MIT RocketTeam

2015-2016 Project Therion Critical Design Review

March 10, 2016

Agenda

- Team Overview
- Competition Overview
- System Overview, Schedule
- Subsystems
  - Propulsion
  - Structures
  - Recovery
  - Avionics
  - Payload
- Systems Level Risks
- Goal Evaluation

Team

50 MIT affiliates

5 subteams

Photo: IREC 2015, Utah

Competition

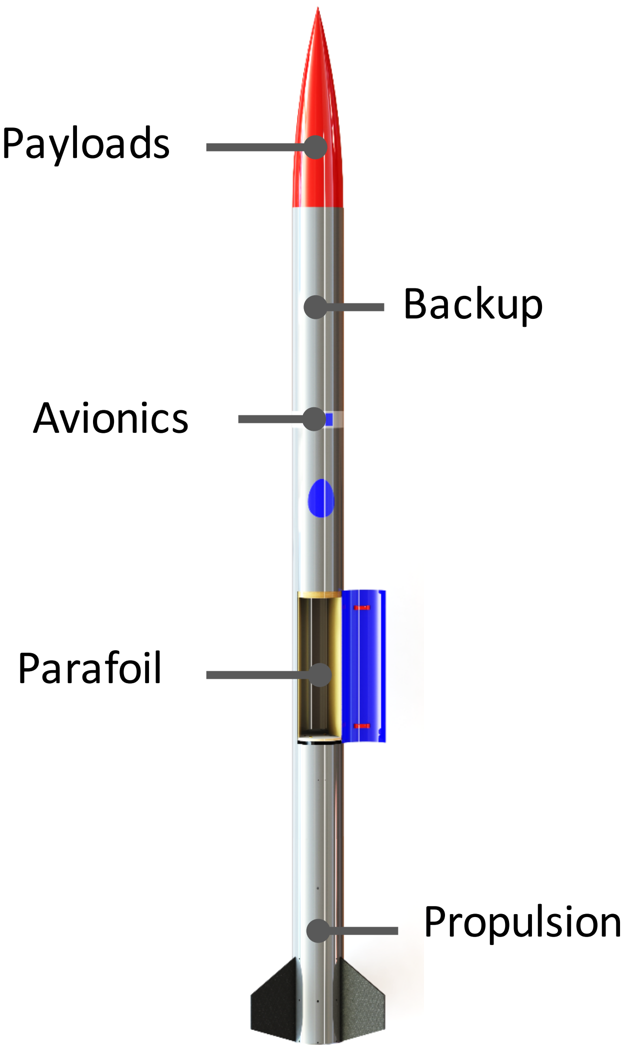
- Intercollegiate Rocket Engineering Competition (IREC)
- Hosted by Experimental Sounding Rocket Association (ESRA)
- Green River Utah, June 2016
- Last year
  - 41 Rockets, 7 countries
  - 1^{st} place in Basic Category
- This year
  - Basic Category
  - 10,000ft Target Apogee
  - 10lb payload
- Preparing for Advanced Category 2017
  - All components student designed and built

Scoring

- Distance from target altitude
- Professionalism
- Payload
  - Complexity
  - Scientific Value
  - Mission Completion
- Recovery
- Poster Presentation

System Spec

- Propulsion
  - COTS Solid M3400
- Recovery
  - Autonomously actuated Parafoil
  - Single separation, dual deploy backup
- Avionics
  - Custom system
  - Live telemetry
- Structure
  - Composite layups
  - FEM analysis on airframe
- Payloads
  - Plasma Physics Experiment
  - OpenCV Optical Flow Experiment



Concept of Operations

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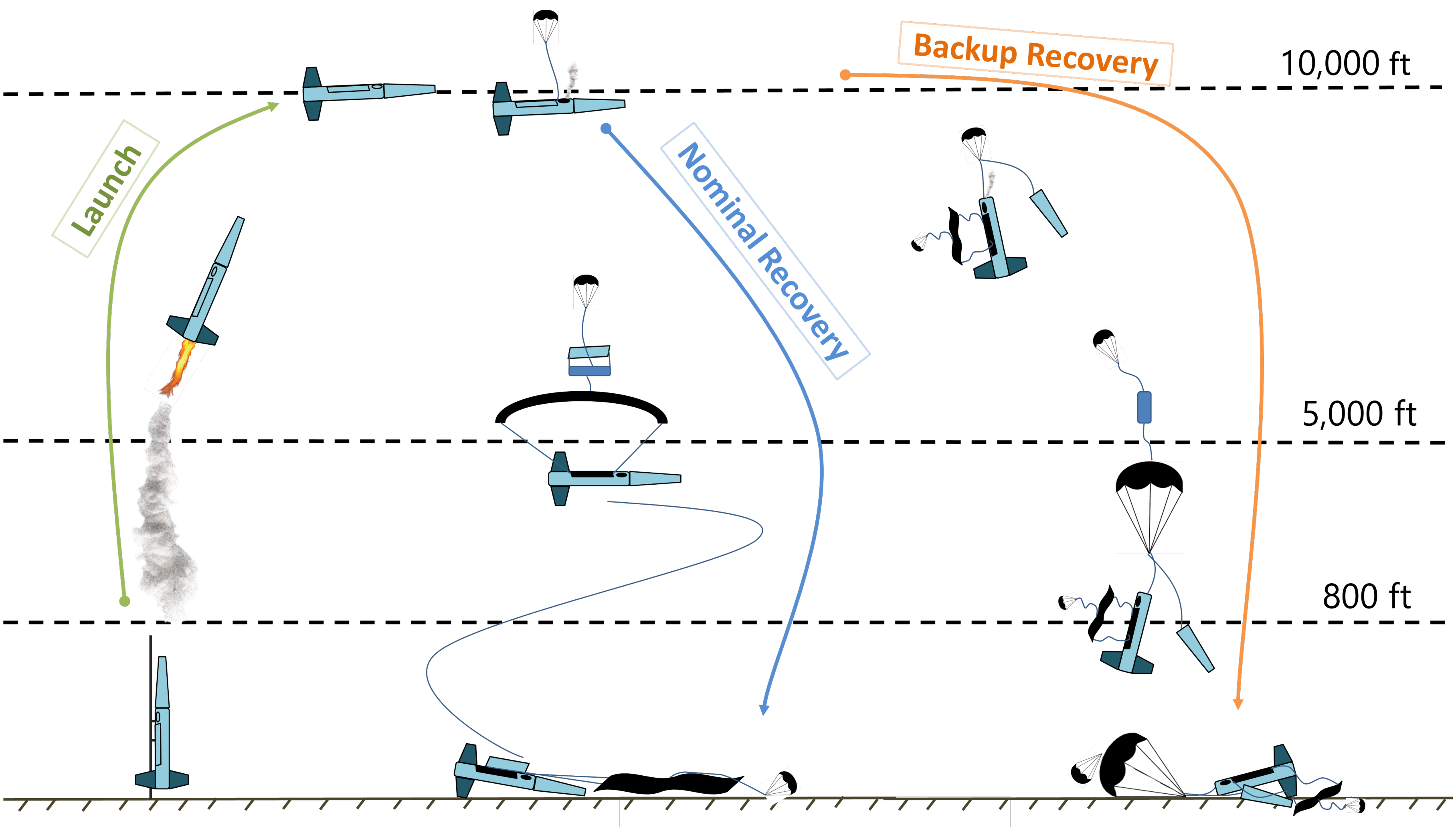

Rocket builds and flights

Launch	Rocket	Features	Date
Flight Test 0	Therion I	Composite wrap, Backup recovery	March 26
Flight Test 1	Therion II	Pure composite structure, Parafoil recovery	April 9
Flight Test 2	Therion III	Full flight test	April 25
IREC	Therion IV	Competition flight	June 15

Propulsion

Project Overview

- 2 Goals
  - Custom Propulsion
  - COTS propulsion for descope

Custom Propulsion

- Many unknown regulations
- Safety concerns
- Tight Schedule

- **Status:** Descoped to COTS motor

Commercial Motor

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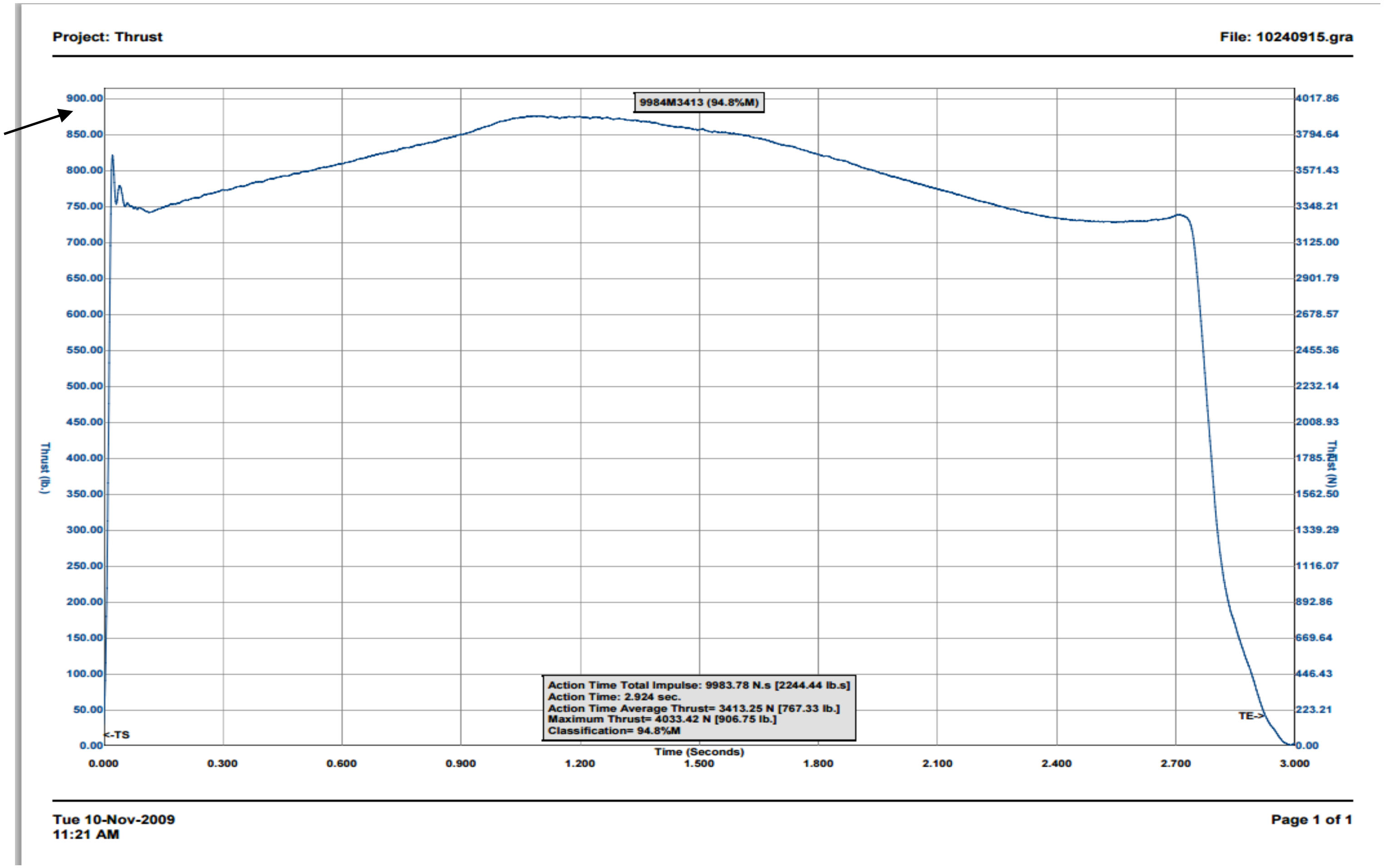
- CTI 9994M3400-P White Thunder
- 9994 Ns Impulse
- Average Thrust: 3421.1 N
- Liftoff mass: 57.3lbs (Dry: 46.7lbs)

Commercial Motor

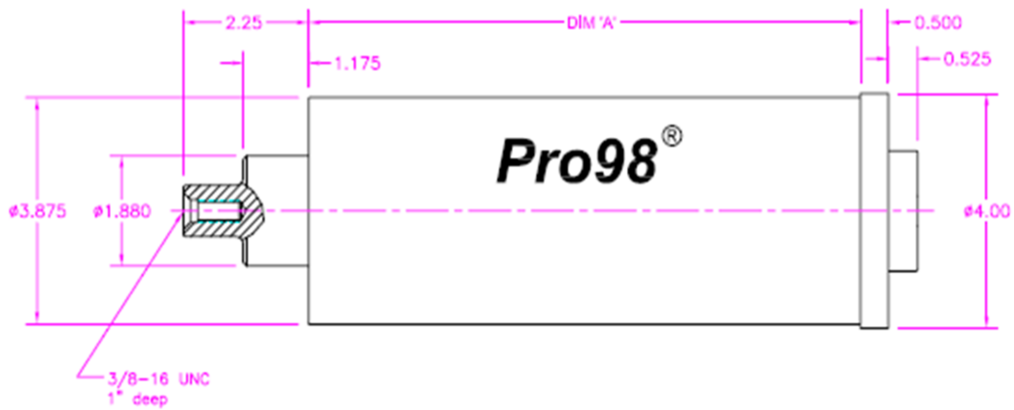
Thrust Curve

900lbs



Motor Casing

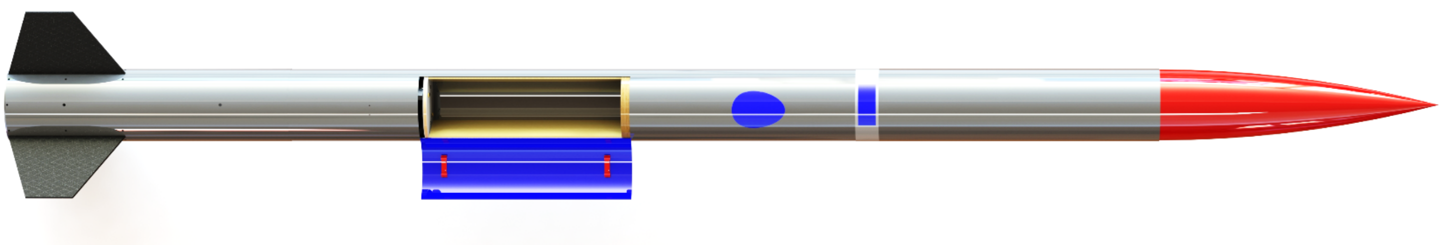
- CTI Pro98-4G case



- Dim 'A' = 27.14in

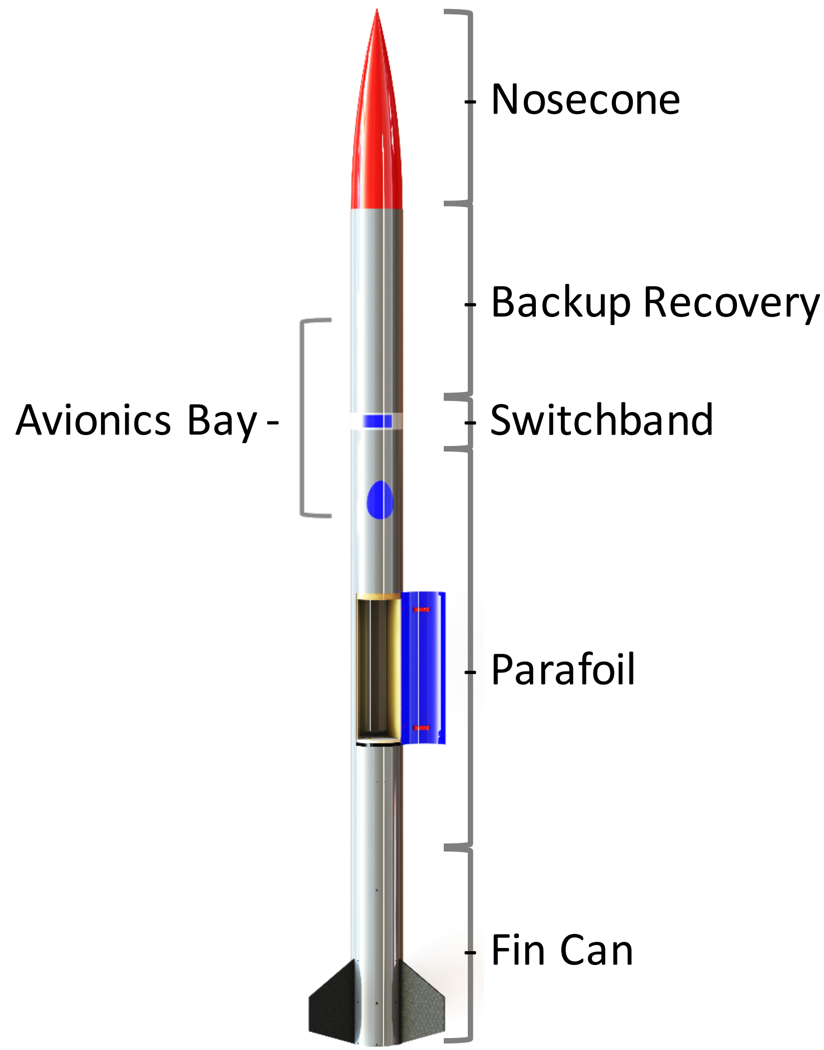
Questions?

Structures



General Specifications

- 6in Diameter
- ~10ft long
  - 24in Fin Can (Prop)
  - 48in Parafoil
  - 2in Avionics Switchband
  - 24in Backup Recovery
  - 24in Nosecone



General Specifications

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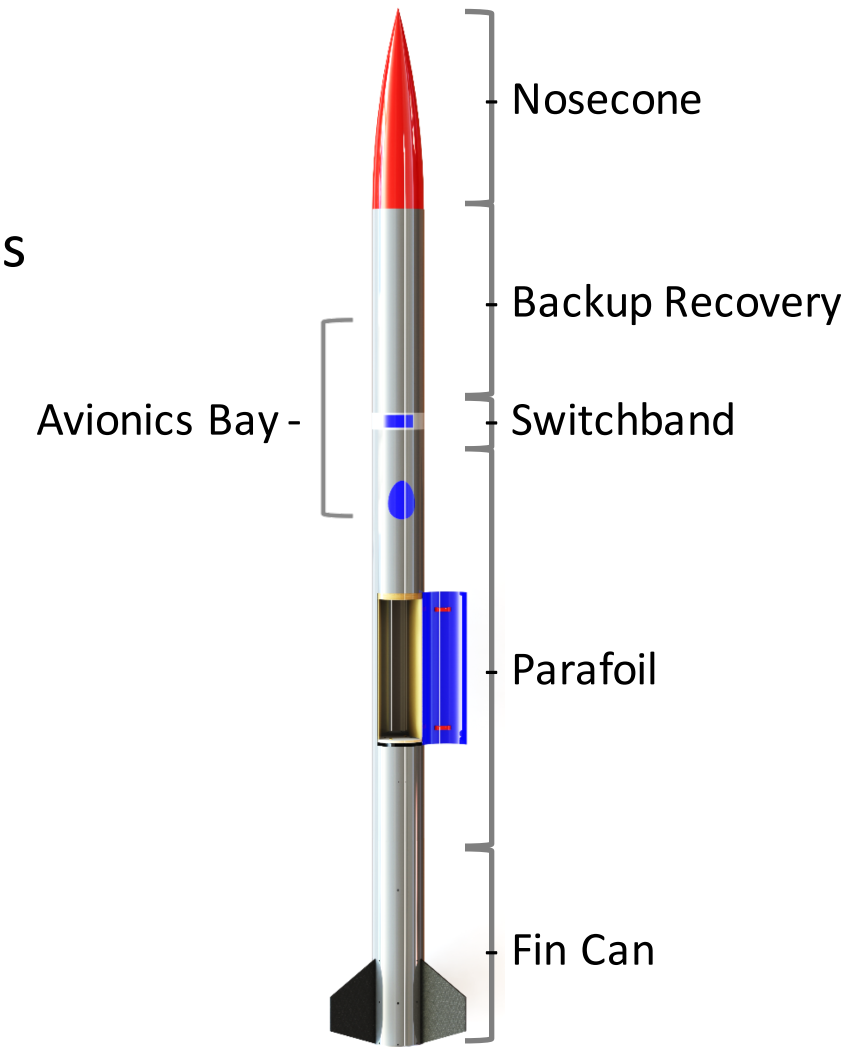
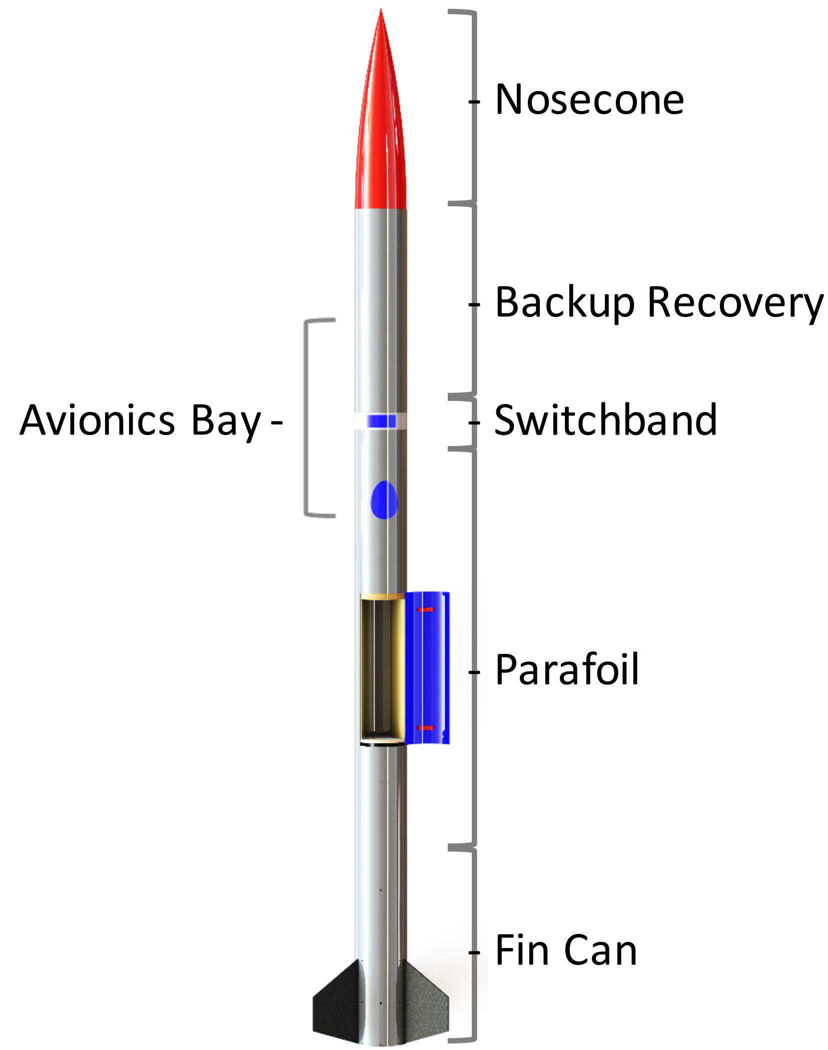
- Nosecone
  - COTS gel-coated fiberglass
  - 4:1 Ogive
- Body tubes
  - 4 ply S-glass
  - 45-45 angle
- Fin Can
  - 4 ply carbon fiber
  - 45-45 angle



General Specifications

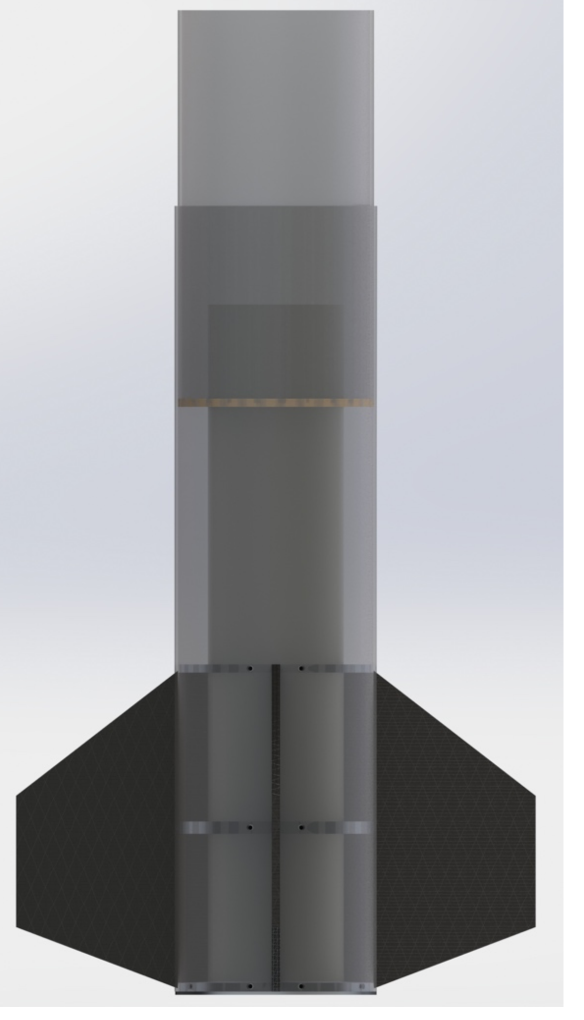
- Couplers
  - COTS phenolic tube
- Bulkheads
  - 0.5in plywood, S-glass sandwich panel



Therion I Progress

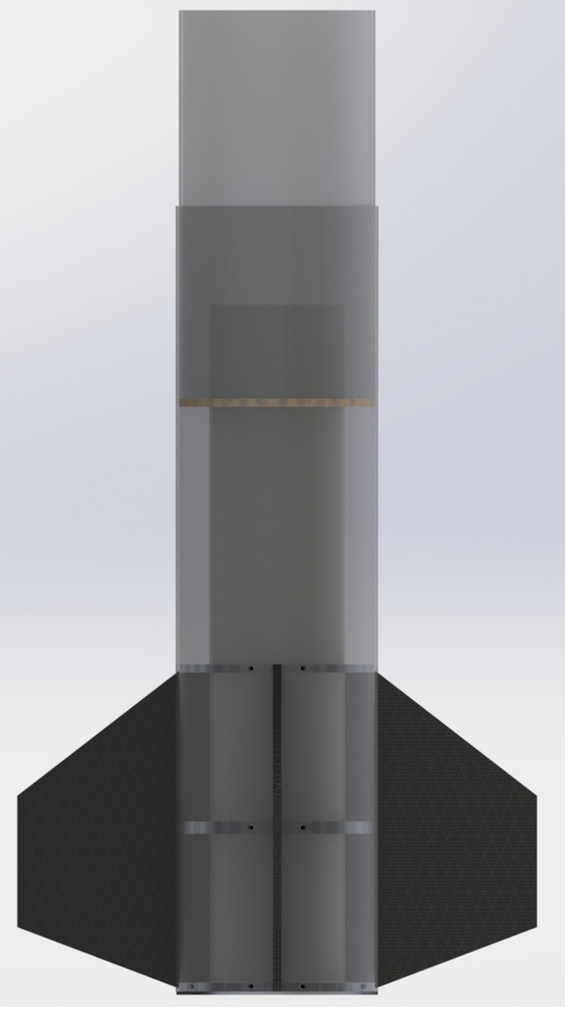
Fin Can Assembly

- 0.5in plywood, carbon fiber centering ring
- Aluminum threaded insert for rail button
- 0.25in aluminum centering ring

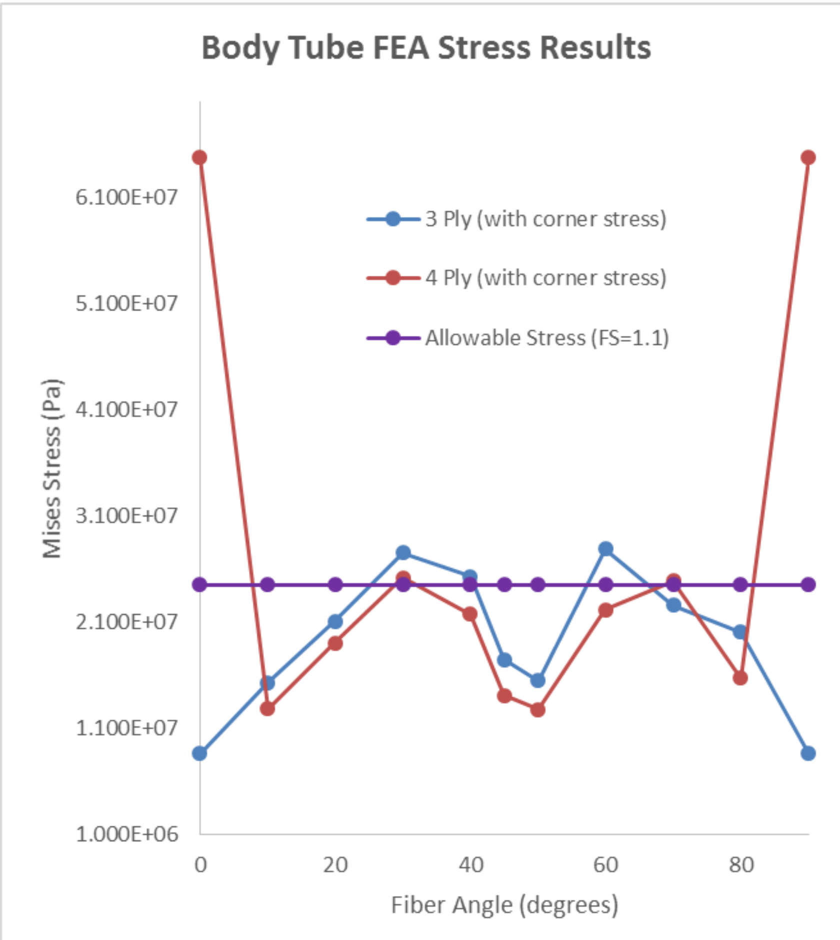


Fin Can Assembly

- 0.375in aluminum centering ring
  - Rail button insert
- 0.375in thrust plate
- Sandwich panel fins
  - 0.25in
  - Foam, 2 ply carbon fiber



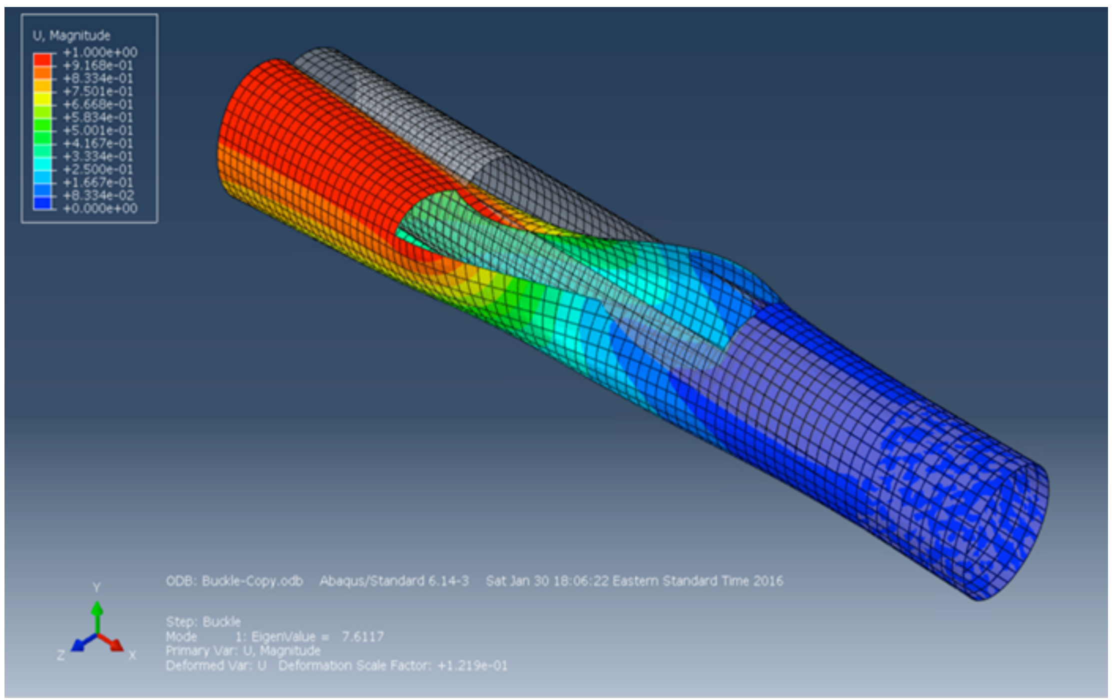
FEM Analysis



- Ran FEA with ABAQUS
  - Swept # of plys and ply angles
- Result: 4 ply, 45 degree angle

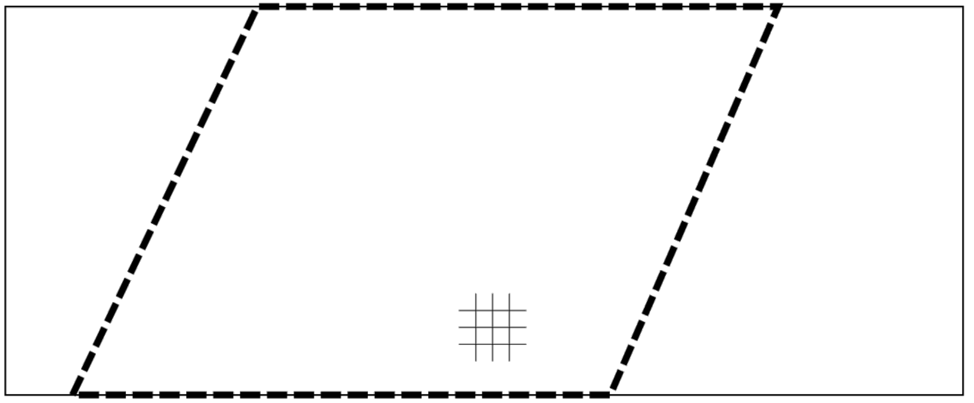
FEA Analysis

- Less than 1mm deflection
- Factor of safety on buckling is 7



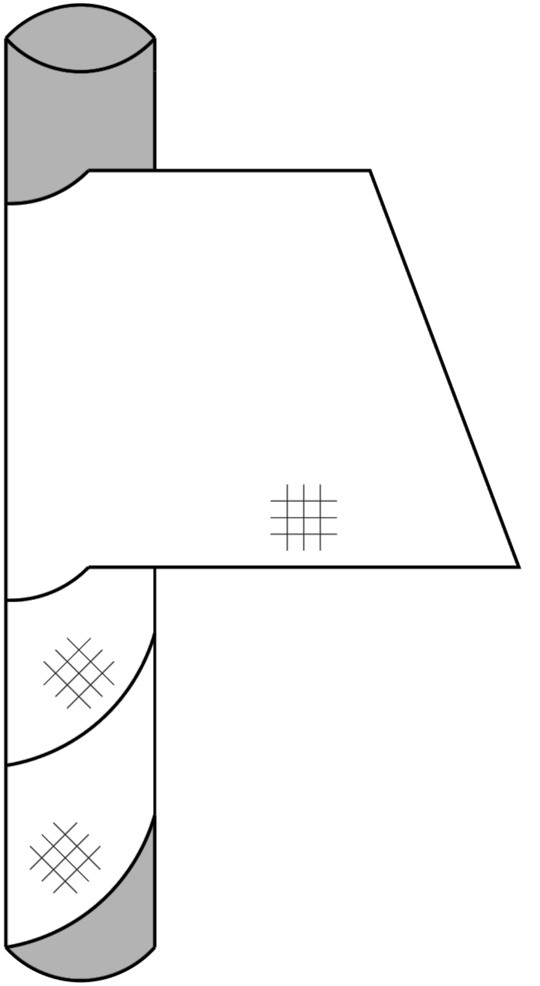
Layup Process

- 4 ply S-Glass
  - 45 and -45 degree fiber angle



Layup Process

- Mandrel Wrapped
- Vacuum at -0.7atm
- Mylar underneath for separation



Questions?

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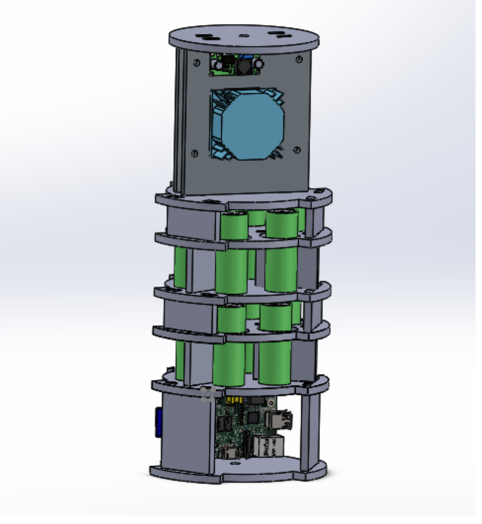
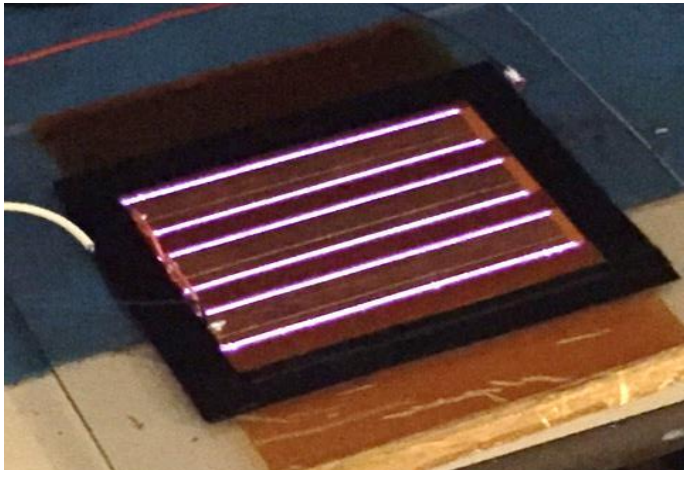
Plasma Physics Experiment

Payload intent

- Use dielectric barrier discharge (DBD) actuators on the rocket nosecone to:
  - Reduce skin drag
  - Shift the shock attachment point aft



Payload module with DBD power supply



DBD electrode prototype

Mode of operation

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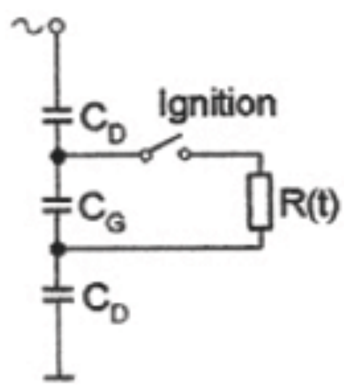
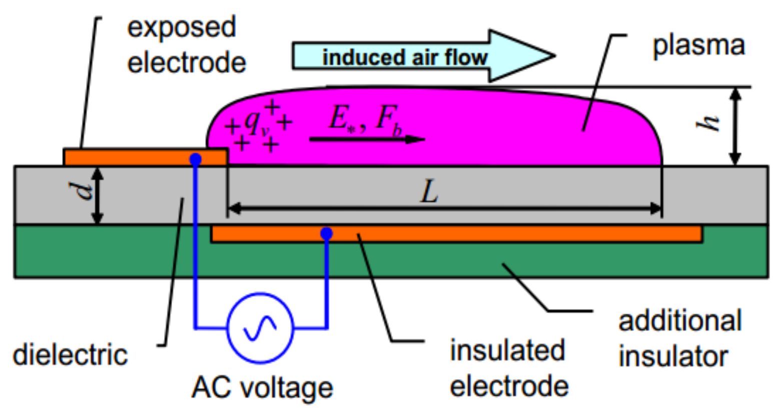
- Dielectric barrier discharge (DBD) actuators use a RF-excited plasma to create a 5-10m/s electric wind
  - Wind vector is tangential to surface, peaks at y=.5mm
  - Primarily a electrohydrodynamic effect*

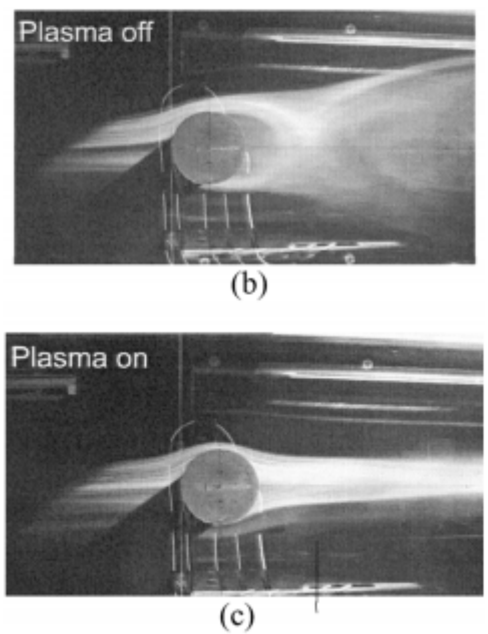




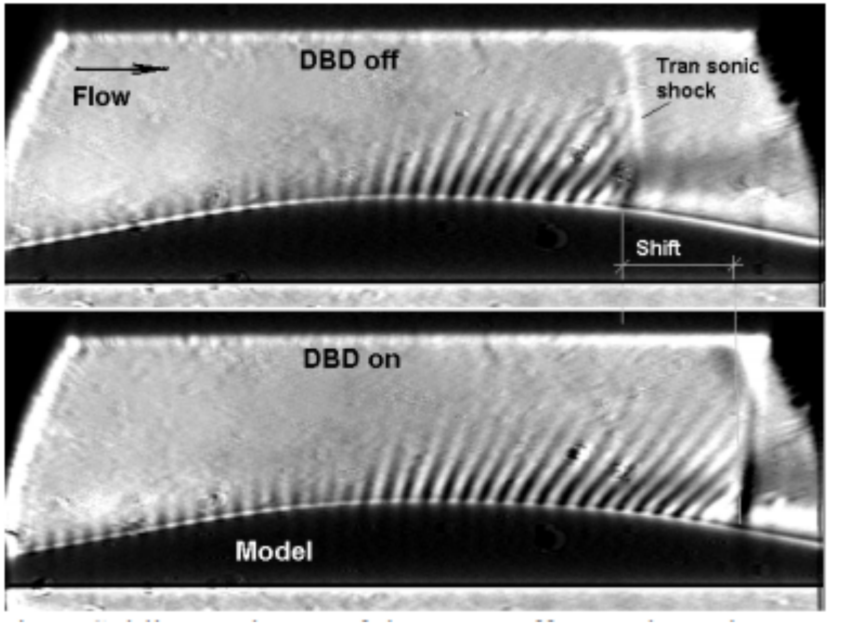
*KOSTOV, K.G.; HONDA, R. Y.; ALVES, L.M.S. and KAYAMA, M.E.. Characteristics of dielectric barrier discharge reactor for material treatment. *Braz. J. Phys*. [online]. 2009, vol.39, n.2 [cited 2016-03-08], pp. 322-325

Mode of operation

- Interactions of the electric wind with the boundary layer can reduce skin friction and promote flow attachment



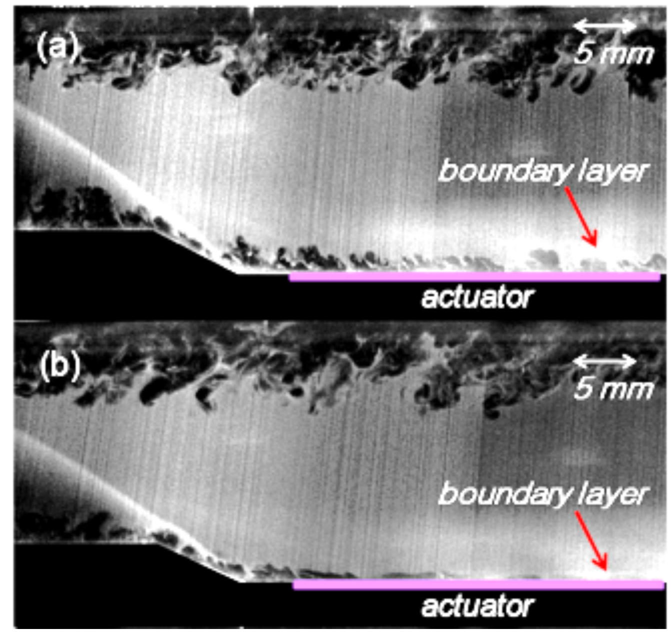
Thomas F O, Kozlov A and Corke T C 2006 Plasma actuators for bluff body flow control. AIAA Meeting (San Francisco, USA, June 2006)paper #2006-2845



Leonov, Sergey, et al. "Supersonic/Transonic Flow Control by Electro-Discharge Plasma Technique." *Proceedings of 25th International Congress of the Aeronautical Sciences*. 2006.

Prior research

- DBD actuators have been shown to reduce drag across a wide variety of flight regimes
  - Kogan et. al.: Flat surface
    - 10m/s flow, 13% drag reduction
  - S. Roy: Vehicle body
    - 30m/s flow, 10% drag reduction
  - A. Duchmann: Airfoil, ~100m/s
    - 3% increase in transition distance from leading edge
  - S. Im – Step in M = 4.7 flow
    - Significant thinning of BL, possible drag reduction



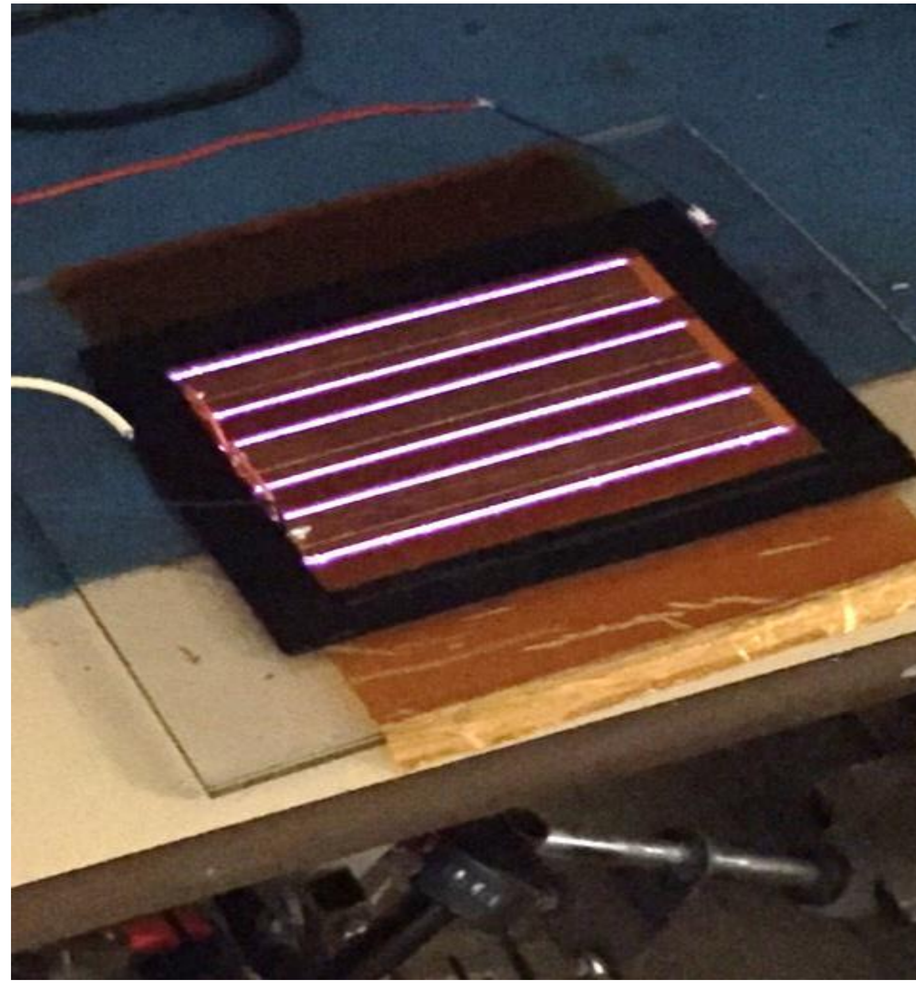
Top: No DBD actuation. Bottom: DBD actuator engaged. Note the significant boundary layer thinning. From S. Im et. al.

- Suggested mechanism: T-S wave damping.
  - EHD effect? Thermal?

Prototype electrodes

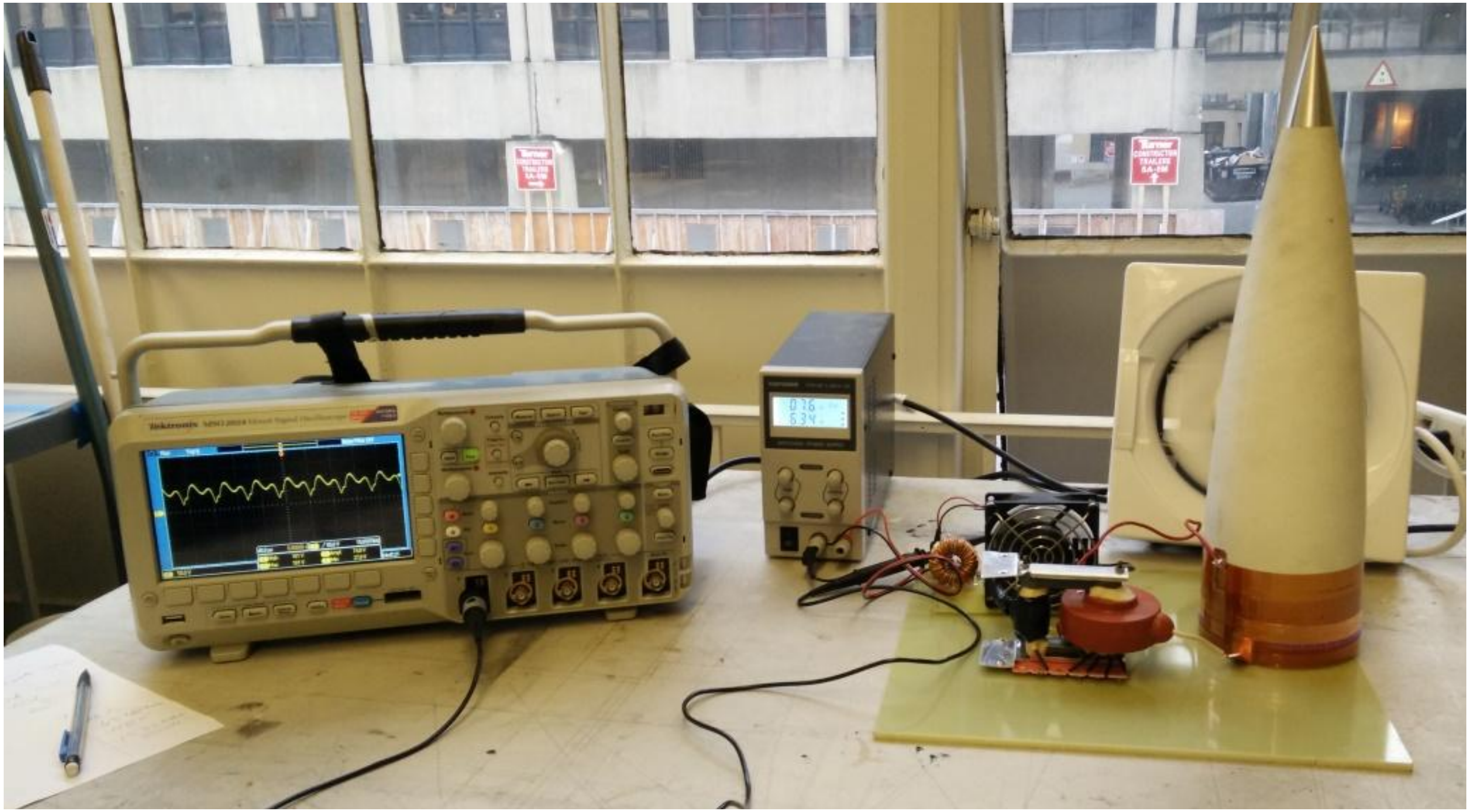
- Our DBD actuators are in series to increase the magnitude of the electric wind

- Electrodes are 10mil Kapton dielectric with Cu conductors
- Top conductor: 6.25mm
- Bottom conductor: 12.5mm
- Offset: 2.0mm
- Driven by 10kV/10kHz



5mil Kapton-copper electrode prototype

Prototype



Wind tunnel tests are in the works

- Hope to show an electric wind velocity > 30m/s

Questions?

OpenCV Optical Flow Experiment

OpenCV Optical Flow Experiment

- Measuring rotation using Lucas-Kanade Optical Flow.

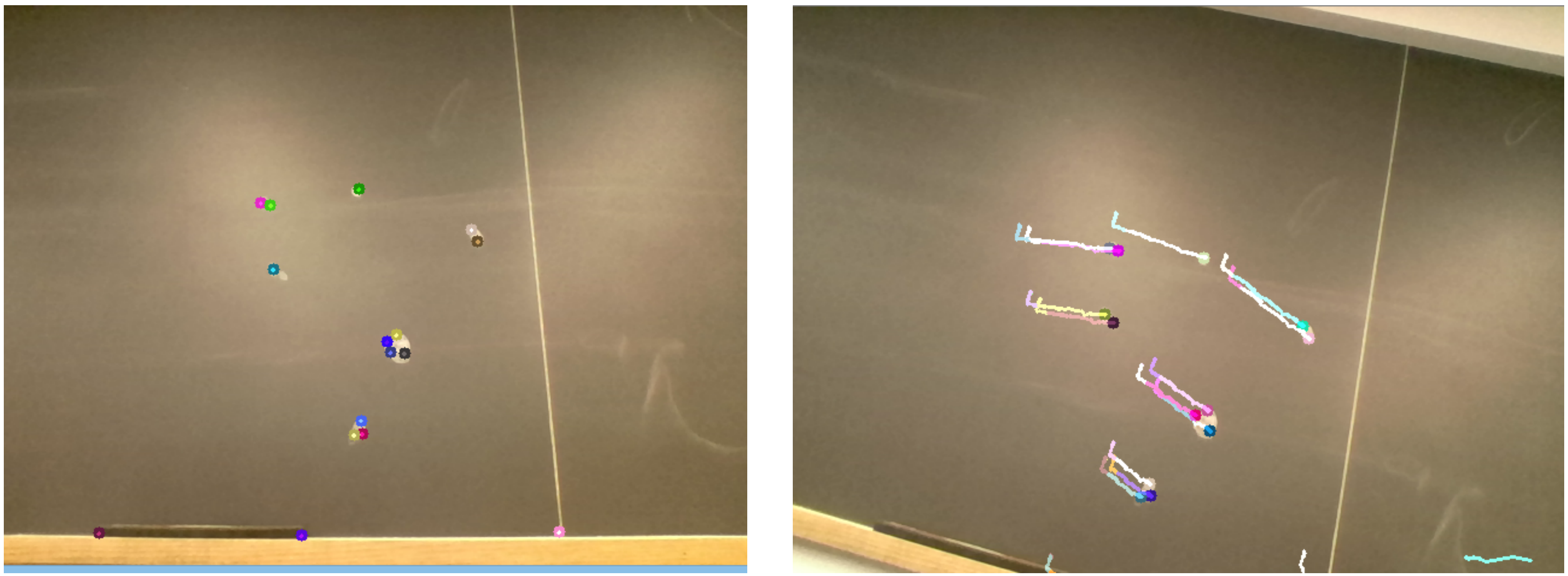
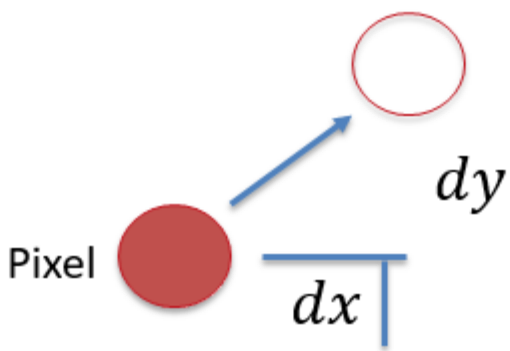


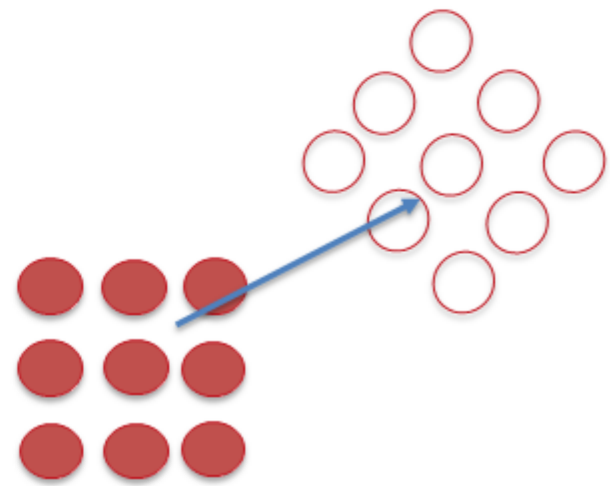
Figure: Visualization of Optical Flow

Lucas-Kanade Method

- A 3x3 pixel patch is used to find displacement

$$I\ (x, y, t) = I(x + dx, y + dy, t + dt) \qquad I_x U + I_y V + I_t = 0$$





Rotation Matrices

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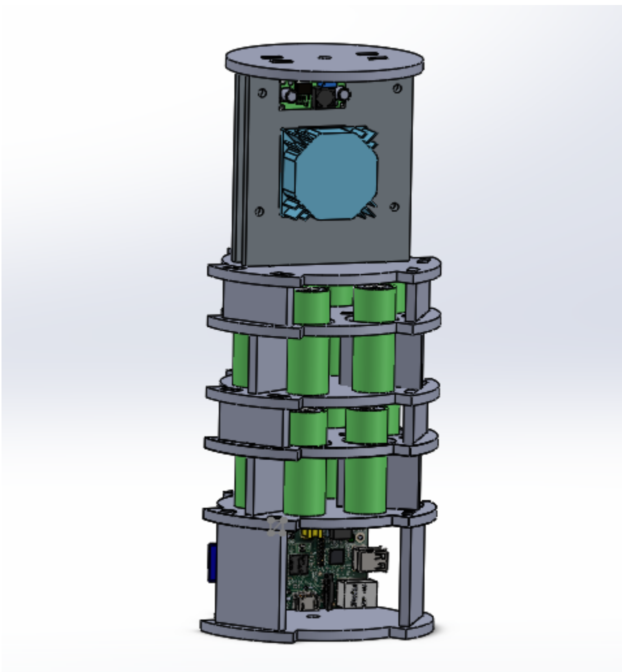
- The rotation matrix for each time step dt is found by inputting displacement

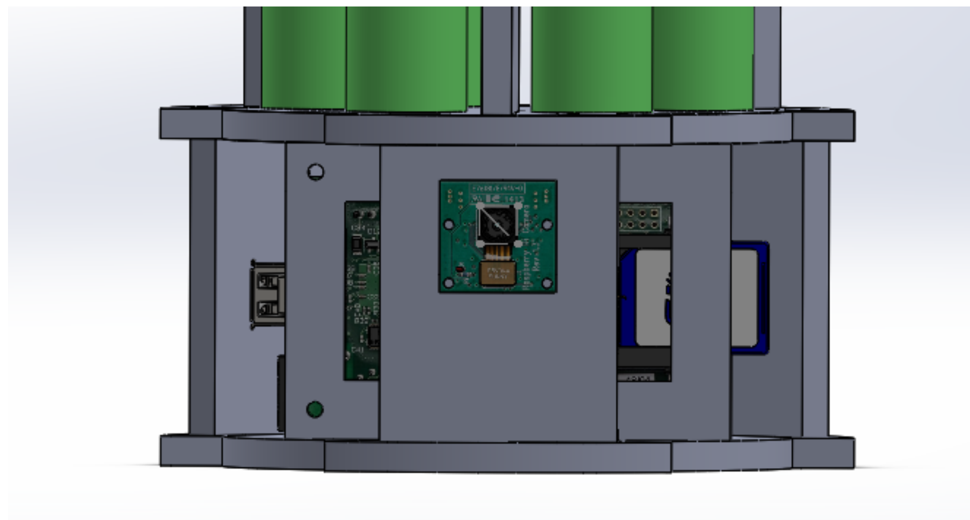
$$R = x'\,x^T\,(xx^T)^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & x_T \\ \sin\theta & \cos\theta & y_T \\ 0 & 0 & 1 \end{bmatrix}$$

Hardware Implementation

- Arducam video camera connected to a Raspberry Pi Model B+

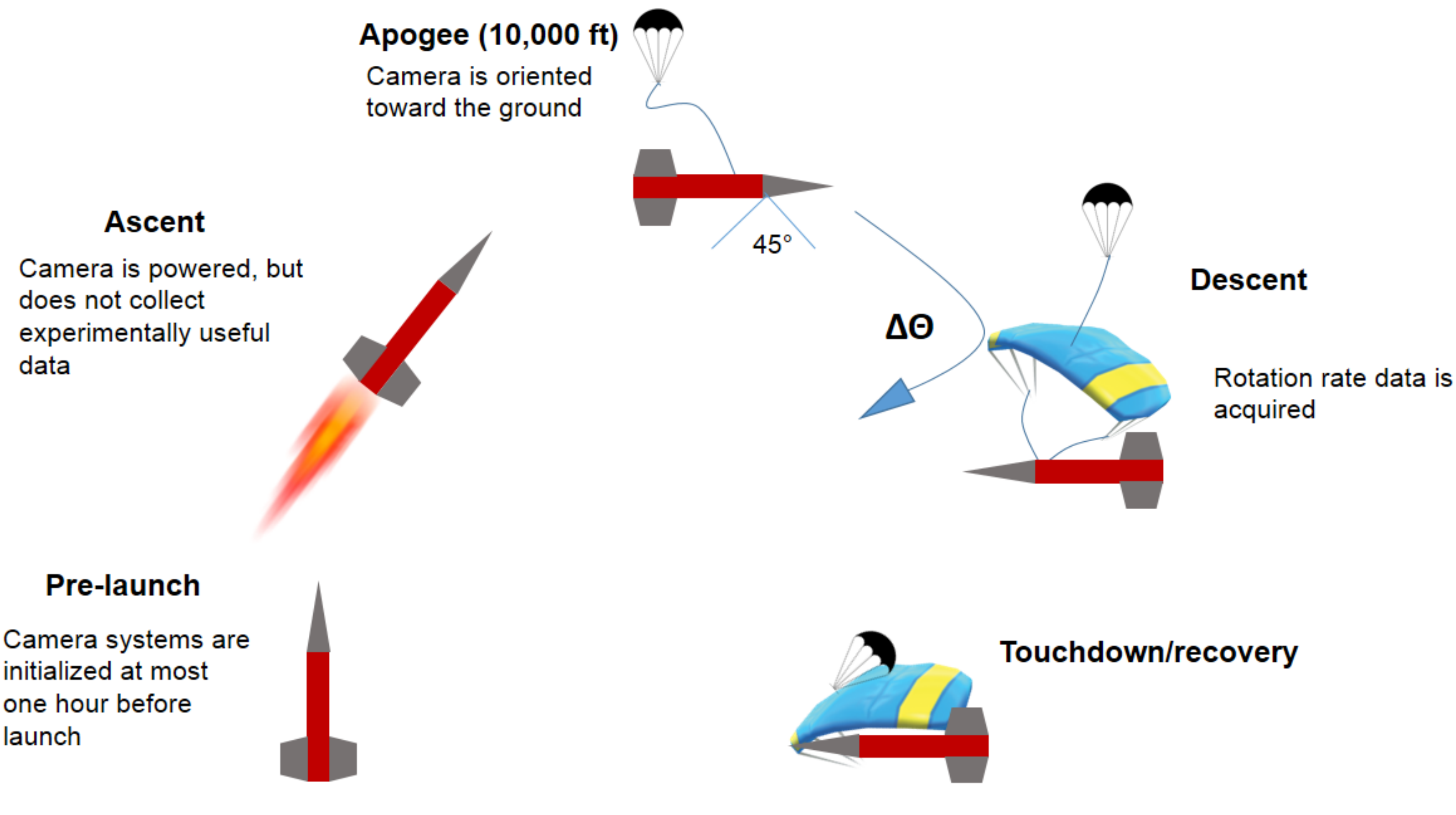


Payload Bay



Optical Flow Experiment Compartment

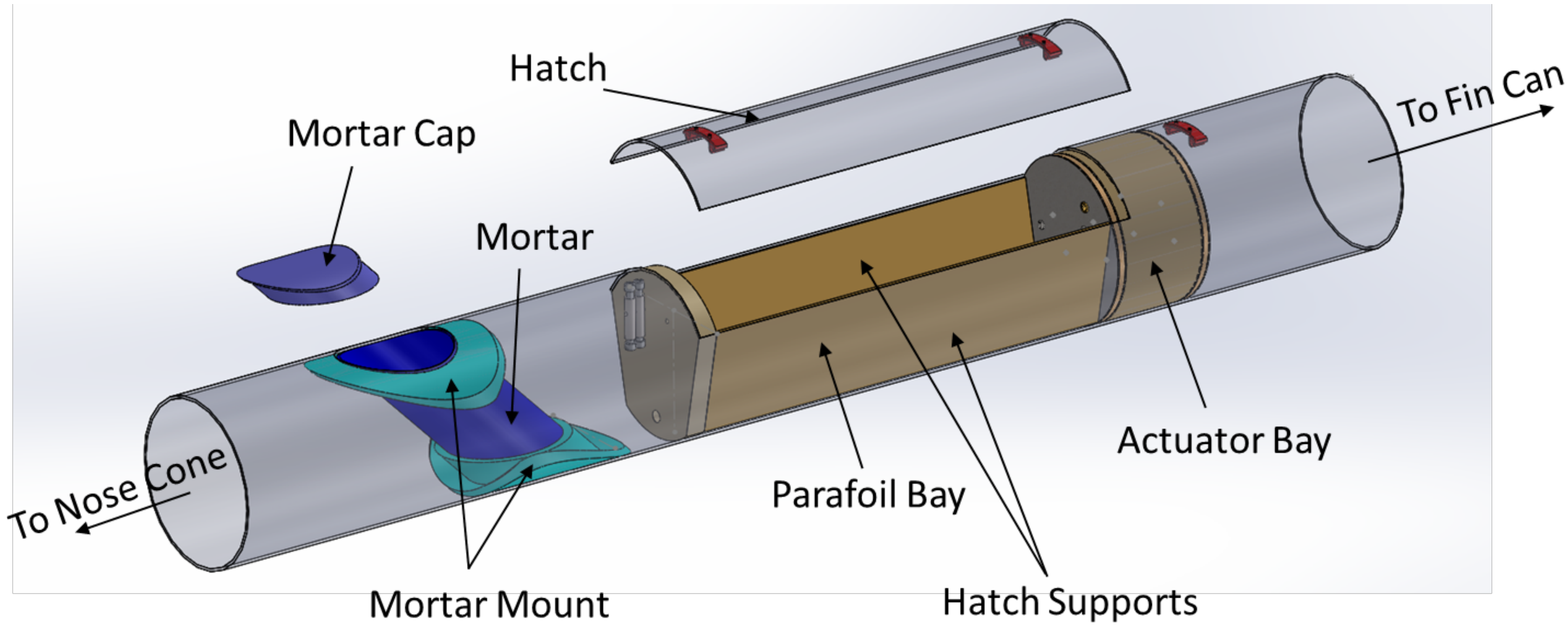
OpenCV CONOPs



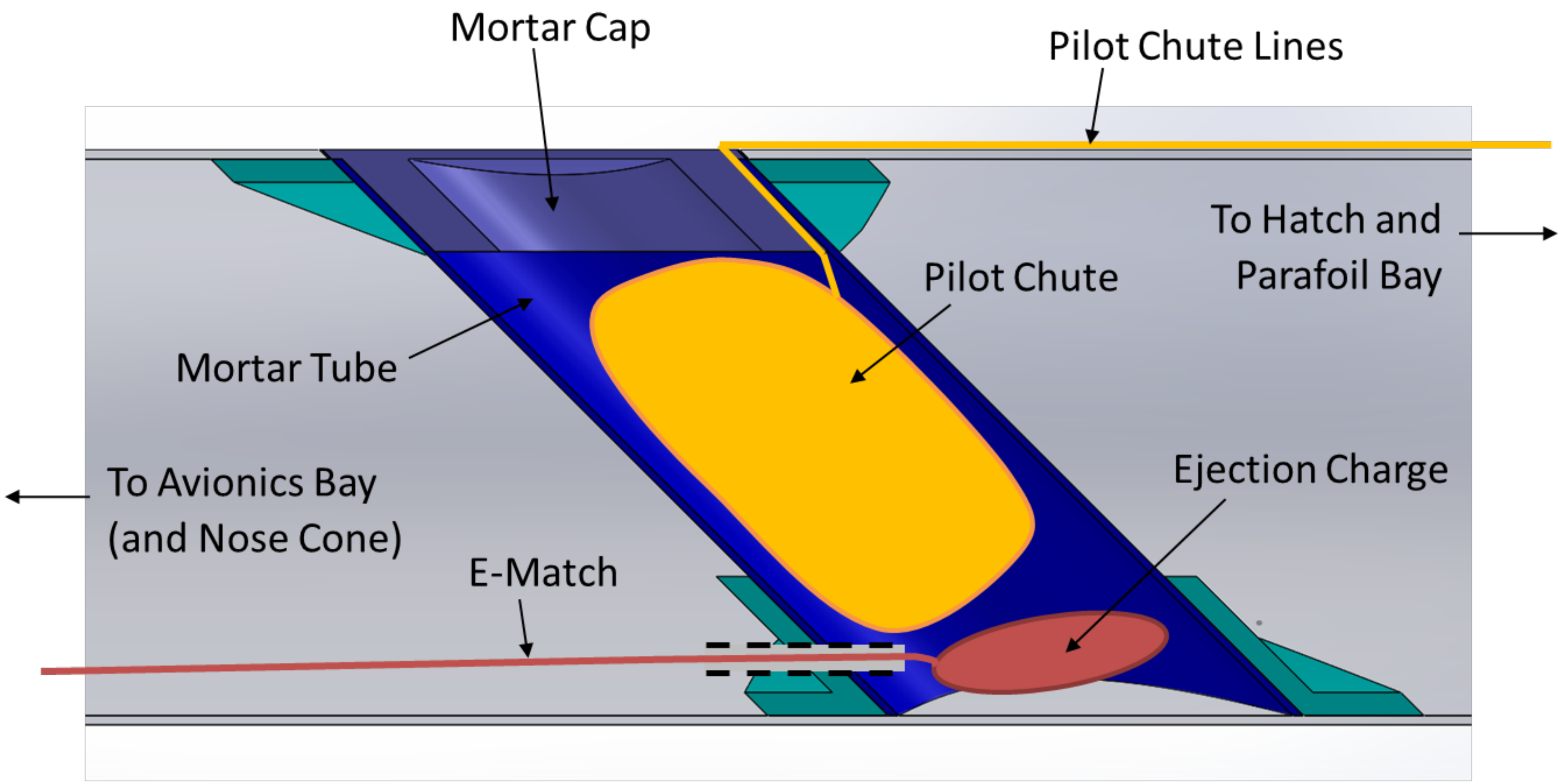
Questions?

Parafoil Recovery

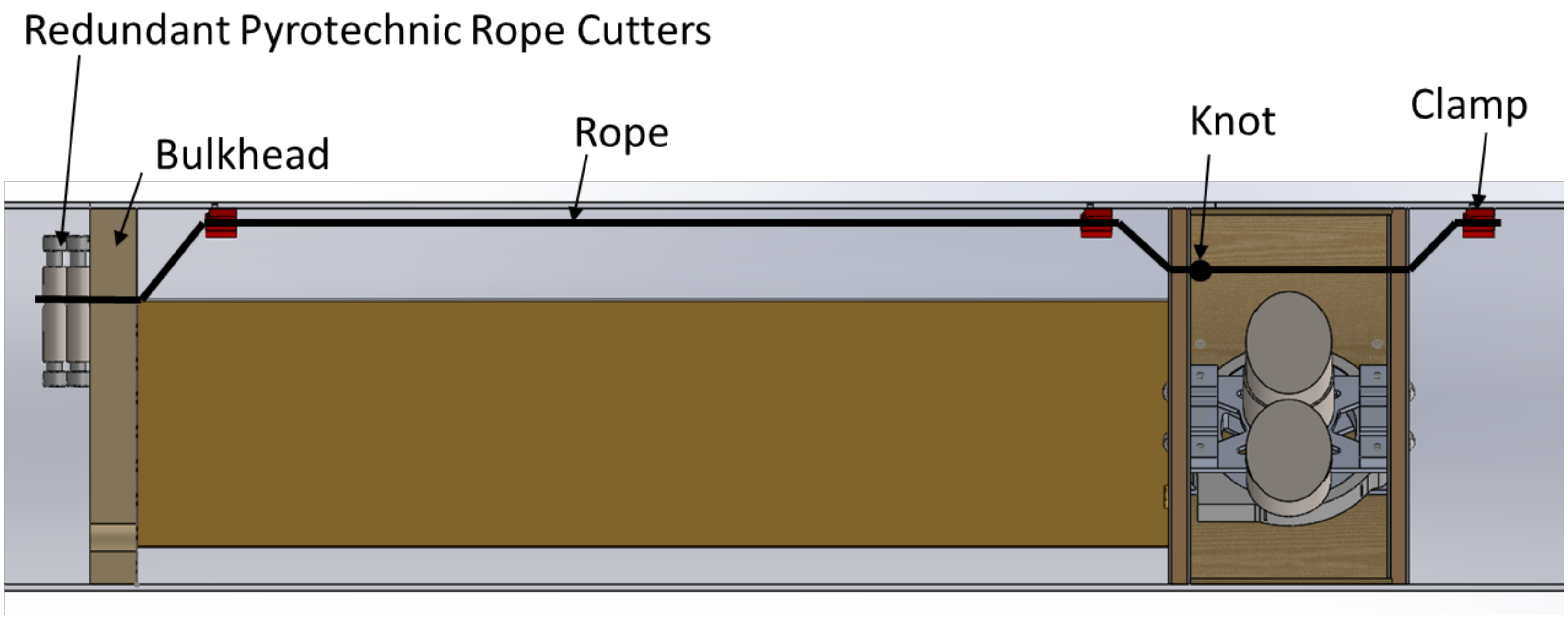
Parafoil Recovery Assembly



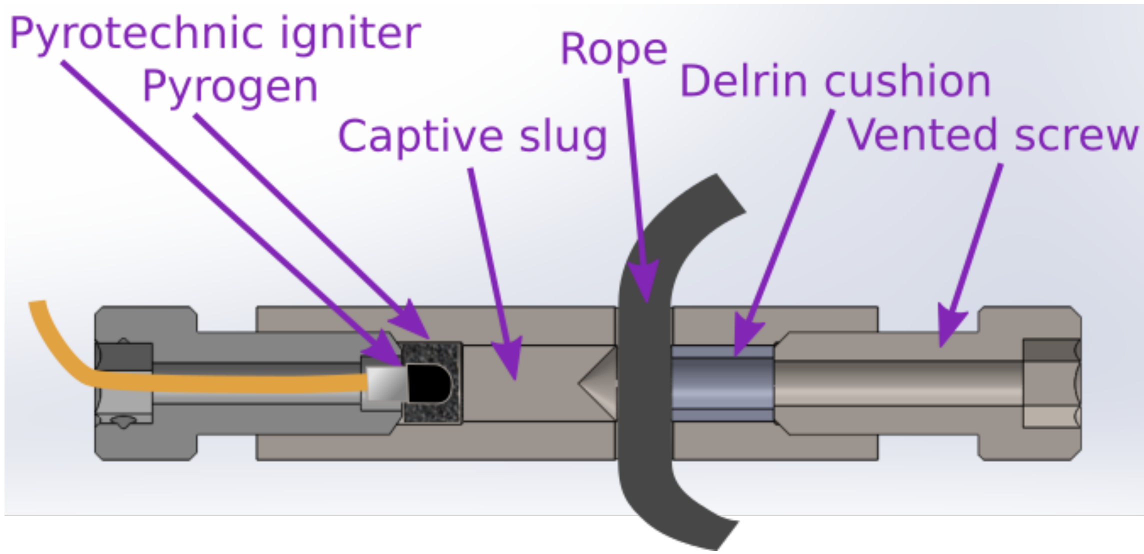
Mortar Assembly



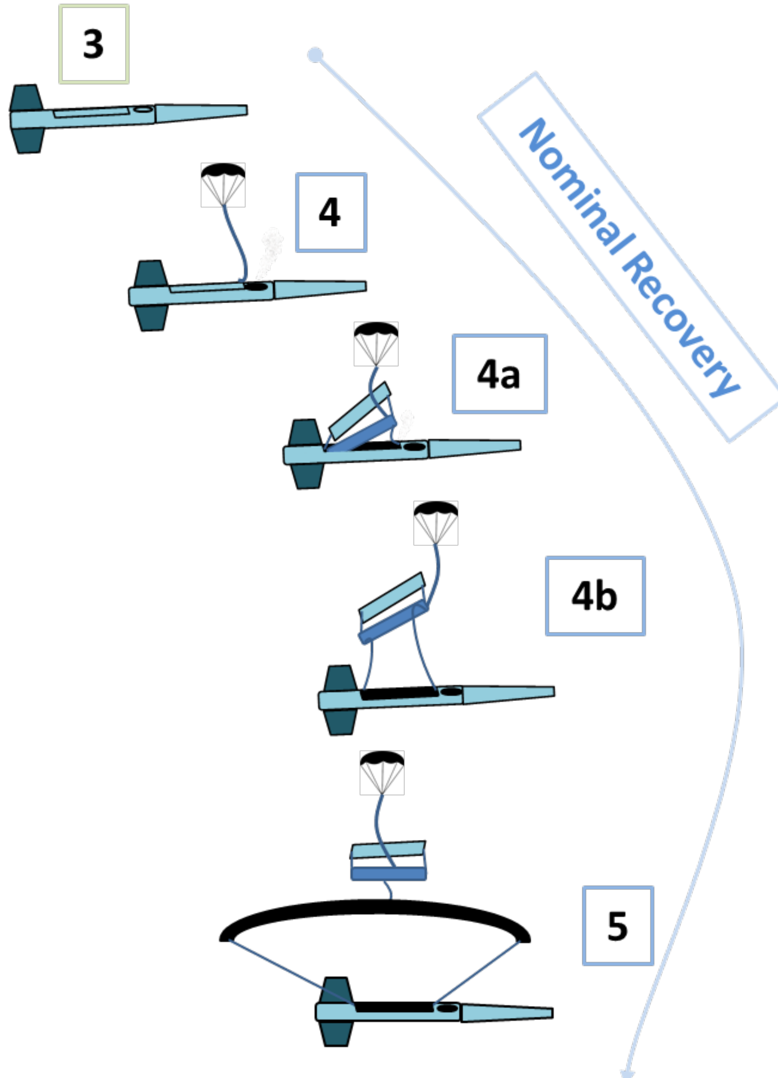
Parafoil Assembly



Pyrotechnic Rope Cutter (PRC)

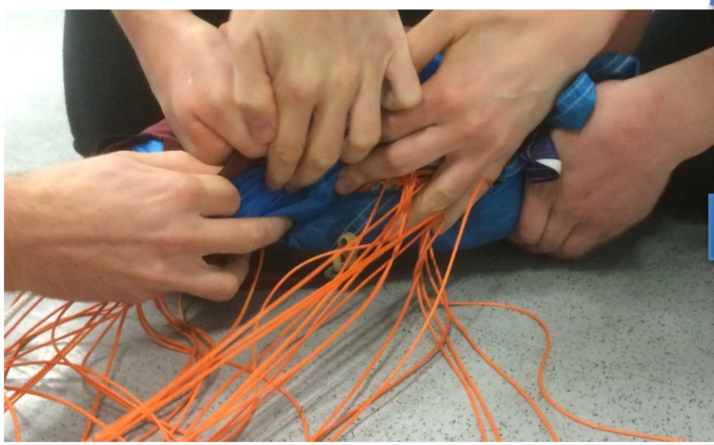


Parafoil CONOPs



Packing the Parafoil

Starting configuration



Final configuration

Parafoil Deployment

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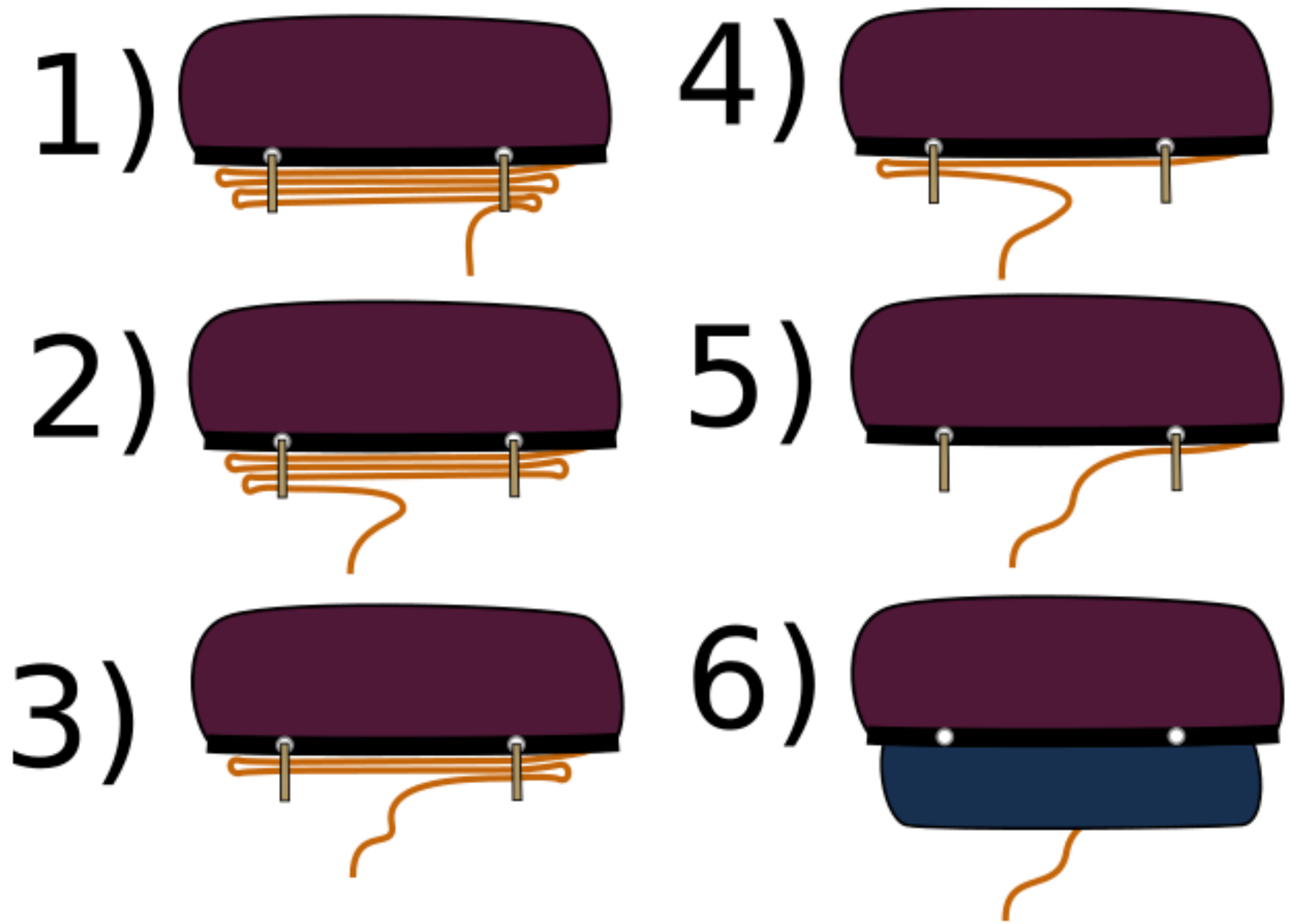
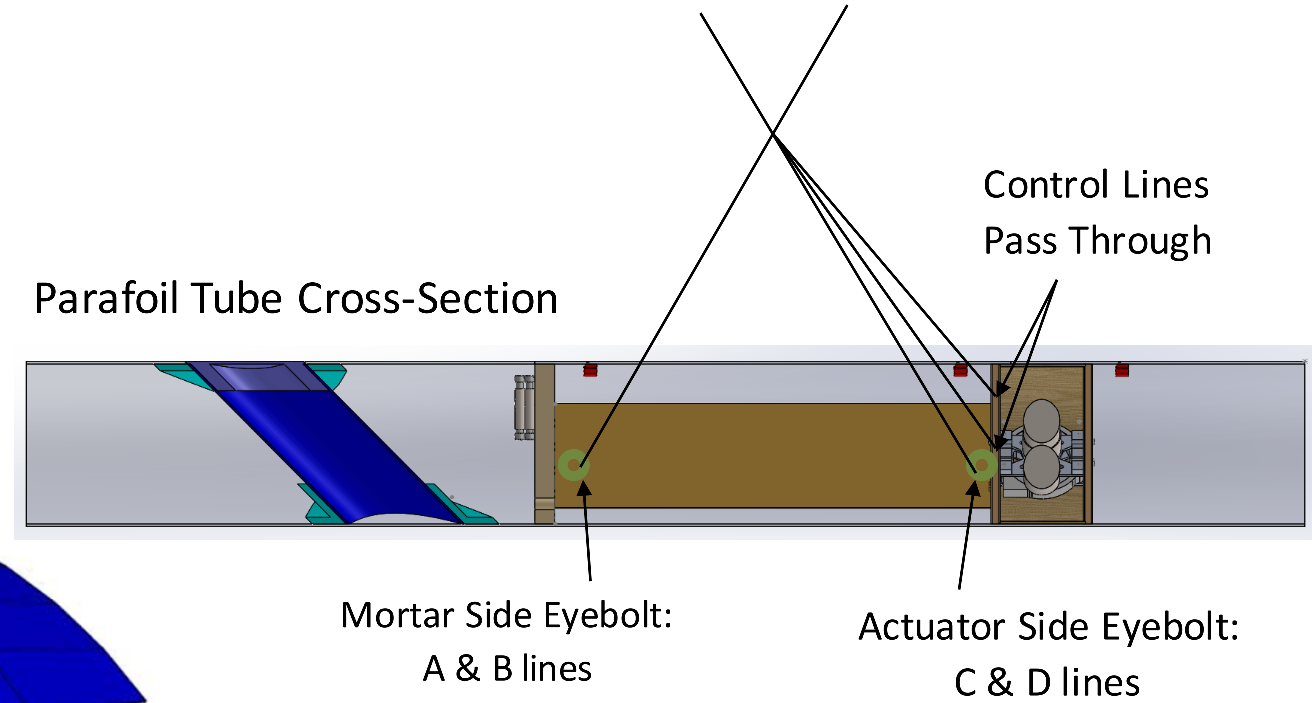
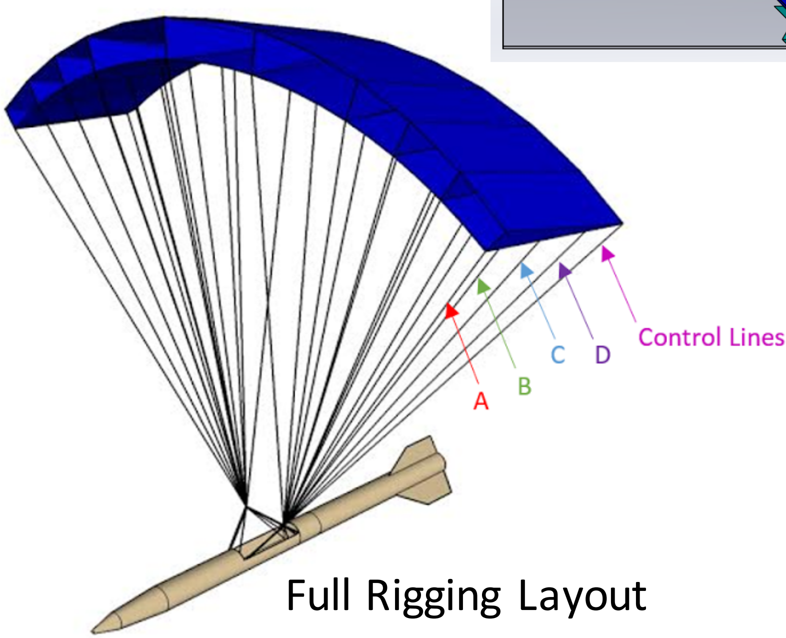


Rigging

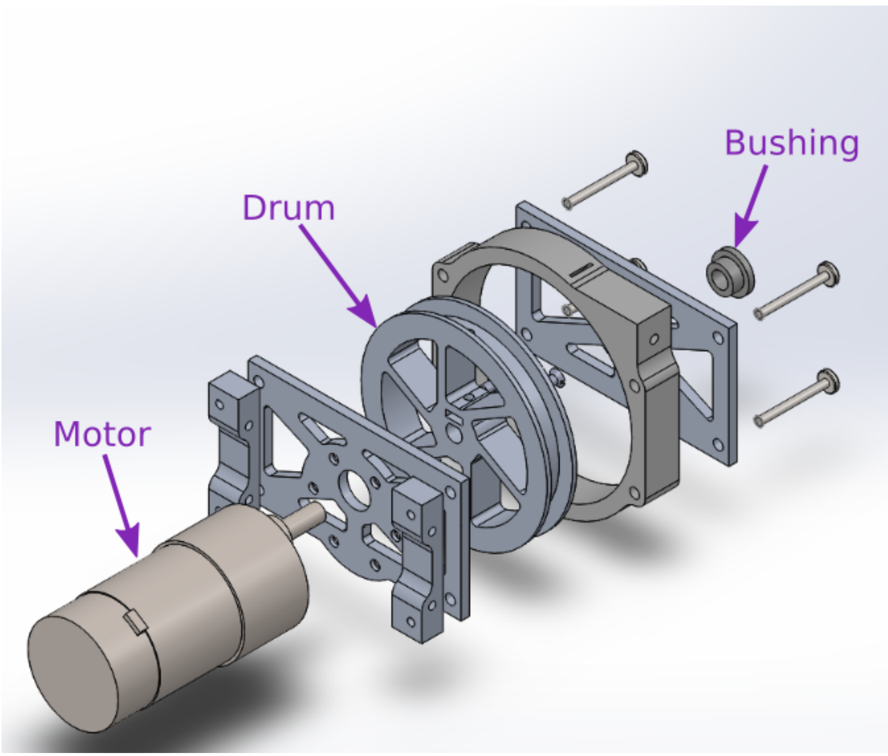


Parafoil Tube Cross-Section

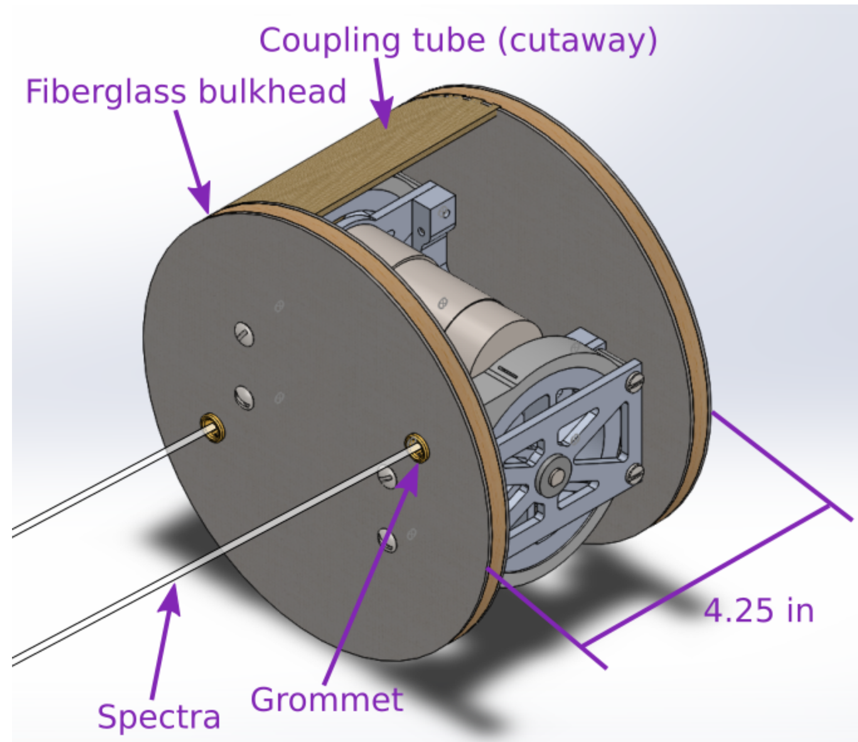


Full Rigging Layout

Actuation



Single Actuator



Assembled Actuator System

Expected Performance

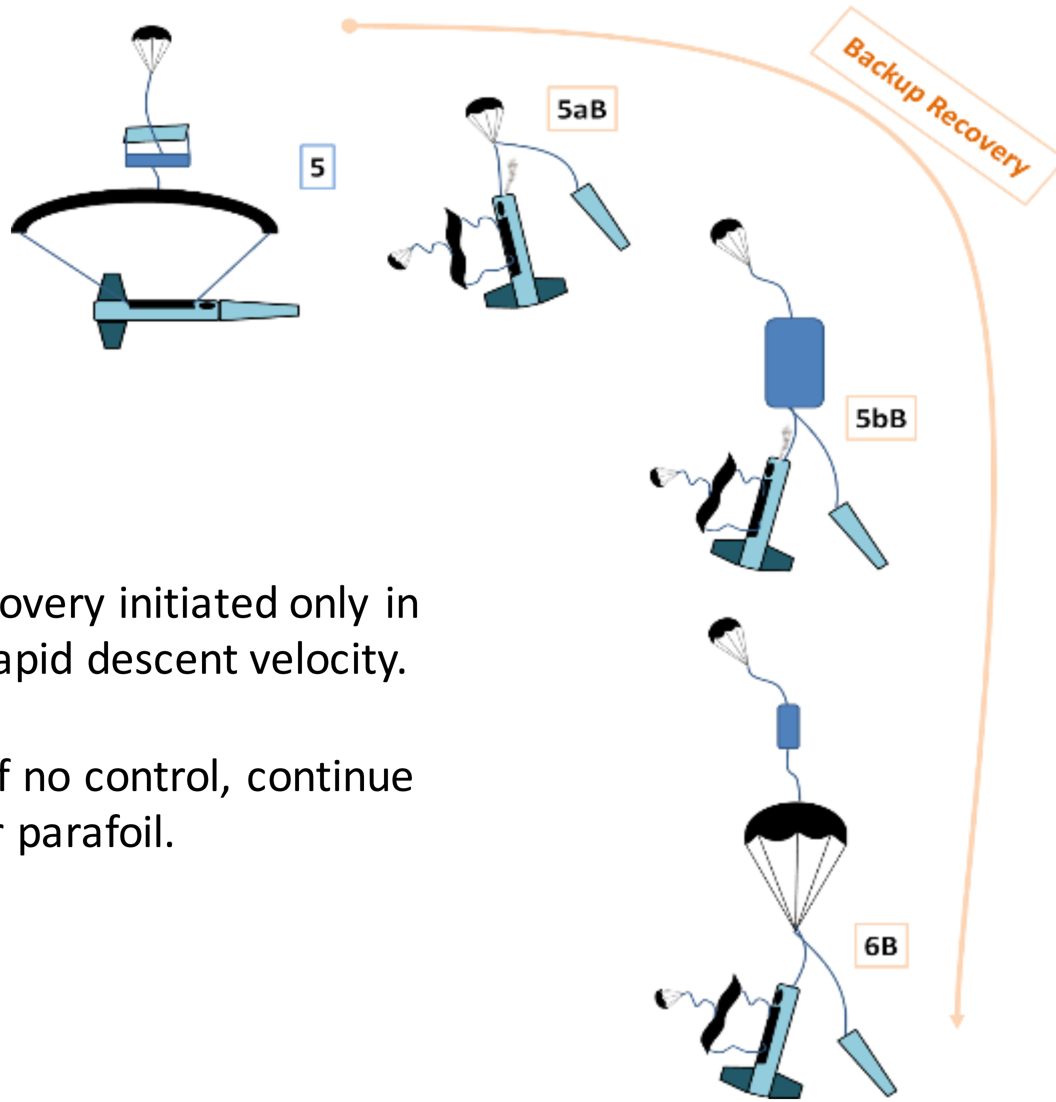
Expected velocity when pilot chute deploys: 15 - 20 m/s

Parachute Name	Parachute Diameter	Opening Shock	Steady Velocity
Pilot	3 ft diameter	31.5 lbs	58.3 ft/s
Parafoil	67 ft sq	472.9 lbs	18.9 ft/s

Questions?

Backup Recovery

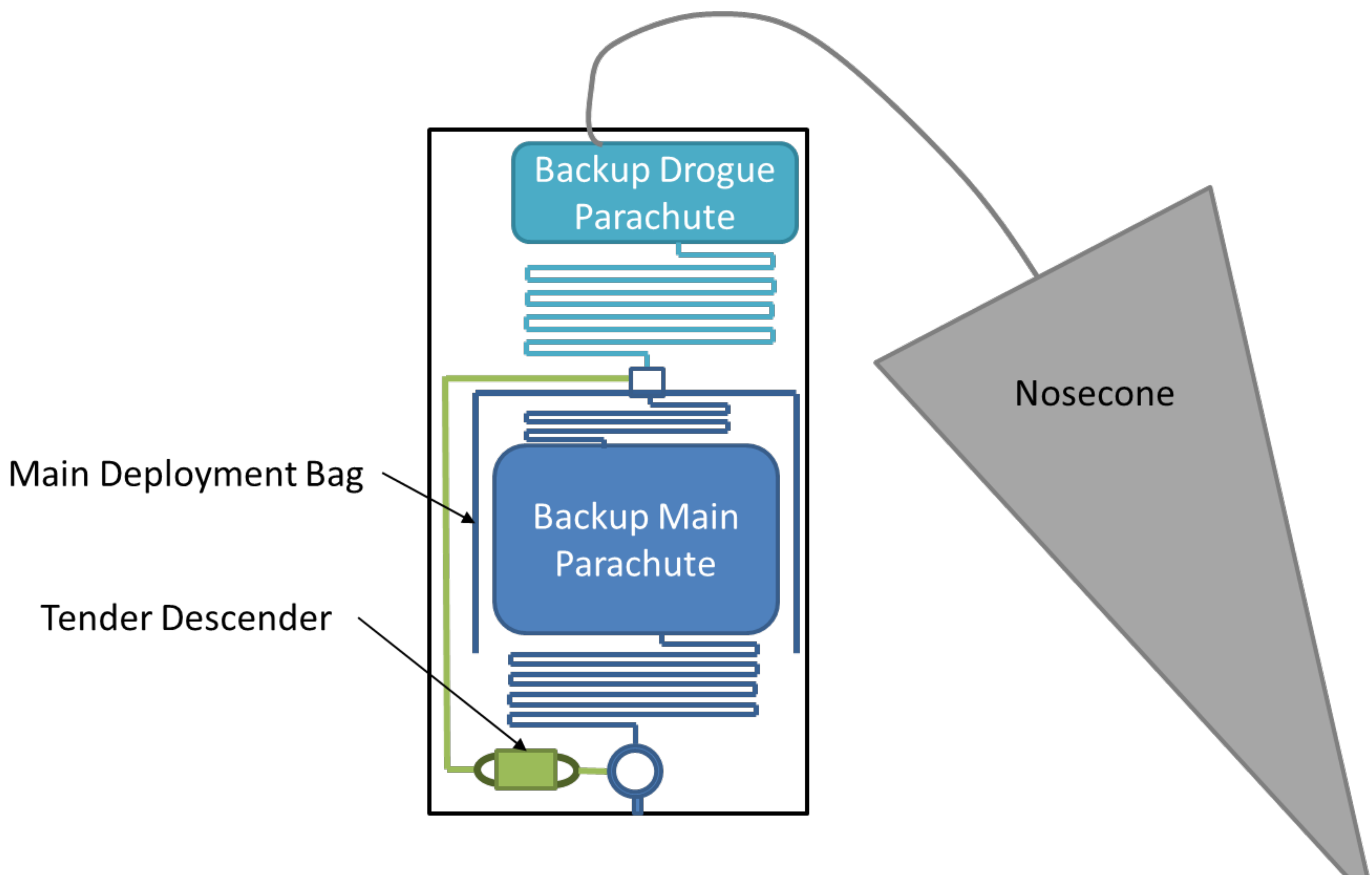
Backup Recovery CONOPs



** Backup recovery initiated only in the event of rapid descent velocity.

In the event of no control, continue descent under parafoil.

Backup Recovery Assembly



Parachute Design and construction

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1.3oz ripstop nylon fabric

Size 46 nylon thread

Nylon tape (seam reinforcements)

Polypropylene webbing (shroud lines)

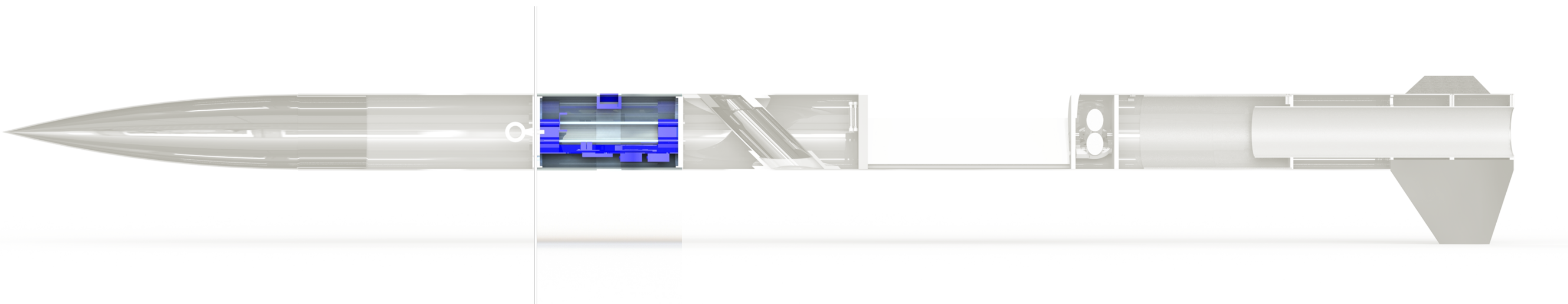
Geometry: Semi-ellipsoidal, 0.707 aspect ratio

Expected Performance

Parachute Name	Parachute Diameter	Opening Shock	Steady Velocity
Drogue	2.5 ft	654.1 lbs	69.9 ft/s
Main	9.5 ft	719.7 lbs	18.4 ft/s

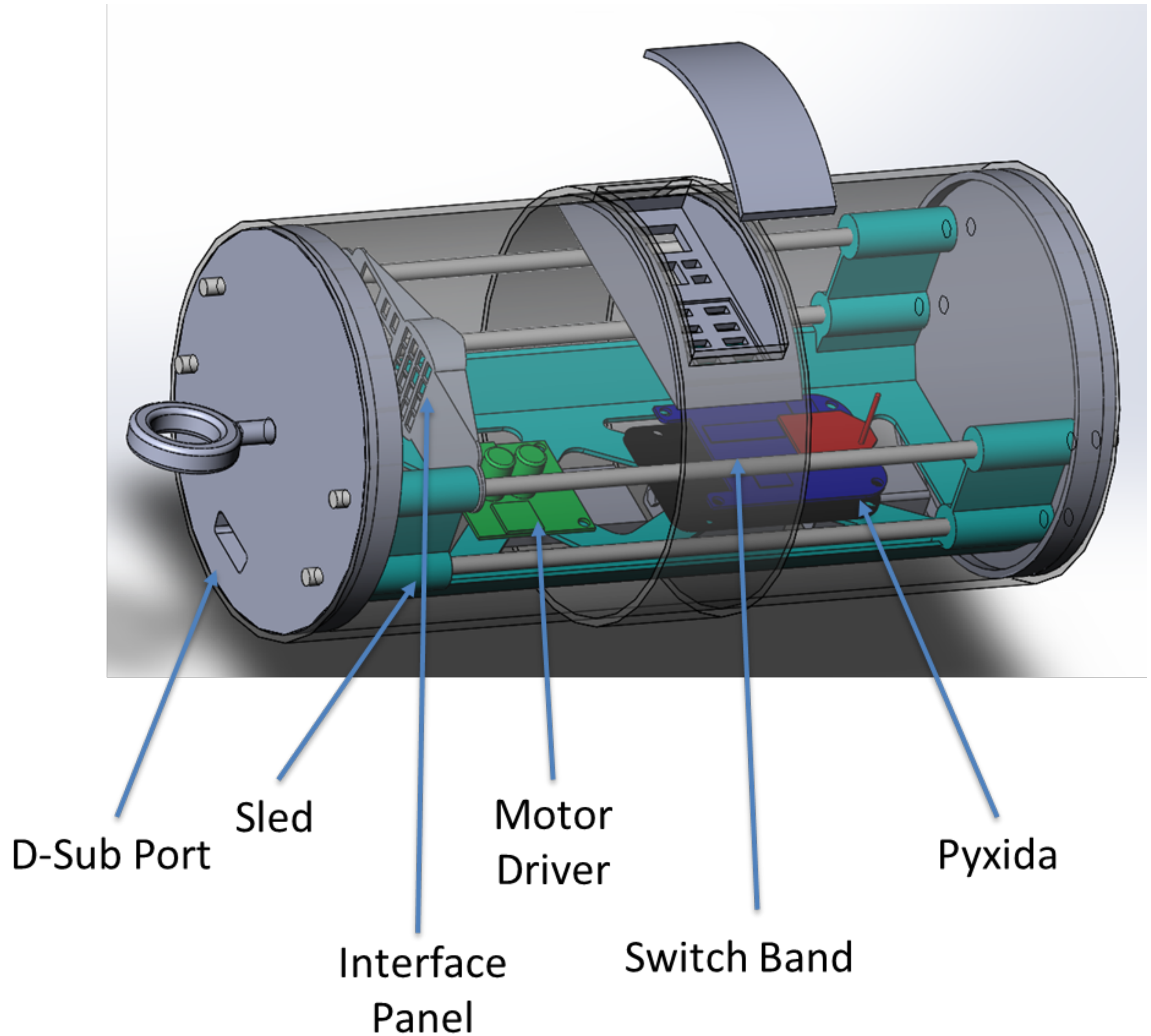
Questions?

Avionics



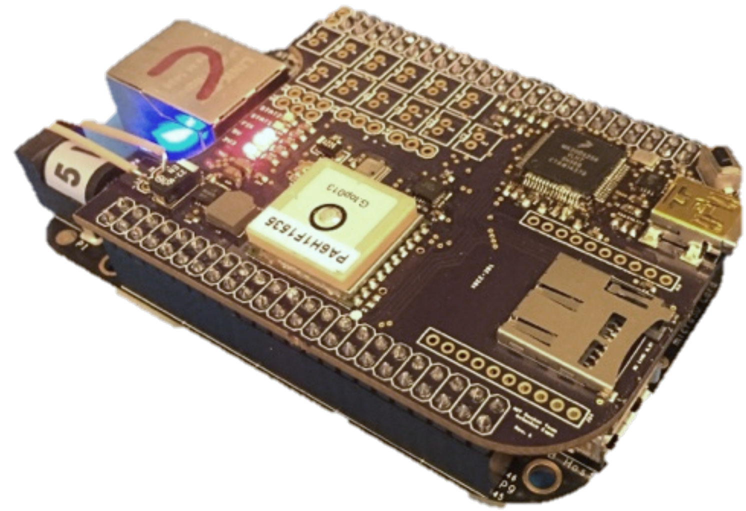
Avionics System

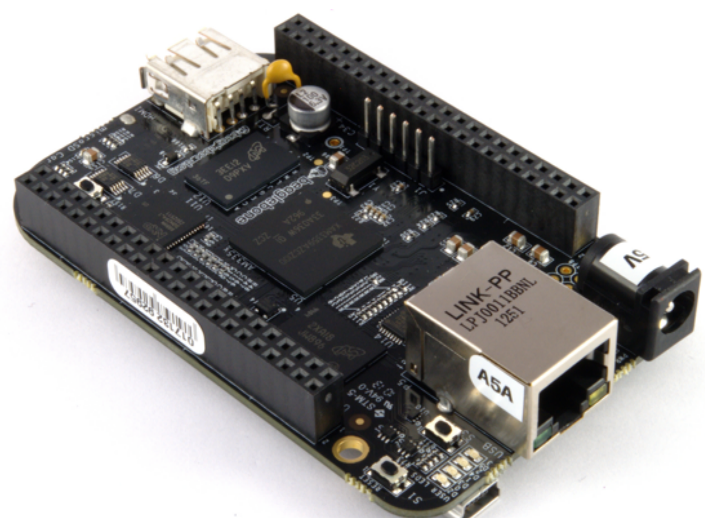
- Structure
  - Coupler
  - Switch band
  - Sled
  - Interface
  - Electronics
  - Batteries



Avionics System

- Pyxida Cape
  - Sensor Read
  - SD Logging
  - XBee Transmitter
- BeagleBone Black
  - Guidance
  - Navigation
  - Control





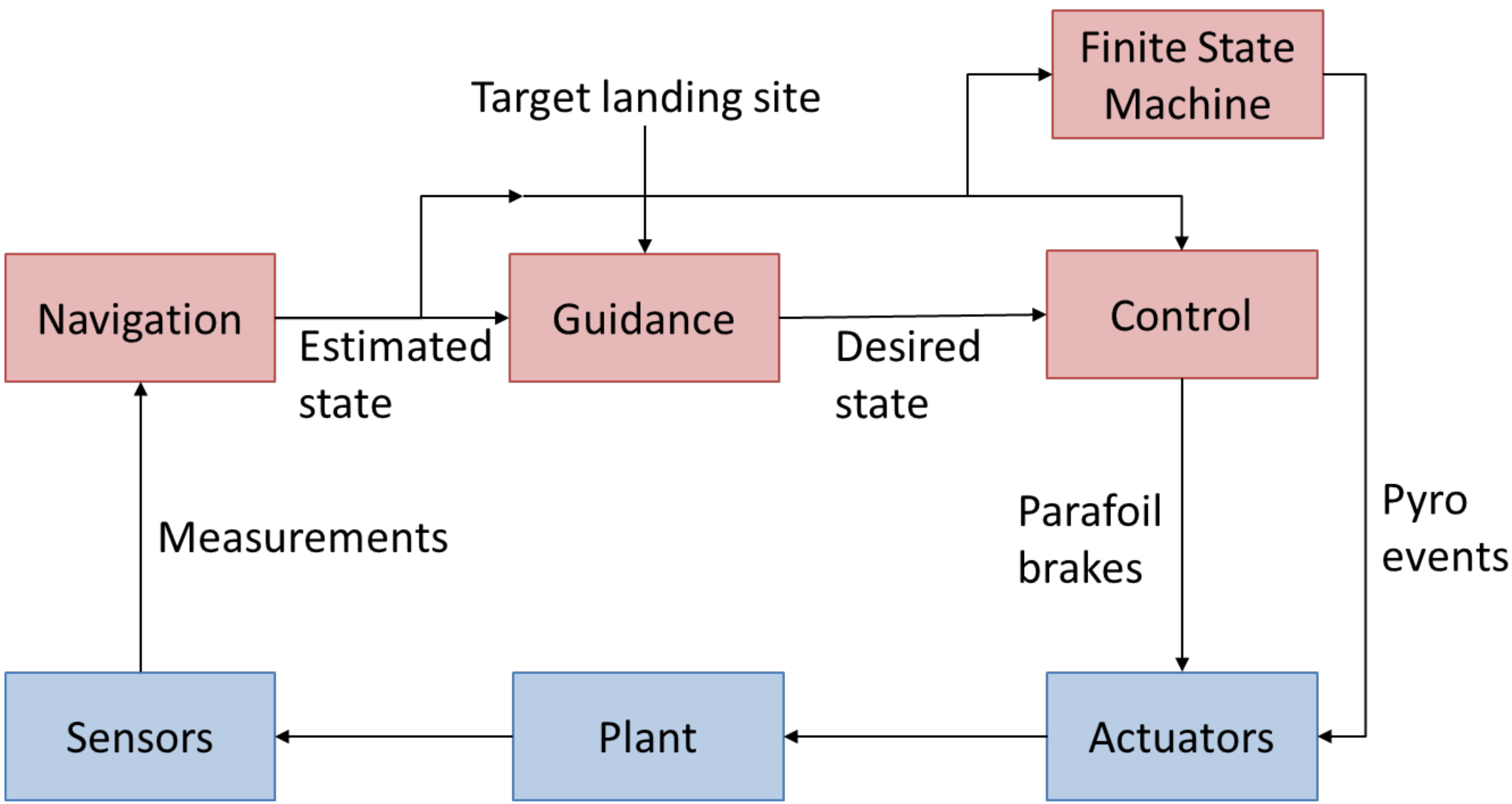
COTS Backup

- A TeleMtrum provides redundancy for pyrotechnics and tracking
- COTS defaults to “ON”
- Pyros inhibited after confirmation of successful event using PNP transistors

Software

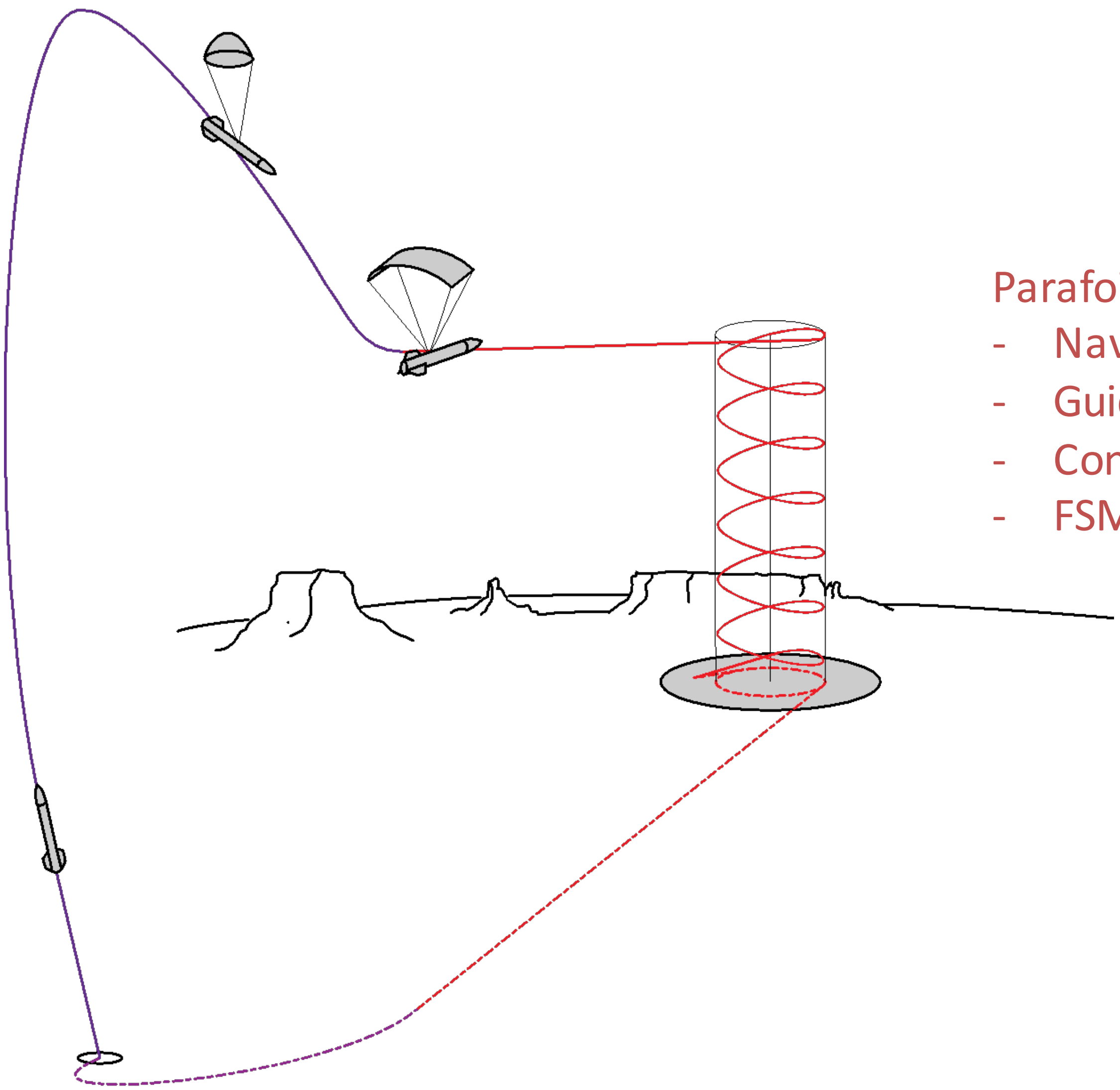
- ARM Microcontroller runs a program written in Arduino flavored C++ to pass the data to the BeagleBone
- BeagleBone runs Debian 8.2 Linux Based OS interpreting Python for GNC
- Ground Station runs Custom and COTS software to receive telemetry

GNC



Finite State Machine
Target landing site
Navigation
Guidance
Control
Estimated state
Desired state
Parafoil brakes
Pyro events
Measurements
Sensors
Plant
Actuators

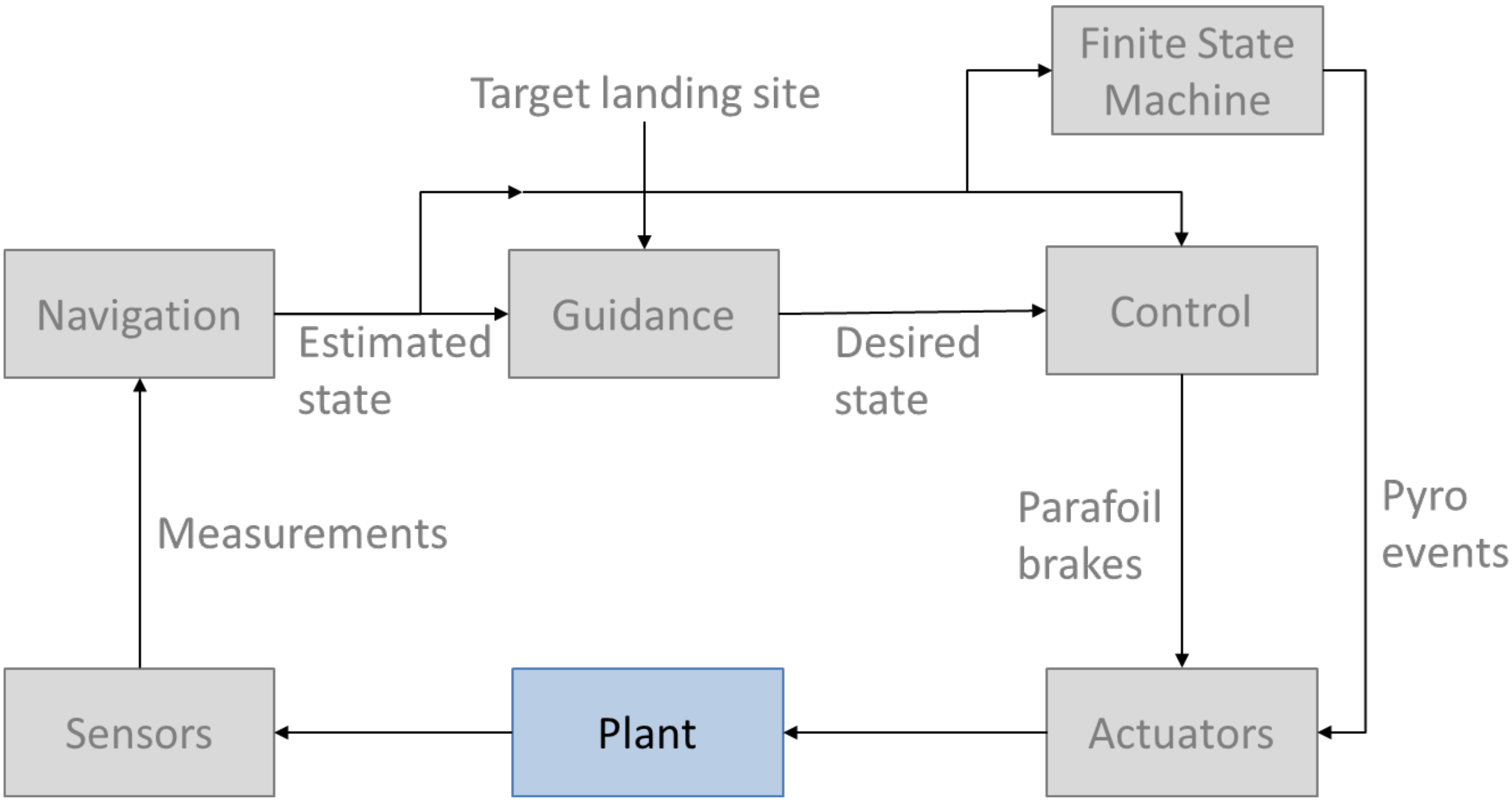
GNC software and mission phases



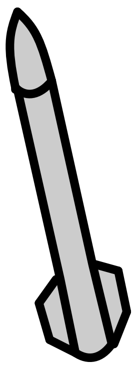
Ascent and pilot chute descent:
- Navigation
- FSM

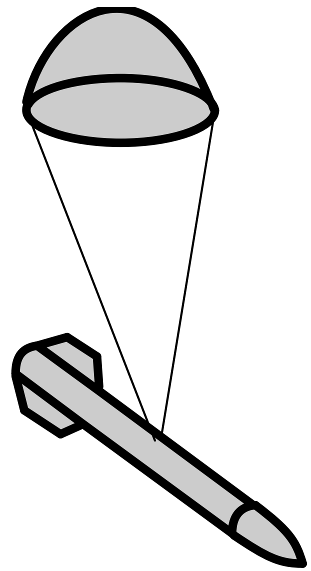
Parafoil flight:
- Navigation
- Guidance
- Control
- FSM

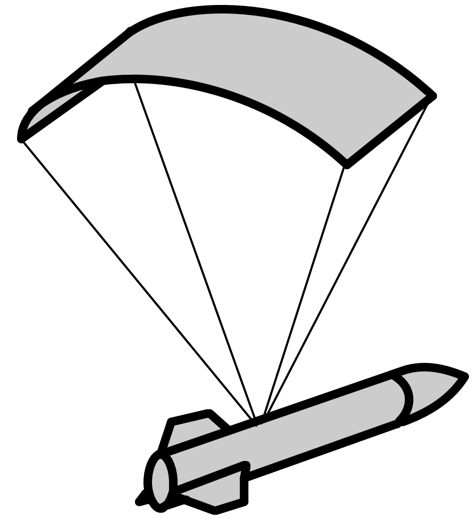
GNC: Plant Model



GNC: Plant Model





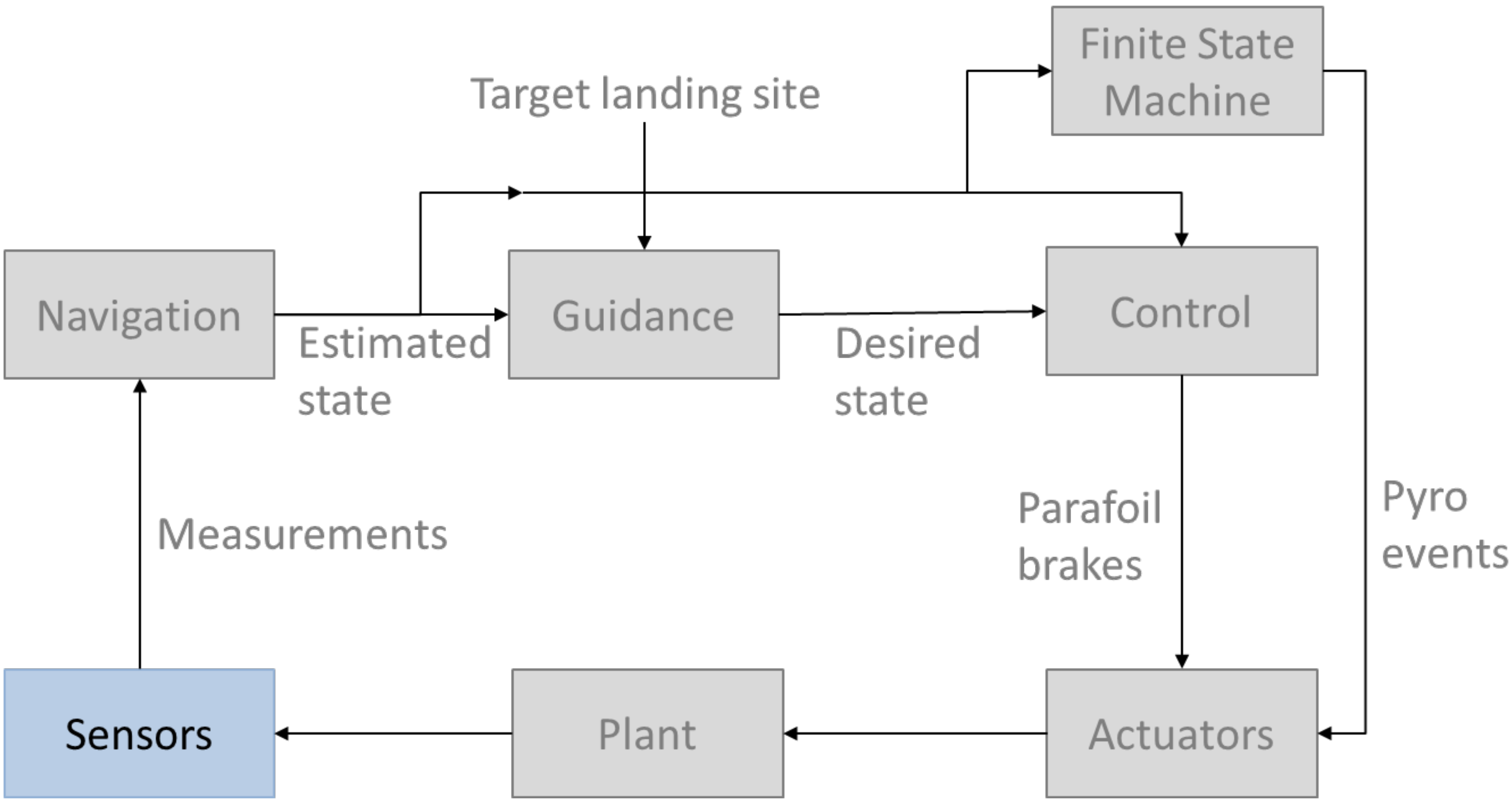


Ascent:
6 DoF rigid body
Gravity
Body aero
Thrust

Pilot descent:
6 DoF rigid body
Gravity
Body aero
Chute aero

Parafoil flight:
4 DoF Dubins car
Const sink rate and airspeed

GNC: Sensors


Finite State Machine
Target landing site
Navigation
Guidance
Control
Estimated state
Desired state
Measurements
Parafoil brakes
Pyro events
Sensors
Plant
Actuators

GNC: Sensors

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Non-linear measurement functions
Roughly normally distributed noise
Plus sensor-specific issues:

Gyro:
Bias walk

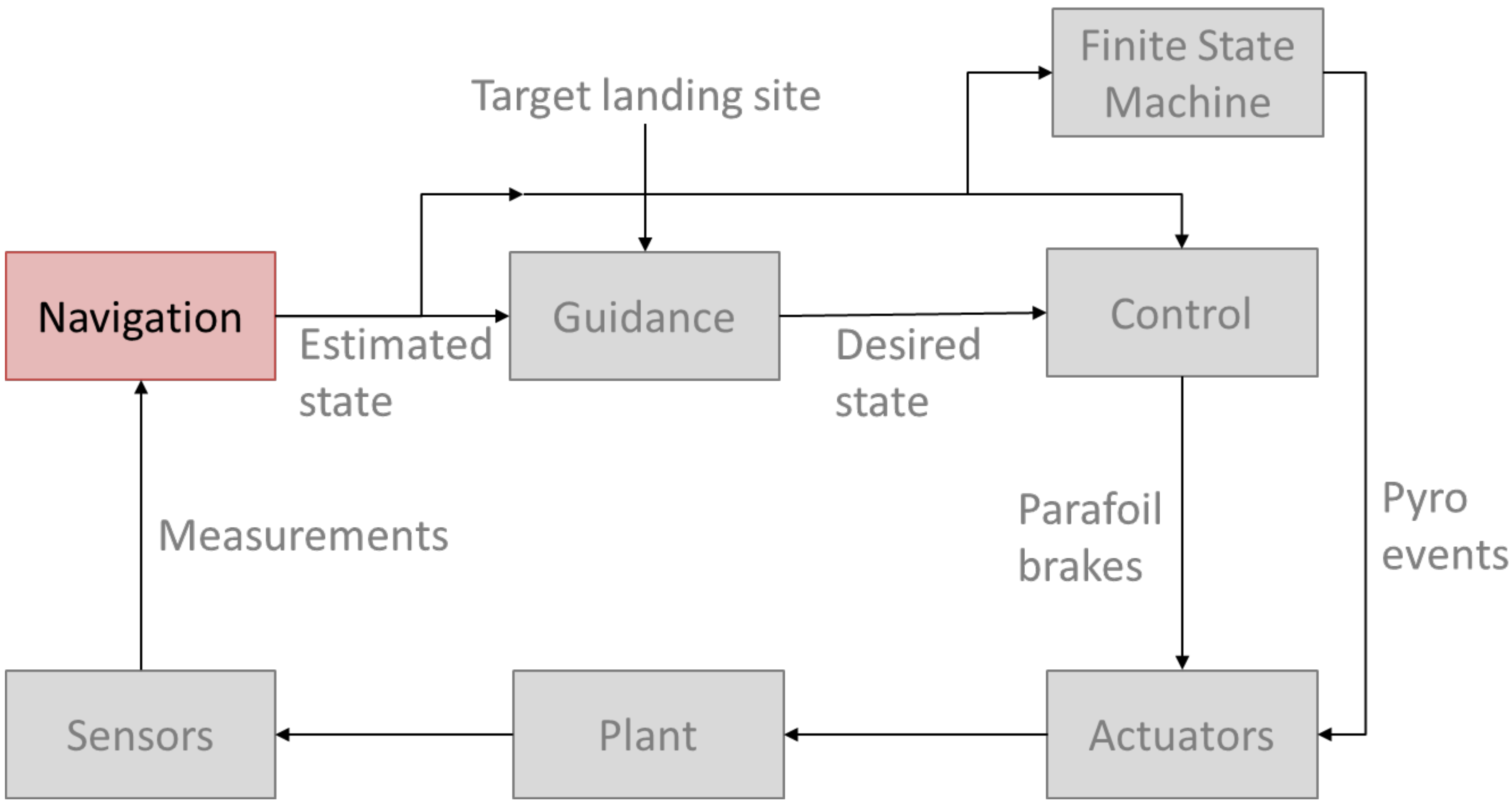
Accelerometer

Magnetometer:
Calibration

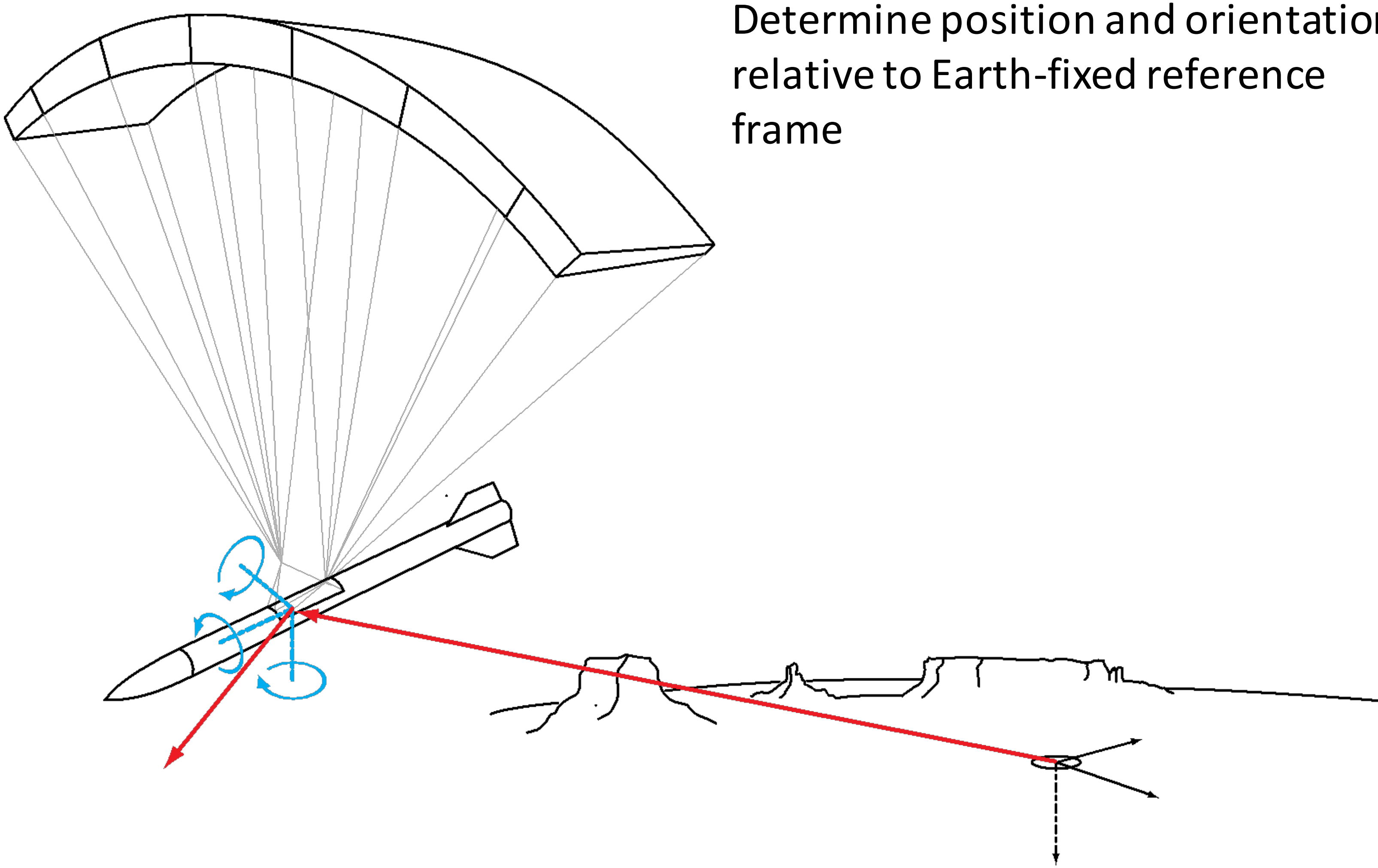
GPS:
Time to lock
Loss of lock
Spherical coordinates
WGS84 vs MSL altitude

Barometer:
Temperature and pressure corrections

GNC: Navigation



GNC: Navigation



Determine position and orientation relative to Earth-fixed reference frame

GNC: Navigation

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- Unscented Kalman Filter
  - Non-linear measurement & dynamics
  - Roughly normally distributed noise
- Quaternion state requires special care

A Quaternion-based Unscented Kalman Filter for Orientation Tracking

Edgar Kraft
Physikalisches Institut, University of Bonn,
Nussallee 12, 53115 Bonn, Germany
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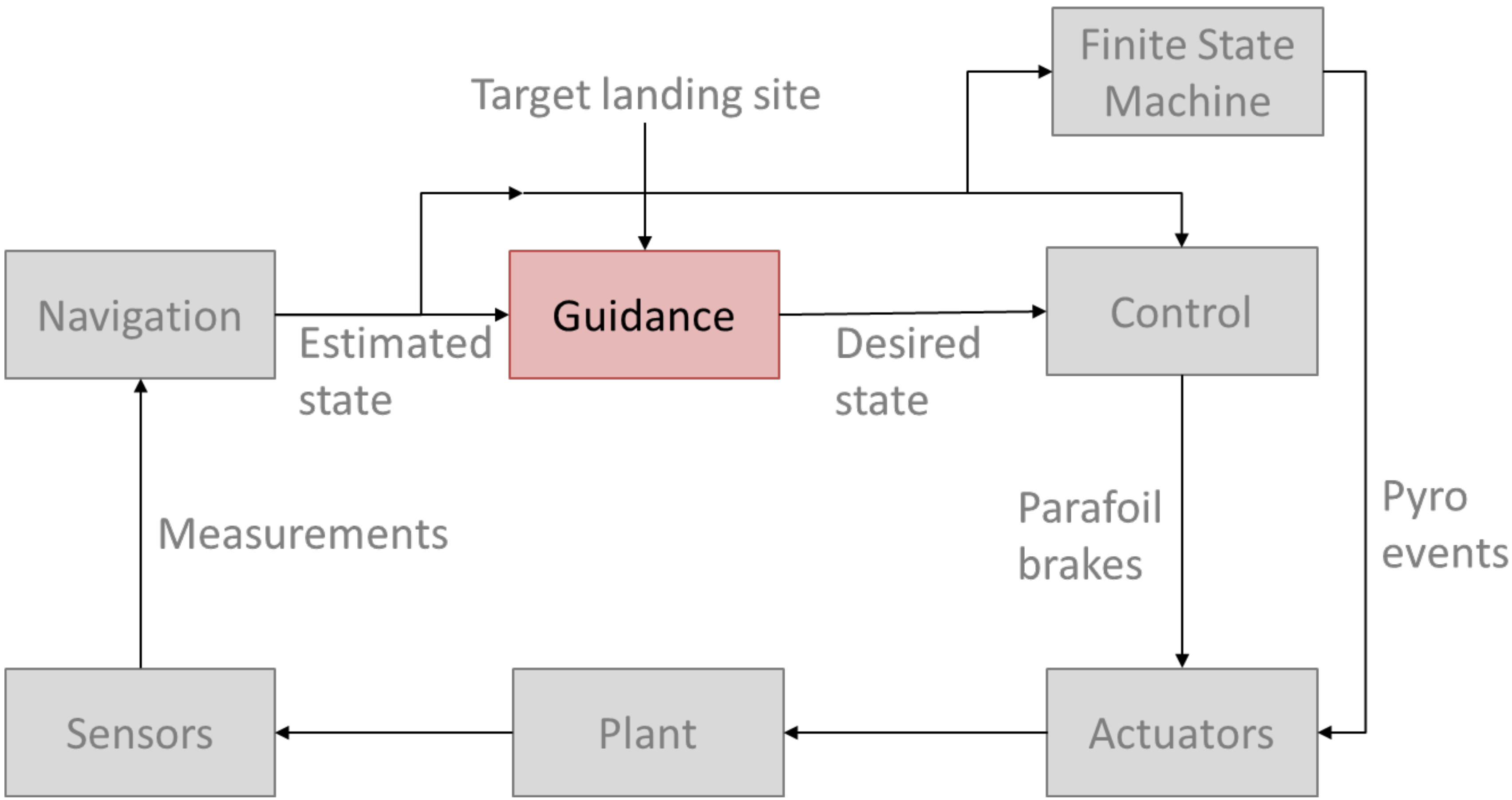
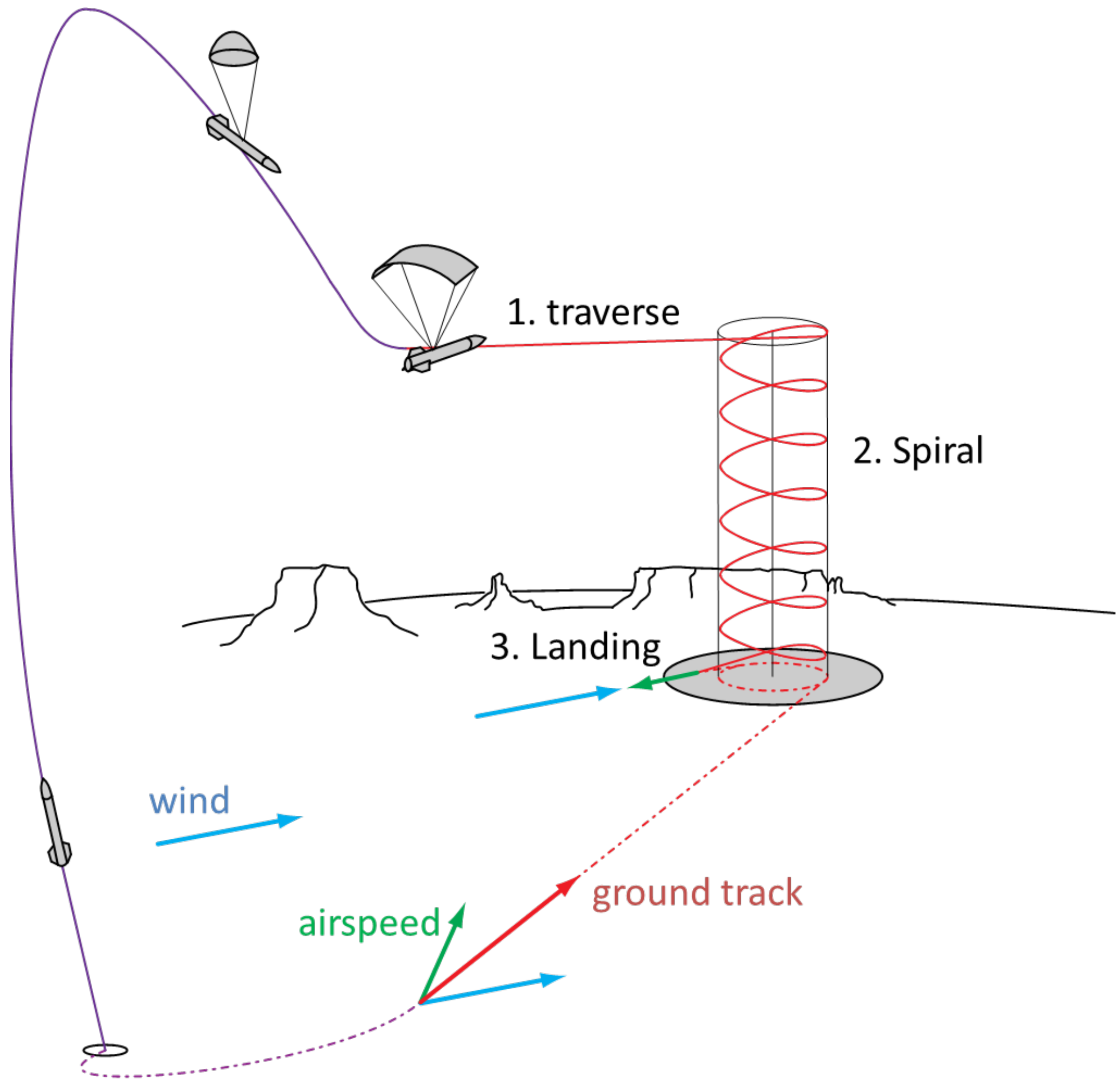
Abstract – *This paper describes a Kalman filter for the real-time estimation of a rigid body orientation from measurements of acceleration, angular velocity and magnetic*

The set of quaternions $\mathbb{H}$ is a superset of the complex numbers $\mathbb{C}$ and the elements can be used to describe spatial rotations similarly to the way complex numbers describe planar

GNC: Guidance



GNC: Guidance



GNC: Guidance

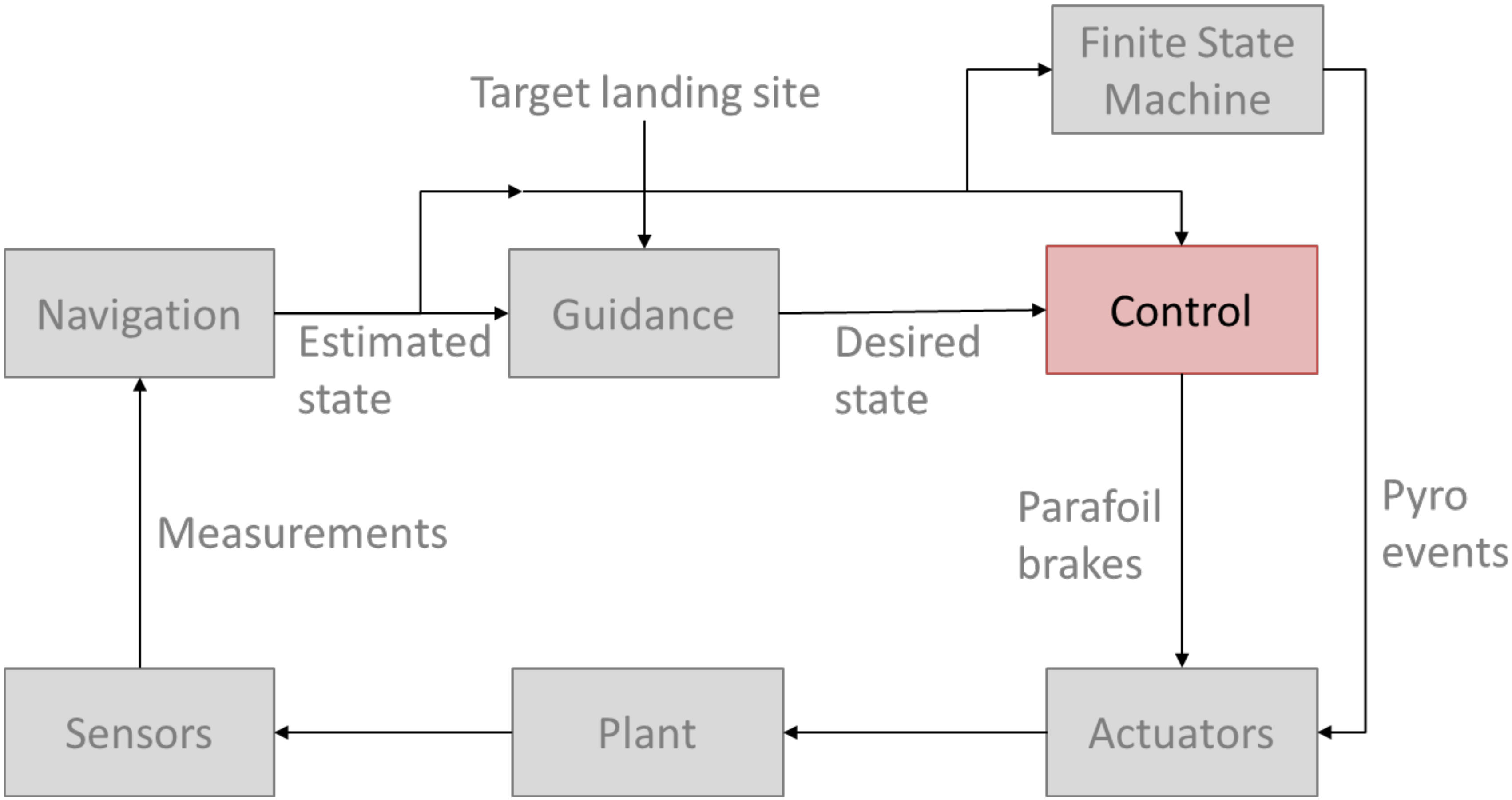
Outputs

- Steering: Send desired yaw and yaw rate to control module
- Flare for landing: Send desired flare setting to control module

GNC: Wind

- Not sensed or estimated in real time
- Estimate loaded into config files on day-of-launch
  - NOAA/FAA FB winds aloft for KGJT airport
- Landing site chosen to be downwind of launch site

GNC: Control



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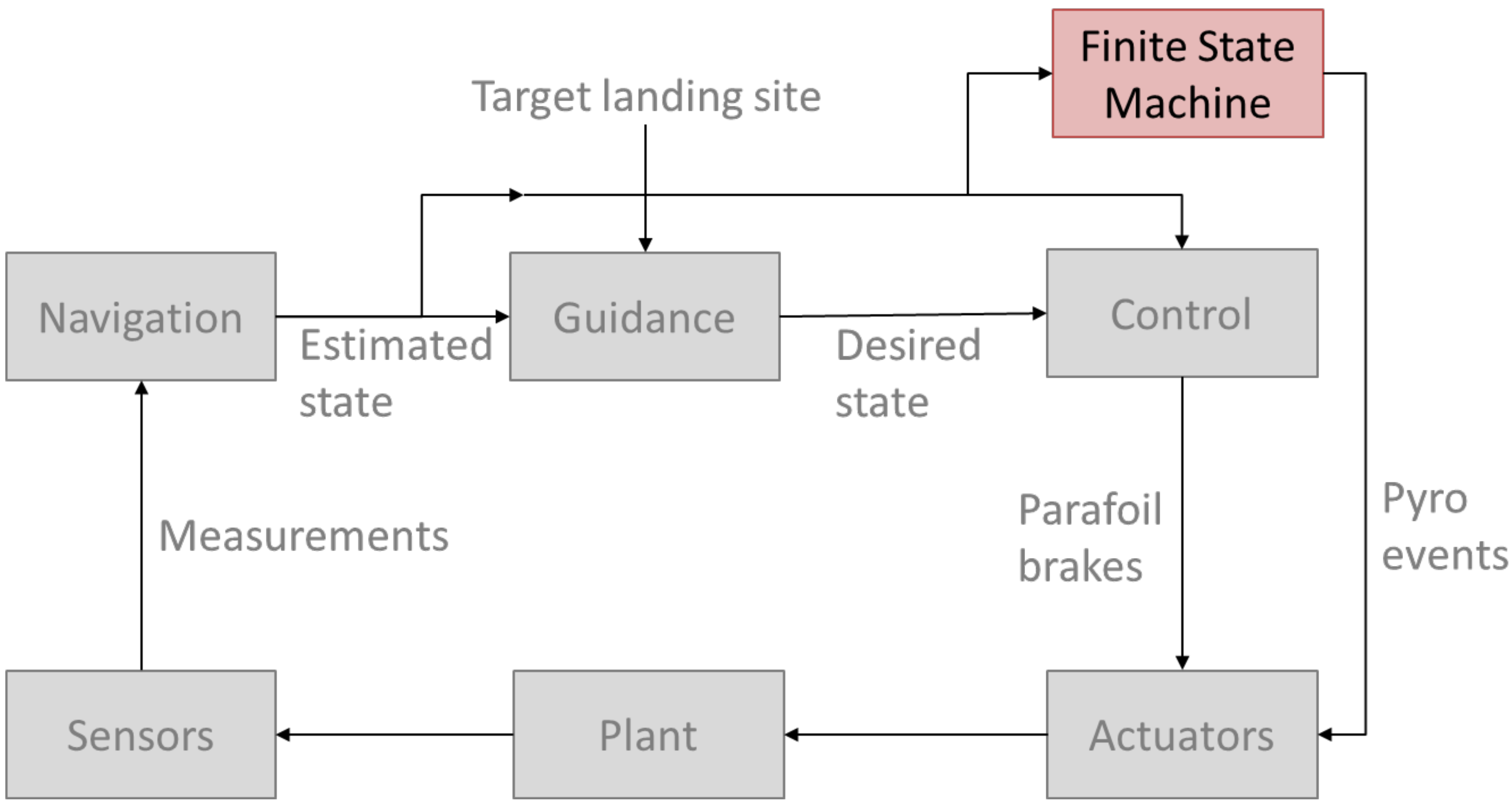
GNC: Control

- PID control of yaw
- Open-loop flare control for landing

GNC: FSM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GNC: FSM

A Finite State Machine (FSM) will compare the current vehicle state to start or end conditions for various vehicle states.

GNC: FSM State Flow

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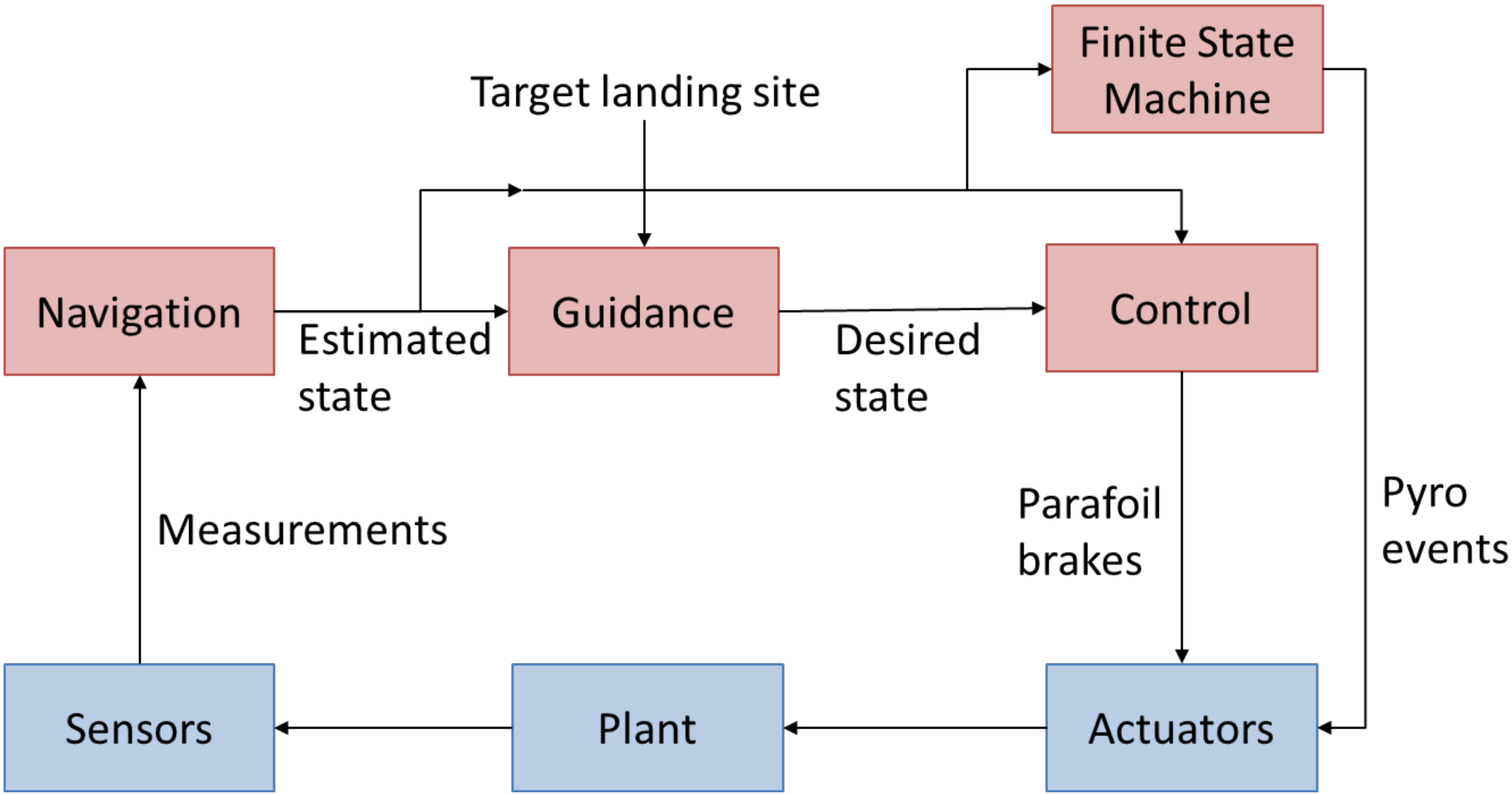
Nominal Modes

1. Idle
2. Startup
3. Boost
4. Coast
5. Pilot
6. Parafoil
7. Low
8. Landed

Contingency Modes:

A. Startup Failure
B. Drogue
C. Main
D. COTS

GNC



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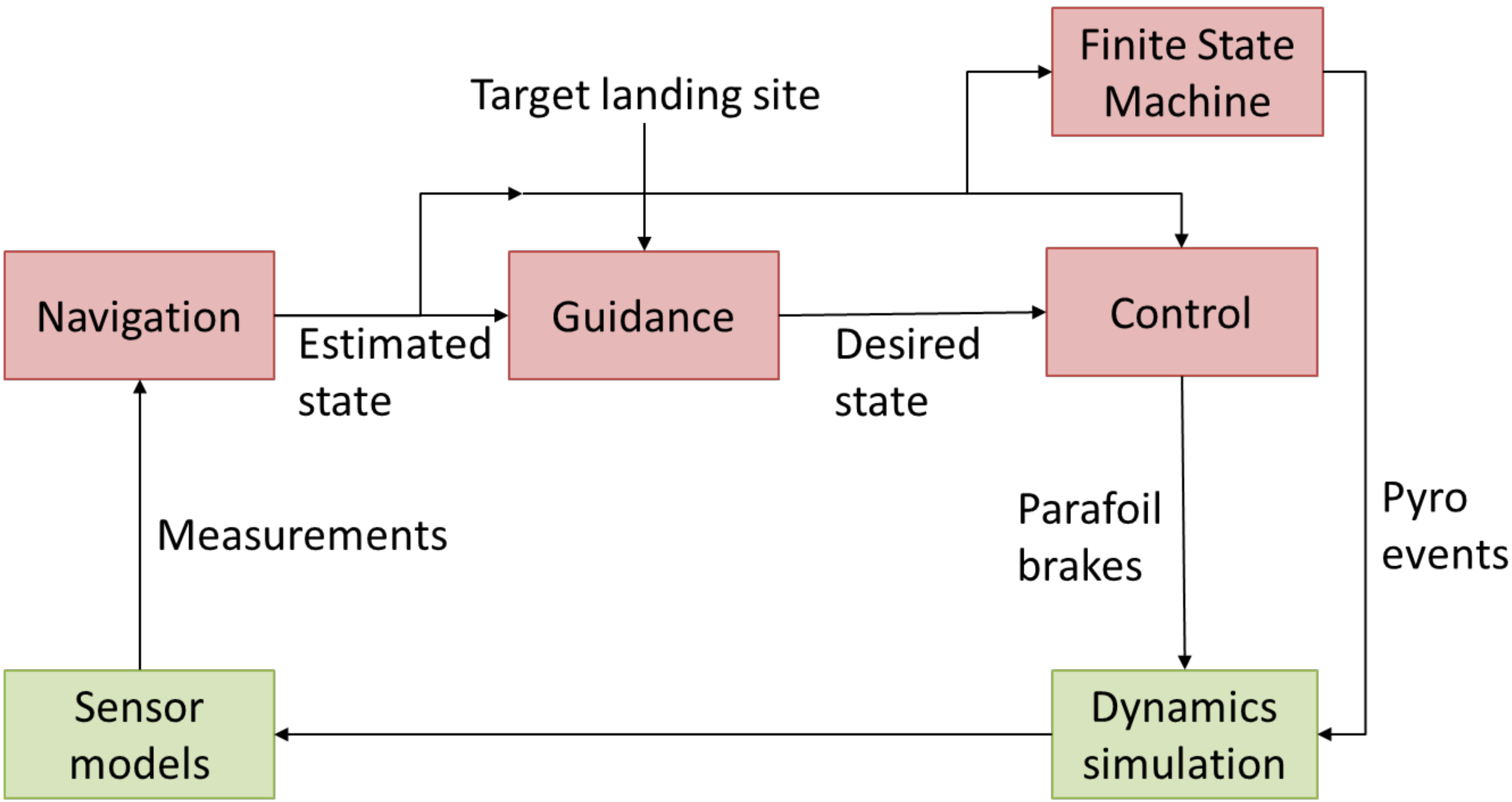
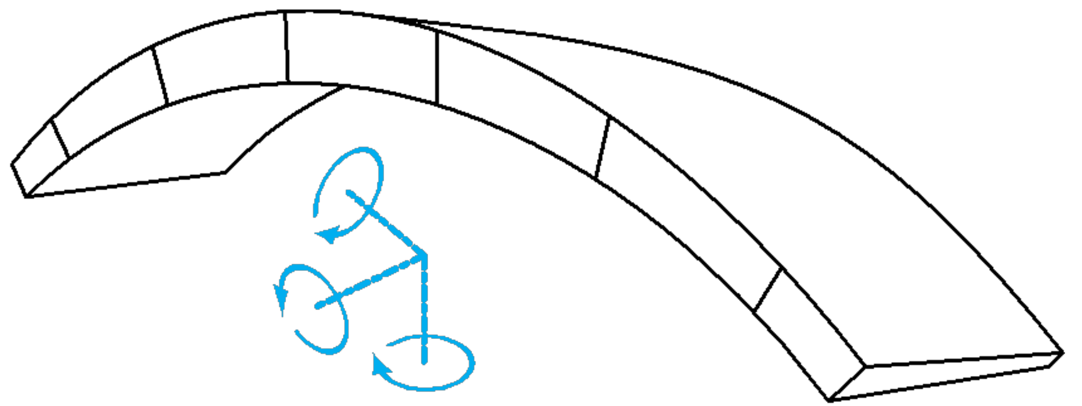
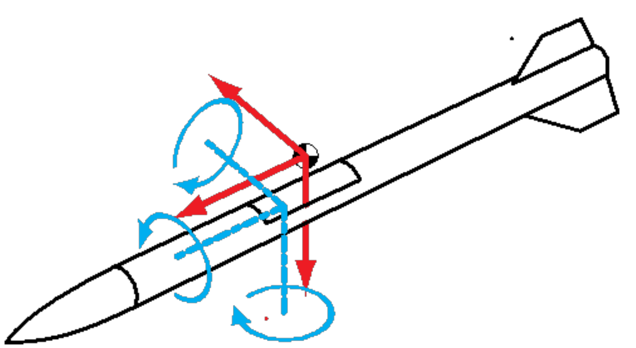
GNC: Simulation and testing



GNC: Simulation of parafoil

- Slegers and Costello:
  - 9 DoF
  - Panel-based aero model
  - C_D , C_L from USAF & NASAS wind tunnel tests
  - Test control and estimation robustness





Questions?

System level risks

Rocket Loss Matrix

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Risk						
Risk	5 (high risk)					
	4			F		
	3		A	B		
	2		D	E		G, H
	1 (low risk)					C, I
		1 (low impact)	2	3	4	5 (high impact)
Impact (with Respect to Loss of Rocket)						

A. Loss of GPS Signal
B. Pyxida Failure
C. COTS Altimeter Failure
D. Actuator Failure
E. Pilot Deployment Failure
F. Parafoil Deployment Failure
G. Drogue Deployment Failure
H. Main Deployment Failure
I. Structural Failure

Project Failure Matrix

Risk	5 (high risk)					
	4			5		
	3			2		
	2		1		3, 7	4
	1 (low risk)					6
		1 (low impact)	2	3	4	5 (high impact)
Impact (with Respect to Project Loss)						

1. Loss of Therion I
2. Loss of Therion II
3. Loss of Therion III
4. Loss of Therion IV
5. Schedule Slip
6. Team Member Safety
7. Budget

Goal Evaluation

- Baseline
  - Within 1000ft of target apogee
  - Full recovery
  - 10lb payload
  - 1 Successful test flight
  - Maximum custom hardware
- Target Goals
  - 10 minute integration
  - Successful Parafoil deployment
  - Full data recovery
  - Control attempted
  - Plasma operational
  - OpenCV operational
- Stretch Goals
  - Live telemetry
  - Lands in target area
  - Within 100ft of target apogee
  - ~~Custom Propulsion~~

Thank You!

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Questions? Further discussion?

Send to:
rt-exec@mit.edu