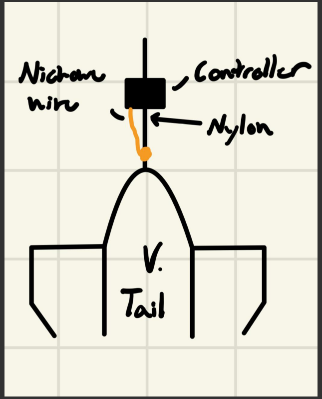
Research

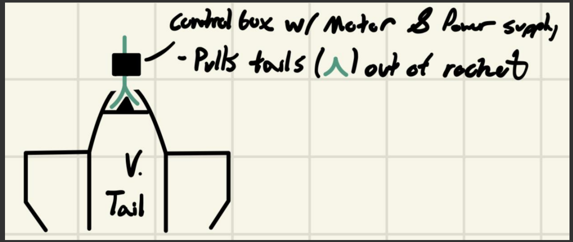
- Multi-Loop Release (Top Left) - Popular in parachuting.
- Retracting Dovetail (Bottom)- Nathan's own concept.
  - Consulting with group for unique design ideas.
- Hot-Wire Release (Top Right) - Common balloon release.

Design

- Solidworks
- KiCAD







Samantha Fortin

Recovery Systems Lead - Individual Report

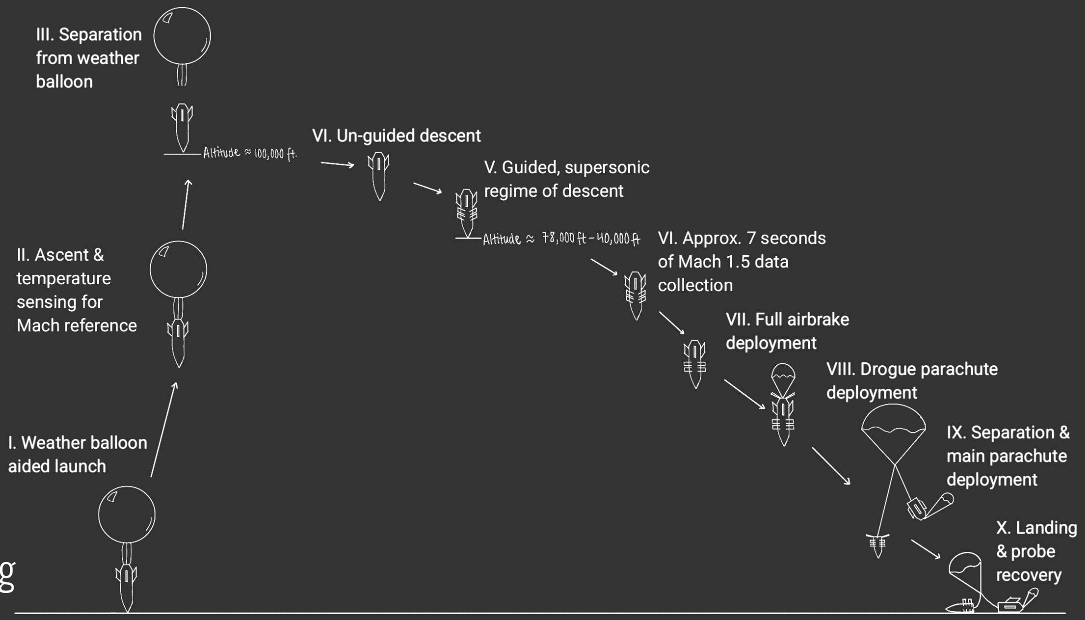
University of Minnesota
Driven to Discover[SM]

Samantha Fortin - Lifelong Learning

- Teamwork & communication in professional setting
  - External design consultation
- Research & design process to meet system requirements
  - Design modification for system limitation developments
  - Project planning & time management
  - Iteration
- MatLab skills applied to physical modeling
- Result analysis & presentation of data

Samantha Fortin - Team Contributions

- Concept of Operations
- **Recovery Systems Lead**
  - Parachute system design
    - Deployment
    - Dimensions
    - Opening forces/shock loading
  - T.W. Knacke. Parachute Recovery Systems Design Manual (1991)



Samantha Fortin - Primary Tasks

Parachute Design

- Recovery system ConOps
- Parachute types
  - Trade study
  - Rocket team consultations
- Deployment
  - Methods
    - Trade study
- Dimensions:
  - Performed calculations in MatLab utilizing equations from Knacke's recovery systems manual

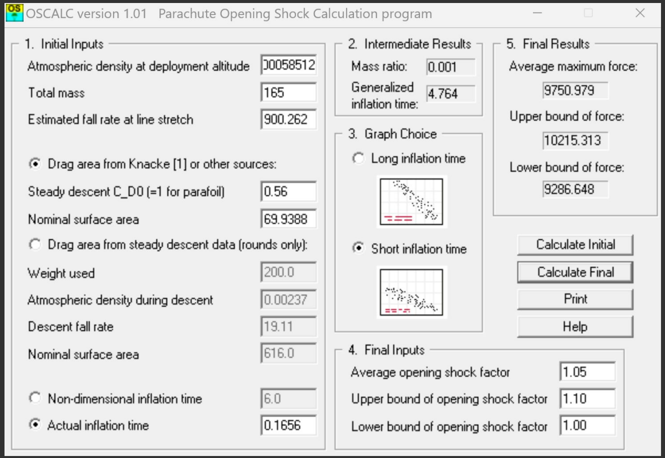
```
%% Recovery Variables
g = 32.1740; % ft/s^2, acceleration due to gravity
c = 1125; % ft/s, speed of sound
W = 165; %lbf, rocket dry weight
V1 = 120; % ft/s, velocity Drogue will slow rocket down to during Main deployment
V2 = 25; % ft/s, velocity Main will slow rocket down to
rho_D = 5.8512*10^(-4); % slugs/ft^3, density @ 40,000 ft MSL (Drogue)
rho_M = 1.9867*10^(-3); %20.48*10^(-4); % slugs/ft^3, density @ 6,000 ft MSL (Main)
CD_D = 0.56; % estimated coefficent of drag for CR at high speeds
CD_M = 0.45; % estimated coefficent of drag for DGB during main deployment
Ng_D = 20; % # of gores of drogue
Ng_M = 12; % # of gores of main

%% Drag = Weight Eqn, Solved for Area => Diameter
% Drogue (D)
n_D = 8; % constant for filling distance as a multiple
VL_D = 1.3 * c; % Mach 1: Velocity at line stretch (ve
q_D = .5*rho_D*V1^2; % lbf/(ft^2) dynamic pressure at
So_D = W/(q_D*CD_D); % ft^2, nominal surface area of D
Do_D = sqrt(So_D*4/pi); % ft, nominal diameter of D; e
tf_D = (n_D*Do_D)/(VL_D^0.9); % Canopy filling time

% Main (M)
n_M = 4; % constant for filling distance as a multiple
VL_M = 120; % Velocity at line stretch, in ft/s
q_M = .5*rho_M*V2^2; % lbf/(ft^2) dynamic pressure aft
So_M = W/(q_M*CD_M); % ft^2, nominal surface area of M
Do_M = sqrt(So_M*4/pi); % ft, nominal diameter of M; e
Ro_M = Do_M/2; % ft, nominal radius of M
tf_M = (n_M*Do_M)/VL_M; % Canopy filling time
```

```
%% Parachute Weight Calculations
% Drogue (conical ribbon)
Wc_D = 0.00694; % lb/(ft^2), specific canopy weight
Wrt_D = 0.00694; % lb/ft/1000-lb strength, specific weight of radial tape
Frt_D = 550; % lb, strength of the radial tape
Nsl_D = Ng_D; % Number of suspension lines
Ls_D = Do_D*1.5; % ft, Length of suspsnsion lines
Wsl_D = 0.0074; %0.0035; % lb/ft/1000-lb strength, Specific weight of kevlar suspension lines
Fsl_D = 2000; % lb, strength of suspension line

% Weight of drogue parachute (conical ribbon)
Wp_D = (SoTRUE_D * Wc_D) + ((DoTRUE_D/2)*Ng_D*Wrt_D*(Frt_D/1000)) + (Nsl_D*Ls_D*Wsl_D*(Fsl_D/1000));
% Packed volume of drogue parachute
fold_t_D = 0; % Thickness of parachute fabric when folded
P_Vol_D = (pi * (DoTRUE_D^2) * fold_t_D) / 4;

% Main (disk gap band)
Wc_M = 0.020833; % lb/(ft^2), specific canopy weight
Wrt_M = 0.00694; % lb/ft/1000-lb strength, specific weight of radial tape
Frt_M = 550; % lb, strength of the radial tape
Nsl_M = Ng_M; % Number of suspension lines
Ls_M = Do_M*1.7; % ft, Length of suspsnsion lines
Wsl_M = 0.0074; %0.0035; % lb/ft/1000-lb strength, Specific weight of suspension lines
Fsl_M = 2000; % lb, strength of suspension line

% Weight of main parachute (DGB)
Wp_M = (So_M * Wc_M) + ((Do_M/2)*Ng_M*Wrt_M*(Frt_M/1000)) + (Nsl_M*Ls_M*Wsl_M*(Fsl_M/1000));
% Packed volume of drogue parachute
fold_t_M = 0; % Thickness of parachute fabric when folded
P_Vol_M = (pi * (Do_M^2) * fold_t_M) / 4;
```

Samantha Fortin - Primary Tasks

Parachute Forces & Shock Loading

- OSCalc: Open source software
  - Enter dimensions & specifications from MatLab calculations and Knacke's recovery systems manual



- MatLab:
  - Equations from Knacke's recovery systems manual
    - Iterative process

```matlab
%% Force of Parachute Opening
% Drogue (D)
Fdrag_D = q_D * So_D;
decel_dist_D = ((1.2*c)^2 - V1^2) / (2*g*(8-1)); % ft, required deceleration distance
CanopyLoad_D = W/(CD_D*So_D); % psf, parachute canopy loading
Cx_D = 1.05; % Opening force coefficent at infinite mass, dimensionless
X_D = 0.32; % Force-reduction factor, dimensionless
openF_D = (CD_D * So_D) * (0.5 * rho_D * VL_D^2) * Cx_D * X_D;
openFlower_D = (CD_D * So_D) * (0.5 * rho_D * VL_D^2) * 1.0 * X_D;
openFupper_D = (CD_D * So_D) * (0.5 * rho_D * VL_D^2) * 1.10 * X_D;
accel_D = openFupper_D / W_slug;
Gforce_D = accel_D / g;

% Main (M)
Fdrag_M = q_M * So_M;
decel_dist_M = (V1^2 - V2^2) / (2*g*(8-1)); % ft, required deceleration distance
CanopyLoad_M = W/(CD_M*So_M); % psf, parachute canopy loading
Cx_M = 1.30; % Opening force coefficent at infinite mass, dimensionless
X_M = 0.05; % Force-reduction factor, dimensionless
openF_M = (CD_M * So_M) * (0.5 * rho_M * VL_M^2) * Cx_M * X_M;
openFlower_M = (CD_M * So_M) * (0.5 * rho_M * VL_M^2) * 1.2 * X_M;
openFupper_M = (CD_M * So_M) * (0.5 * rho_M * VL_M^2) * 1.4 * X_M;
accel_M = openFupper_M / W_slug;
Gforce_M = accel_M / g;
```

Nathan Gall

Individual Report

UNIVERSITY OF MINNESOTA
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Nathan Gall-Lifelong Learning

- Communication and Teamwork
    - My design process relied heavily on the design and analysis of other members (Aerodynamics, Dynamic Properties)
    - Facilitated consultation with other Collins team to get CFD analysis
    - Provided consultation with other Collins team on dynamics simulation
- Research and Design
    - Researched relevant literature on missile dynamics and control
    - Iterated Controller design to meet robustness requirements
- Technical Skills
    - Robust Control
    - Uncertainty Modeling
    - Simulink Modeling

Nathan Gall-Design Contributions

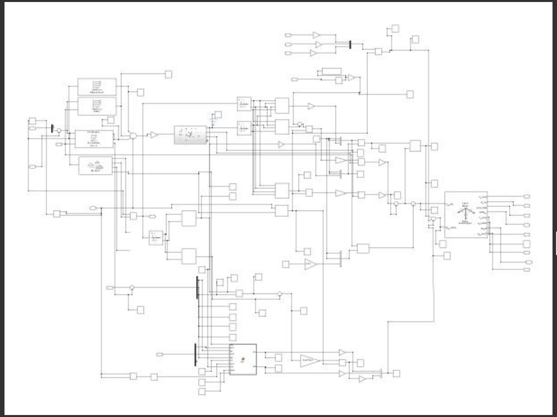
Control Systems Lead

-Dynamic Modeling

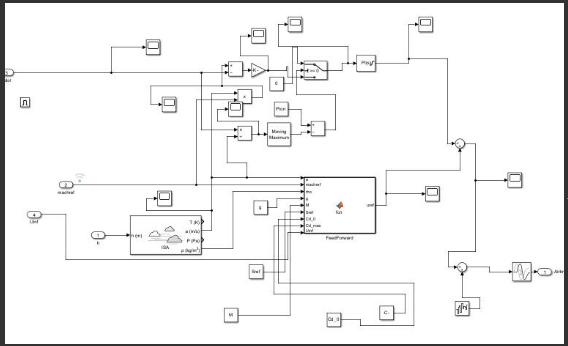
- Reduced order aerodynamic model
- Uncertainty quantification
- Nonlinear simulation in Simulink

-Control design

- PI + Feedforward control for mach reference
- μ-Synthesis for Attitude Control



High fidelity dynamics model



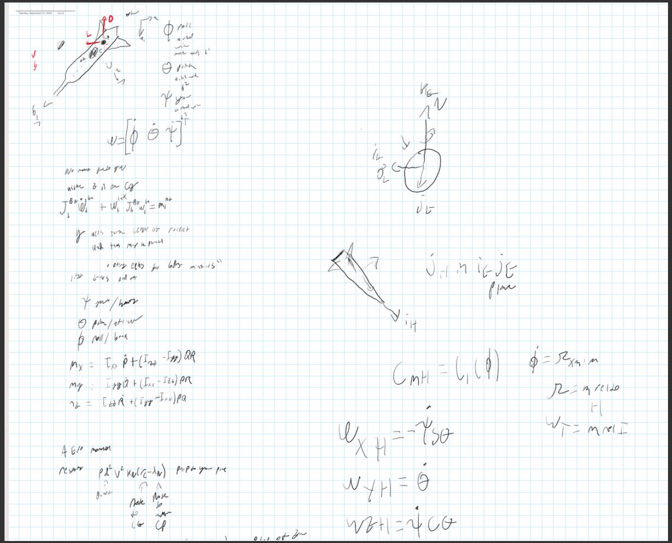
Air Brake Control Logic

Nathan Gall-Primary Tasks

Design Process

1. Model System
2. Determine Requirements
3. Choose Control Method
4. Synthesize Controller
    a. Analyze Performance
        i. If unable to meet requirements, return to step 3
    b. Simulate system
        i. If fail, tune parameters
5. Reduce Complexity of Controller

Initial dynamic model scratchwork



PI control Design Script

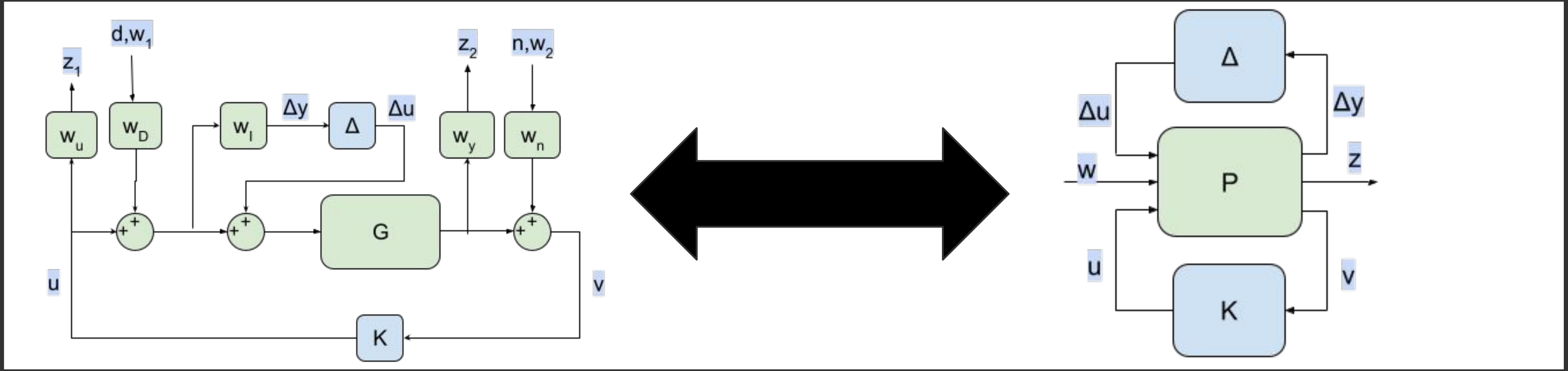
```
%parameters

uhat = ureal("uhat",0.5,"range",[0 1]);%actuation range

Cd_0 = 0.354;%base CD
Cd_max = 1.7;%Max possible CD
%create A and B matrices
A = -rho/M*Sref*Cd_0*Uinf-rho/M*Sref*(Cd_max-Cd_0)*uhat*Uinf;%df/dx
B = -1/2*rho*Sref/M*(Cd_max-Cd_0)*Uinf^2;%df/du
Z = g-1/2*rho/M*Uinf^2*Sref*Cd_0-1/2*rho*Uinf^2*Sref*(Cd_max-Cd_0)*uhat...
    - A*Uinf -B*uhat;%f(x_0)-Ax_0-Bu_0

G = ss(A,B,1,0);%create state space mode
Gd = ss(A,1,1,0);%Disturbance model
De_airbrake = 5.9;%expected deflection scaling

Dd = 250;

%normalize plant mode
Gs = De_airbrake\G;
Gds = De_airbrake\G;

%sample unceratain plants
Gsamp = usample(Gs,1e3);

%TF with maximum bandwidth (UNUSED)
Gmax = usubs(Gs,"SoS",299,"rho",0.326,"uhat",1);
```

```
%Bound Gain
[Usys_AB,Info_AB] = ucover(Gsamp,Gs.NominalValue,0);
Gcover = Usys_AB.NominalValue*(1+Info_AB.W1);

%Plot system response
figure()
bode(Gs)
hold on
grid on
% bode(Gmax,'r')
bode(Gcover,'r')
title("Airbrake Response")


%Get system response parameters
[Gsnum,Gsdom] = tfdata(Gmax);
[Gcnum,Gcdom] = tfdata(Gcover);
k = Gsnum{1}(2);
k_c = Gcnum{1}(2);
tau = Gsdom{1}(1)/Gsdom{1}(2);
tau_c = Gcdom{1}(1)/Gcdom{1}(2);
theta_delay = 0.2;
tc = 1;

%Synthesize PI controller using SIMC rules
Kpi = 1/k*tau/(tc+theta_delay)*(1+1/(s*min(tau,4*(tc+theta_delay))));
Kpi_cover = 1/k_c*tau_c/(tc+theta_delay)*(1+1/(s*min(tau_c,4*(tc+theta_delay))));
[PInum,PIden] = tfdata(Kpi);
[PIcnum,PIcden] = tfdata(Kpi_cover);
```

Nathan Gall-Primary Tasks

Attitude Control Design

- Normalize models to maximum signal size
- Model System Uncertainty: Input Multiplicative, Unstructured Complex matrix
- Create Shaping filters
  - Uncertainty: 25% low frequency move to 40% above 5 rad/s
  - Lowpass reflecting PSD of gyro spec
  - Disturbances: lowpass with cutoff ~1rad/s to reflect Kolmogorov Spectrum
  - Control Action: penalize response above 300 rad/s
  - Roll Response: penalize errors <60 rad/s
  - Pitch/Yaw Response: penalize errors <1 rad/s
- Assemble plant model into standard form
- Synthesize Controller using musyn from MATLAB Robust Control Toolbox



Pranav Kartha

Embedded Systems Lead - Individual Report

UNIVERSITY OF MINNESOTA
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Pranav Kartha - Lifelong Learning

Communication

- Learned the importance of timely coordination with team members
- Time management and reconciling project progress with other coursework
- Determining clear deliverables

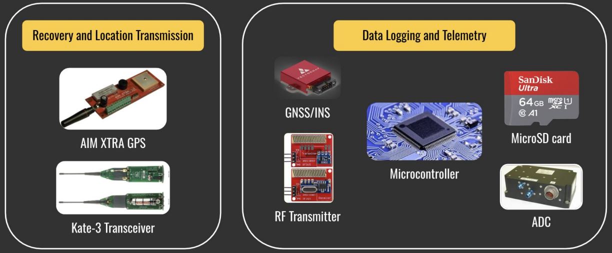
Research/technical skills

- Learned how to research
- Gained experience in electronic design
  - Reading datasheets
- Learned about heat transfer
  - Forced convection
  - Radiation

Pranav Kartha - Primary Tasks

Avionics design

- Parts selection
  - Determination of required peripherals
  - Choosing accurate sensor to reference Mach number
- Requirements verification
  - Ensuring components can achieve required performance in operating conditions
- Circuit design
  - Creating schematic symbols
  - Making required connections for communication between microcontroller and peripherals



Pranav Kartha - Primary Tasks

Thermal analysis

- Determination of heat transfer during ascent and descent
  - Ascent:
    - Using the Nusselt number correlations for forced convection over a flat plate to determine heat transfer coefficient
    - Determining radiative dissipation to the environment
  - Descent
    - Using isentropic compressible flow theory to determine upper bound for temperature
- Ensuring heat loss/gain is within limits for electrical components
- Selection of insulation and heating material

```
for dev = -20:5:15
    [t, T] = ode45(@(t, T) deltaTemp(t, T, u, m, L, A, dev), t, T_init);
    T = T - 273.15;
    if dev > 0
        label = sprintf("ISA+%d", dev);
    elseif dev < 0
        label = sprintf("ISA%d", dev);
    else
        label = "ISA";
    end
    plot(alt, T, "DisplayName", label);
    hold on
end
title("Airframe Temperature vs Altitude", "FontSize", 14)
xlabel("Altitude (m)", "FontSize", 14)
ylabel("Temperature (deg C)", "FontSize", 14)
legend("FontSize", 14)

T_maxMach = atmosisa(12000) + 15;
M_max = 2;

stagnationTemp = T_maxMach*(1 + M_max^2*(1.4 - 1)/2) - 273.15;

function dTdt = deltaTemp(t, T, u, m, L, A, isaDev)
    Re_crit = 5e5;
    Pr = 0.71;
    T_0 = 273; % K
    k_0 = 0.0241; % W/m*K
    S_k = 194; % K
    c = 1000; % J/kg*K
    e = 0.175;
    e_sky = 0.741 + 0.0062*(273.15 + 15);
    sigma = 5.670374419e-8;
```

```
clear; close all

%% Constants/ICs
u = 5; % m/s
L = 3.91; % m
m = 19.5; % kg
A = 1.59; % m^2
T_init = atmosisa(0); % K
Re_crit = 5e5;
Pr = 0.71;
T_0 = 273; % K
k_0 = 0.0241; % W/m*K
S_k = 194; % K
c = 1000; % J/kg*K
e_sky = 0.741 + 0.0062*(273.15 + 15);

%% Anon funcs
k = @(T) (T/T_0).^(3/2).*((T_0 + S_k)./(T + S_k)).*k_0; % Sutherland's Law
Re = @(nu) u*L./nu;
Nu = @(Pr, Re) 0.6774*Pr.^(1/3).*Re_crit.^(1/2)/(1 + (0.0468./Pr).^(2/3)).^
h = @(Pr, nu, T) Nu(Pr, Re(nu)).*k(T)./L;

%% Simulation
alt = 1:30480;
t = alt/5;
[T_inf, ~, ~, ~, nu, ~] = atmosisa(u*t);

plot(alt, h(Pr, nu, T_inf))

% [T, a, P, rho, nu, mu] = atmosisa(alt(t));
% hs = h(Pr, nu, T);
%
% plot(t, hs)
```

Liam Normand

Individual Report

UNIVERSITY OF MINNESOTA
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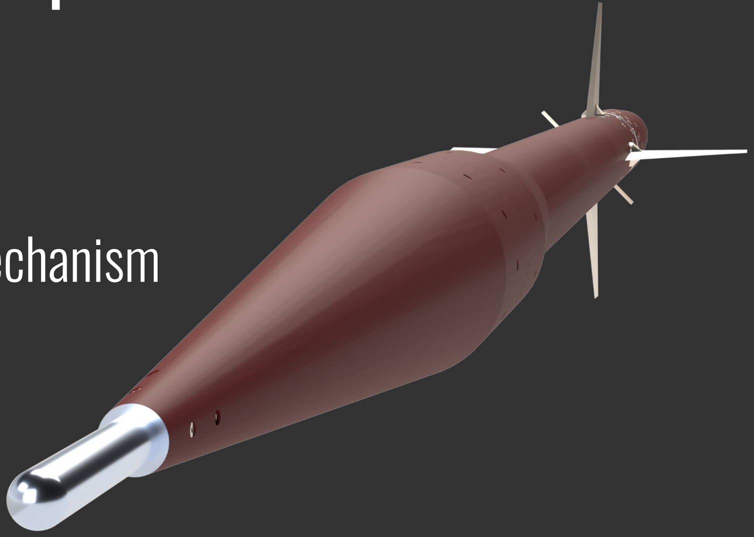
Liam Normand – Lifelong Learning

- **Communication**
  - Clear descriptions of project requirements and asking clarification questions as they arise
  - Determining breakdown of responsibilities for individual team members
  - Asking for assistance with complicated problems and unfamiliar topics
- **Technical Skills and Design**
  - Gained further experience with large assemblies in CAD
  - Integration of commercial systems and familiarization with locating technical component specification documents
  - Better understanding material requirements and properties
  - Focus on use of standard COTS hardware where possible for cost reduction and ease of component sourcing
  - Design for manufacturability and limited available tooling

Liam Normand – Primary Responsibilities

CAD Lead

- Vehicle system layout and ballistic simulations
- Vehicle CAD – Everything except for airbrake mechanism
  - Airframe dimensions and profile
  - Recovery system and payload mounting points
  - Control surface actuator selection and integration
  - Material selection
- Component Renders



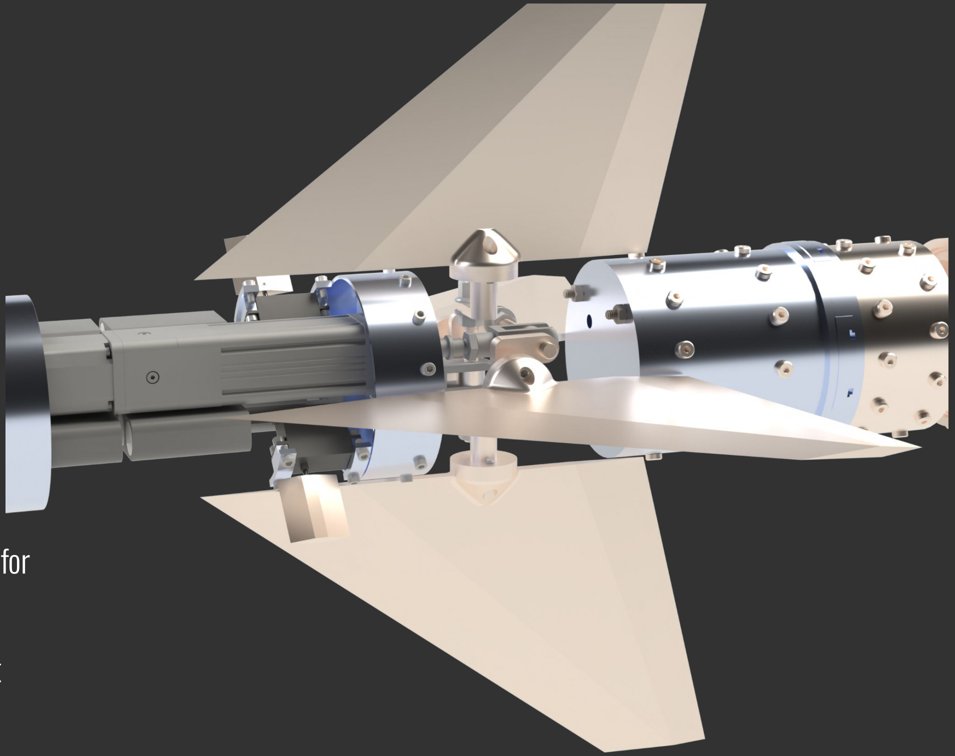
Liam Normand – Engineering Process

Determination of Requirements

- Small angular range of actuation with high torque
- Large system acceleration and positional accuracy feedback
- Small cross-sectional profile to fit inside airframe
- Achievable power source (24V, 90W nominal, DC)

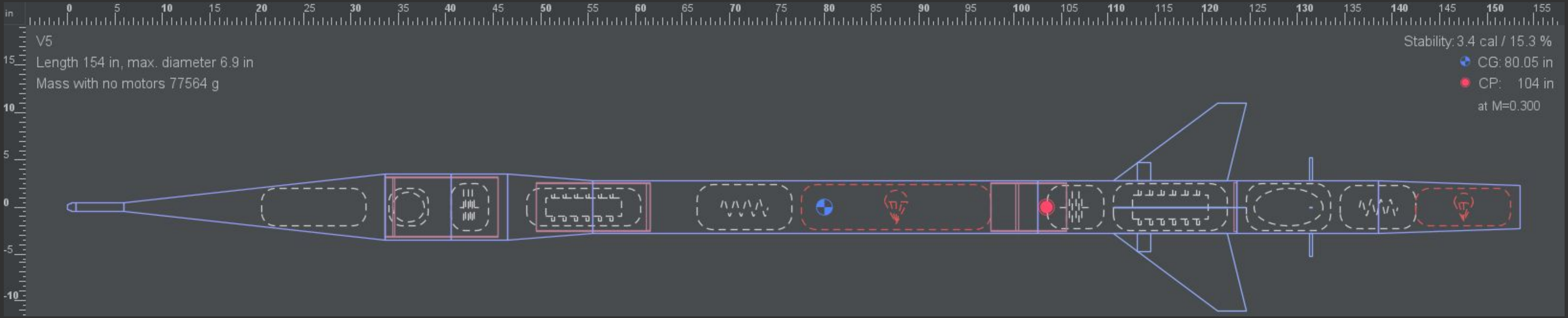
Design of control actuator bay

- Component research and selection for capable actuators
    - Initially sought direct drive with a servo motor, but found no satisfactory high-torque servos commercially available
    - Considered augmentation with a gearbox, but found no commercially available gearboxes that fit inside airframe
    - Considered linear actuation systems inspired by the AIM-9
    - Read through component catalog and technical specifications for multiple SKUs from multiple suppliers, settling on a 32mm standard from Ewellix
- After identifying a capable actuator, moved to design a mechanism that utilized its advantage of high driving force and flange mounting



Liam Normand – Engineering Process

Using known tools as a starting point for new applications



Quentin Saylor

Aerodynamics Lead - Individual Report

University of Minnesota
Driven to Discover℠

Quentin Saylor: Lifelong Learning

Communication

- Importance of clear and timely communication with other group members
- Division of tasks, alterations to workloads based on challenges

Planning and Time Management

- Estimation of required time, planning and internal deadlines, flexibility

Technical Skills

- Enhanced understanding of compressible aerodynamics
- Learning about failure analysis and mitigation strategies
- Development of complete and rigorous testing procedures to ensure compliance to all requirements

Quentin Saylor: Primary Responsibilities

Aerodynamics Lead

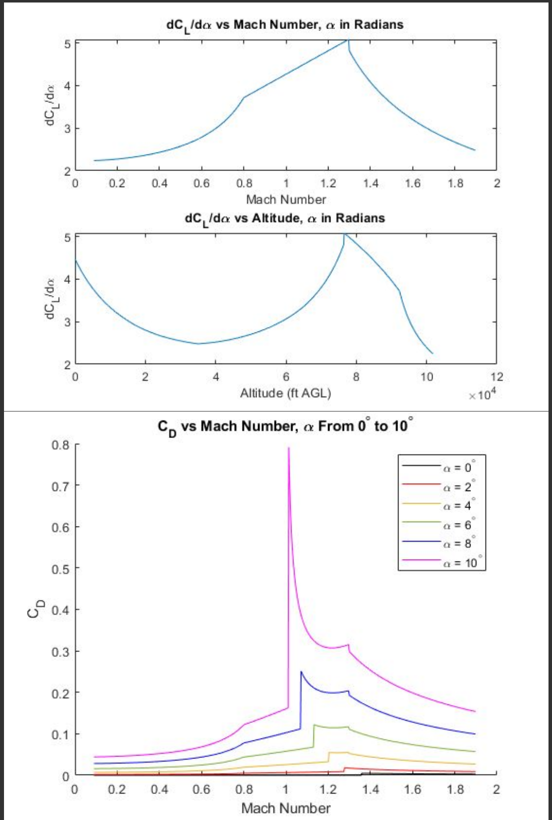
- Analytical C_L and C_D predictions for attitude control system
- Analytical approximate force predictions for airbrake deployment
  - Hand calcs used to determine expected torque force from airbrake actuator
- Assistance in conceptual design of attitude control actuators
  - Method of actuation of fins, assistance in airbrake mechanical design

Logistics and Systems Engineering Contributions

- Led development and primary contributor to completion of FMEA
- Developed plans for testing campaign of vehicle and subsystems
- Developed preliminary Gantt chart for build and test phase

Quentin Saylor: Aerodynamic Calculations

- Used compressible aerodynamics to model coefficients of attitude control surfaces
  - Wave drag accounted for in drag modeling
  - Transonic regime approximated via interpolation due to lack of exact analytic model
  - Results determined to be accurate for design decisions in absence of access to CFD analysis
- Airbrake drag approximated with pressure difference between upwind and downwind sides
  - Obtained via isentropic relations with correction factor
  - Analytical computations used as fallback due to inability to obtain external CFD analysis



Quentin Saylor: Logistics and Systems Engineering

Failure Mode Effects and Analysis

- Developed updated FMEA criteria from PDR, increased granularity of criteria
- Led development of list of potential failure modes, FMEA characterization of modes, and mitigation strategies

Test Campaign Development

- Developed multi-phase ground and flight testing campaign for system
- Ensured testing would fully verify compliance to all requirements, and ensure safety in current and future test procedures

Build and Test Gantt Chart: Developed Preliminary Schedule, Deadline Dates (BRR, FRR)