Astrobee System

Design Overview

0g Robotics Research Facility

AES, SPHERES Program, SPHERES users

Testbed Capabilities

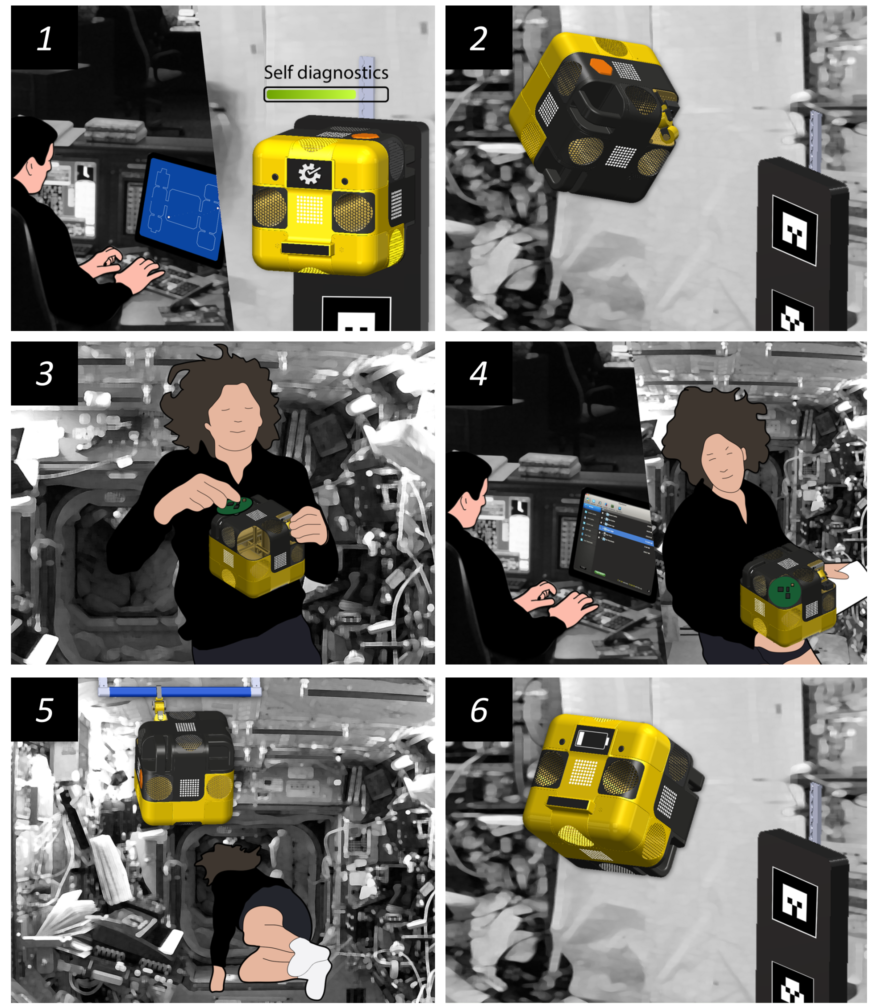
- Multiple free flyer operations
- Mobile sensing & manipulation tasks
- Holonomic motion
- Remote control
- Host payloads with physical and software interface
- Not reverse compatible with existing SPHERES payloads (without an adaptor)

Outline

- Design drivers
- System design
- Free Flyer basic packaging
- Lightning tour of subsystems
- Major changes since PTR1

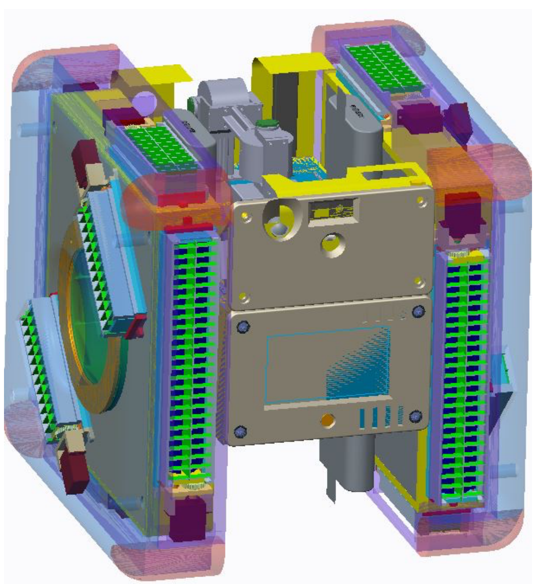
Design Drivers

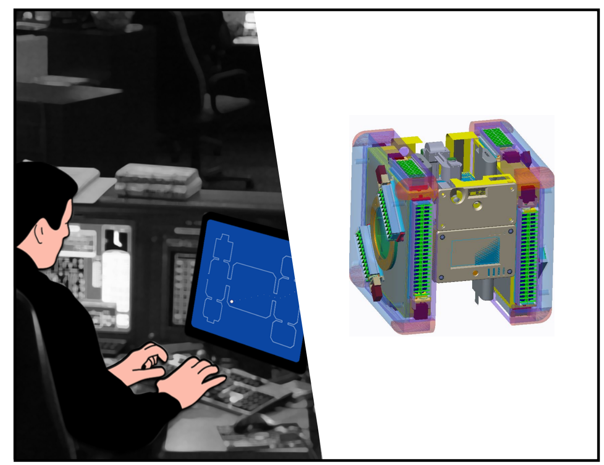
- Multiple ops scenarios: General navigation, docking, perching, guest science
- Research platform: Carry payloads, extensible, crew interaction
- Operate in ISS crew cabin: safe, human factors
- Adjustable automony: Support both live teleoperation and autonomous plan execution
- 6 DOF holonomic control: thrust in any direction, rotate about any axis
- Reduce crew overhead: Autonomous resupply
- Multi-hour sortie duration: power efficient
- Multi-year service lifetime: reliable, serviceable, upgradeable



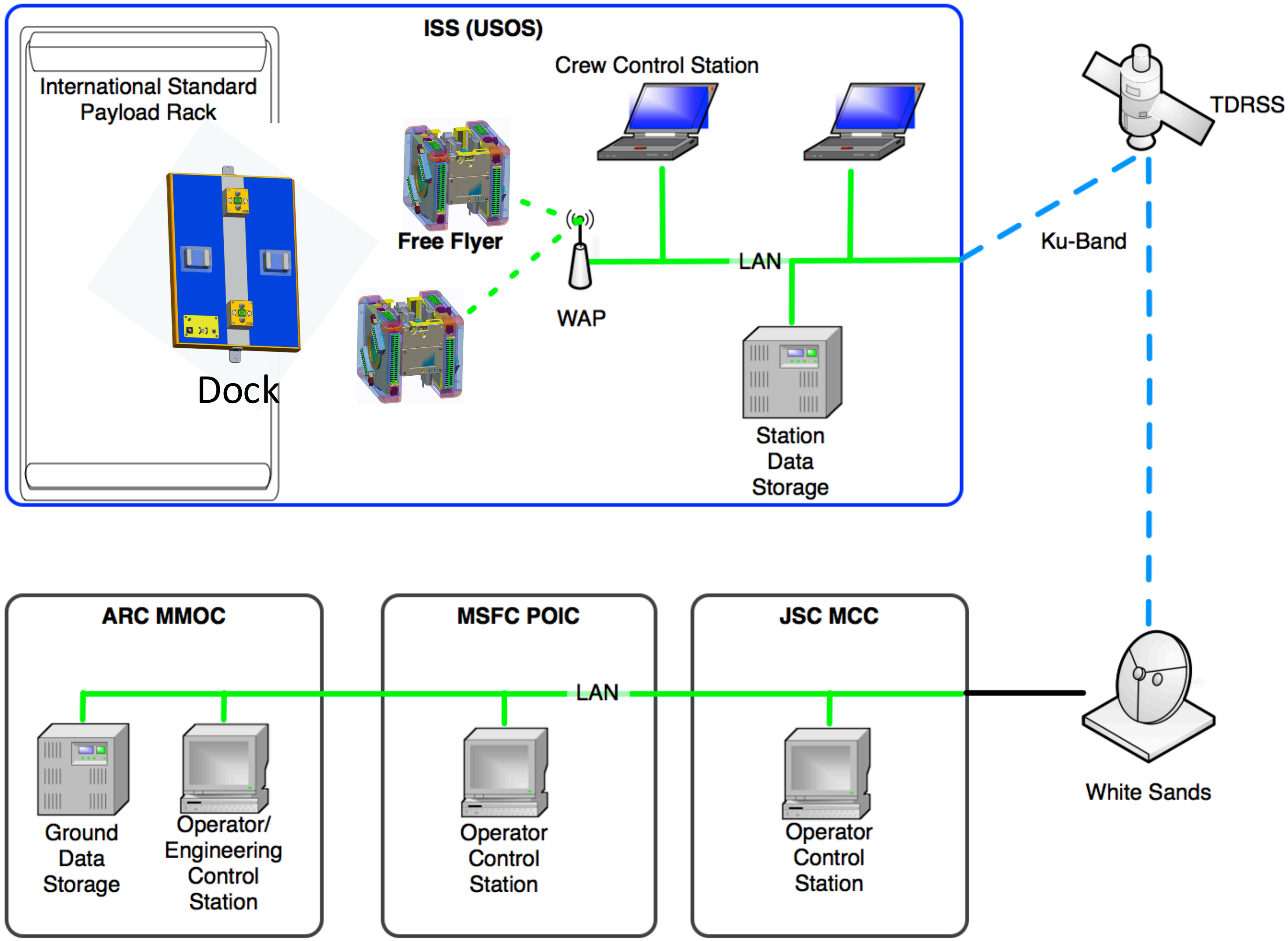
Astrobee Elements

- Astrobee
  - Free Flyer
  - Dock
  - Ground Data System

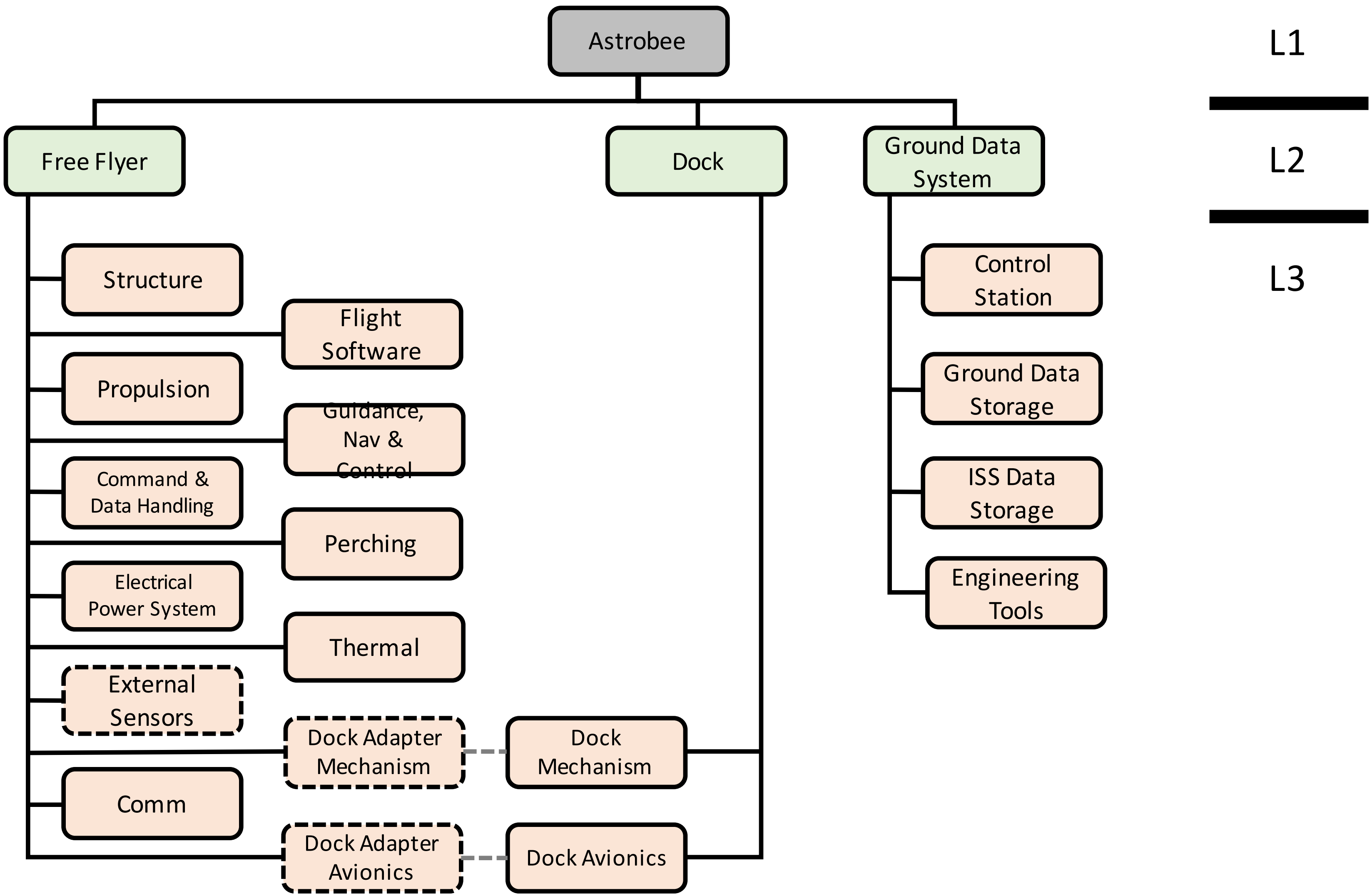




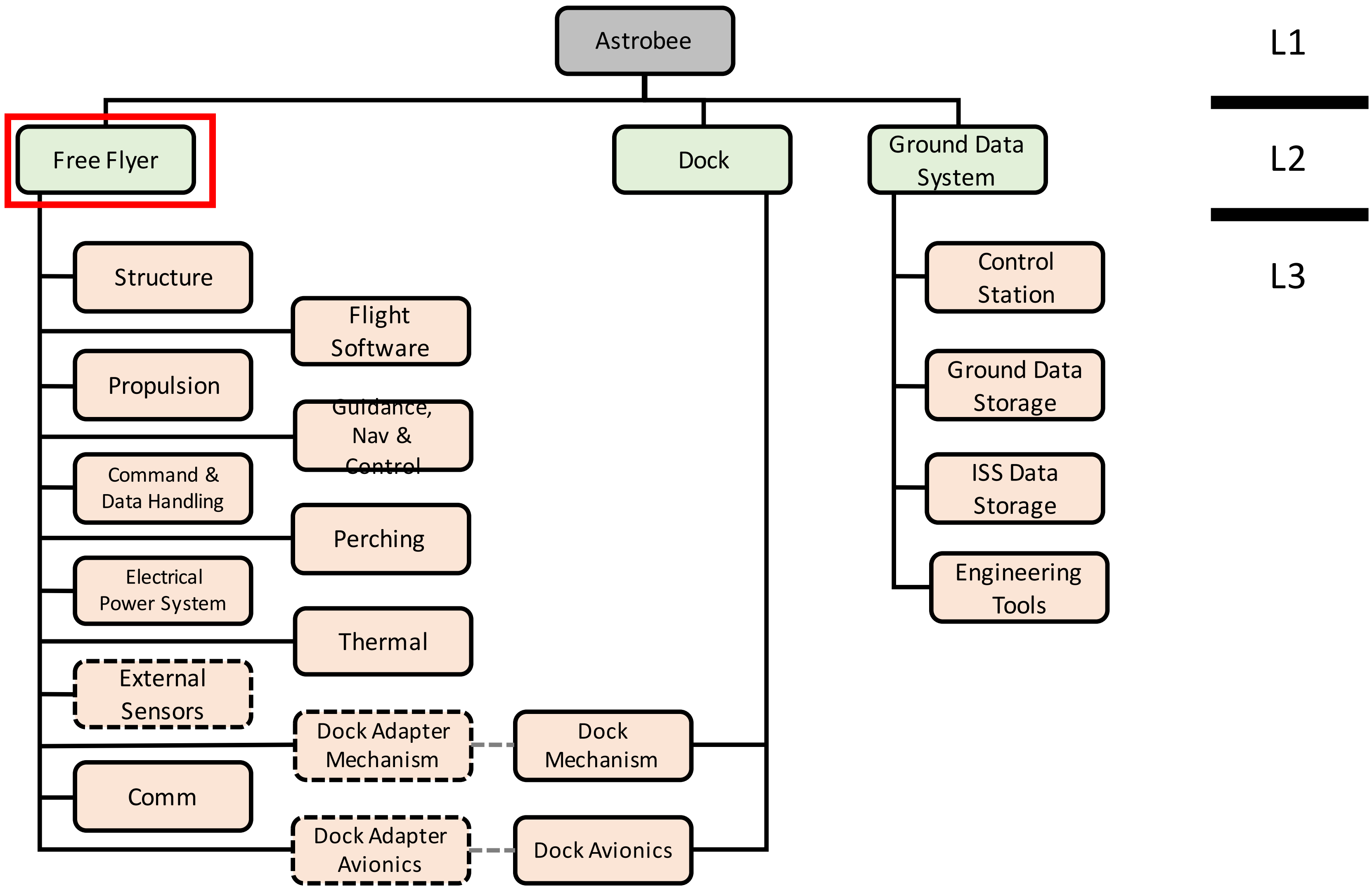
System Architecture



Subsystems


Astrobee
Free Flyer
Dock
Ground Data System
L1
L2
L3
Structure
Flight Software
Propulsion
Guidance, Nav & Control
Command & Data Handling
Perching
Electrical Power System
Thermal
External Sensors
Dock Adapter Mechanism
Dock Mechanism
Comm
Dock Adapter Avionics
Dock Avionics
Control Station
Ground Data Storage
ISS Data Storage
Engineering Tools

Subsystems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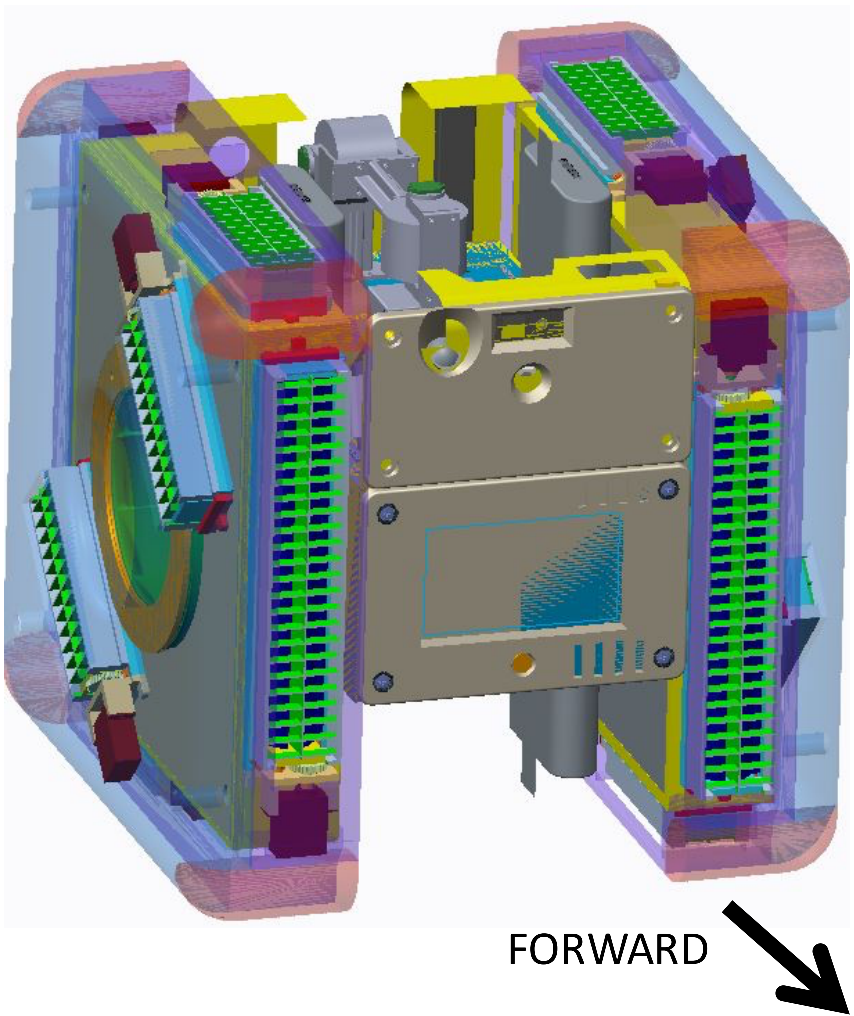
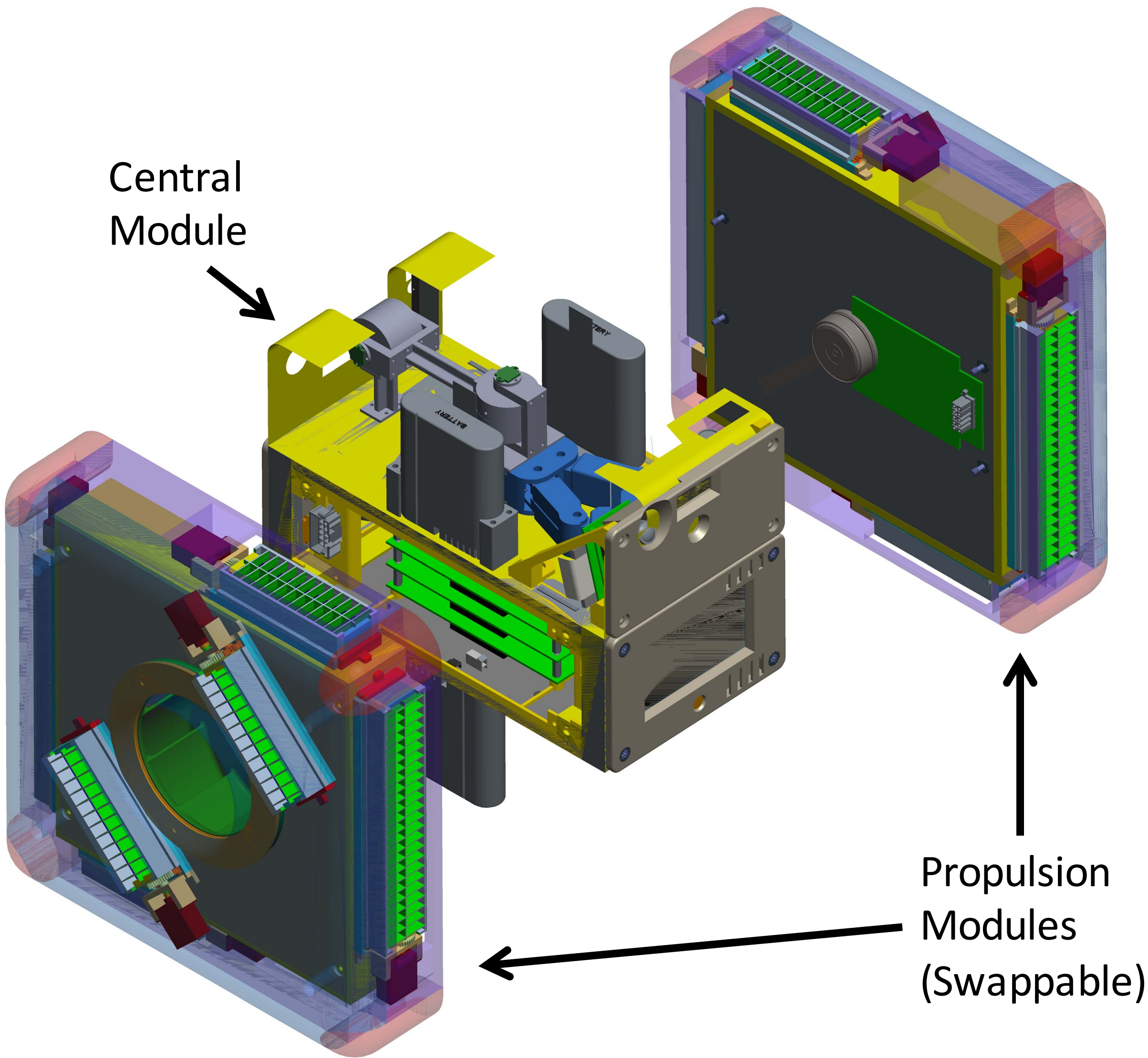
Shape



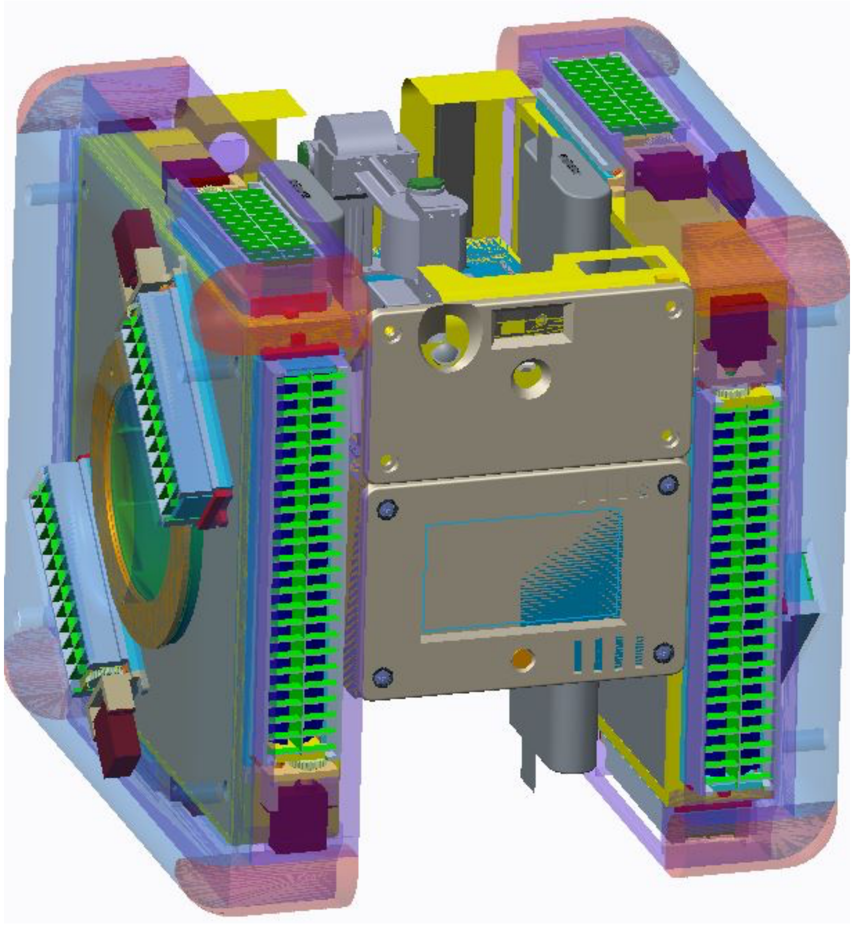
12 x 12 x 12 inches
6 kg mass

Basic Packaging

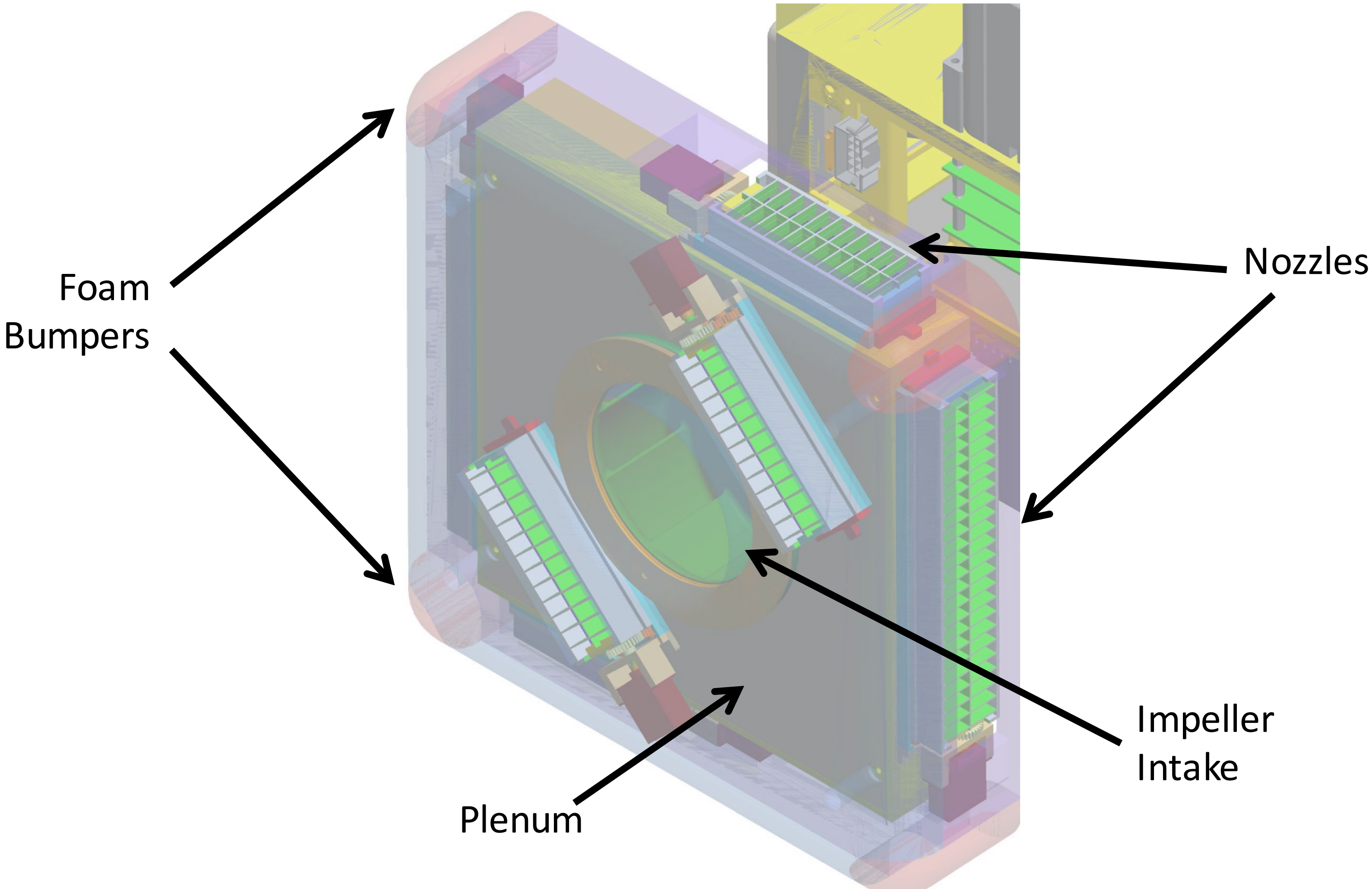


Or More Poetically

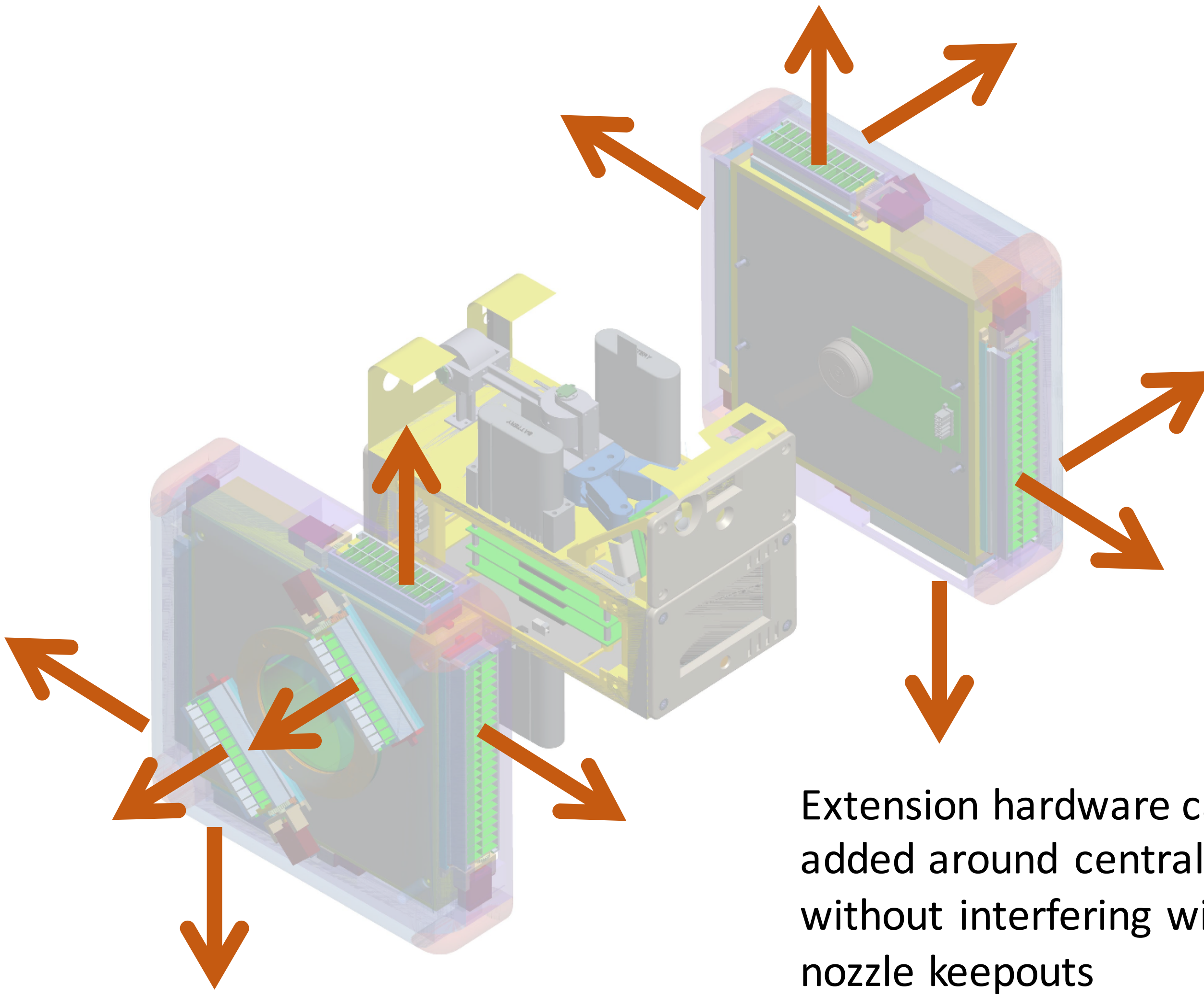
"Sideways Hamburger"



Propulsion Module

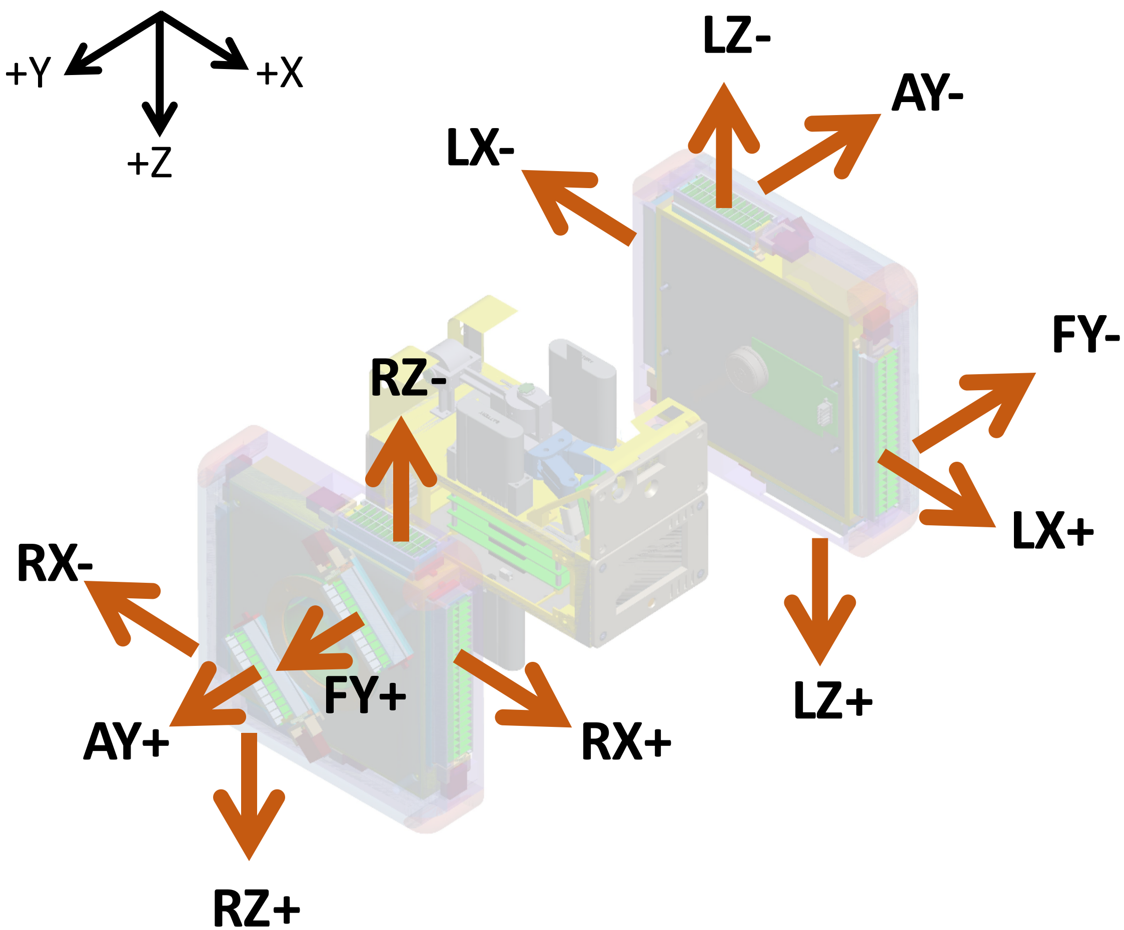


12 Nozzle Layout



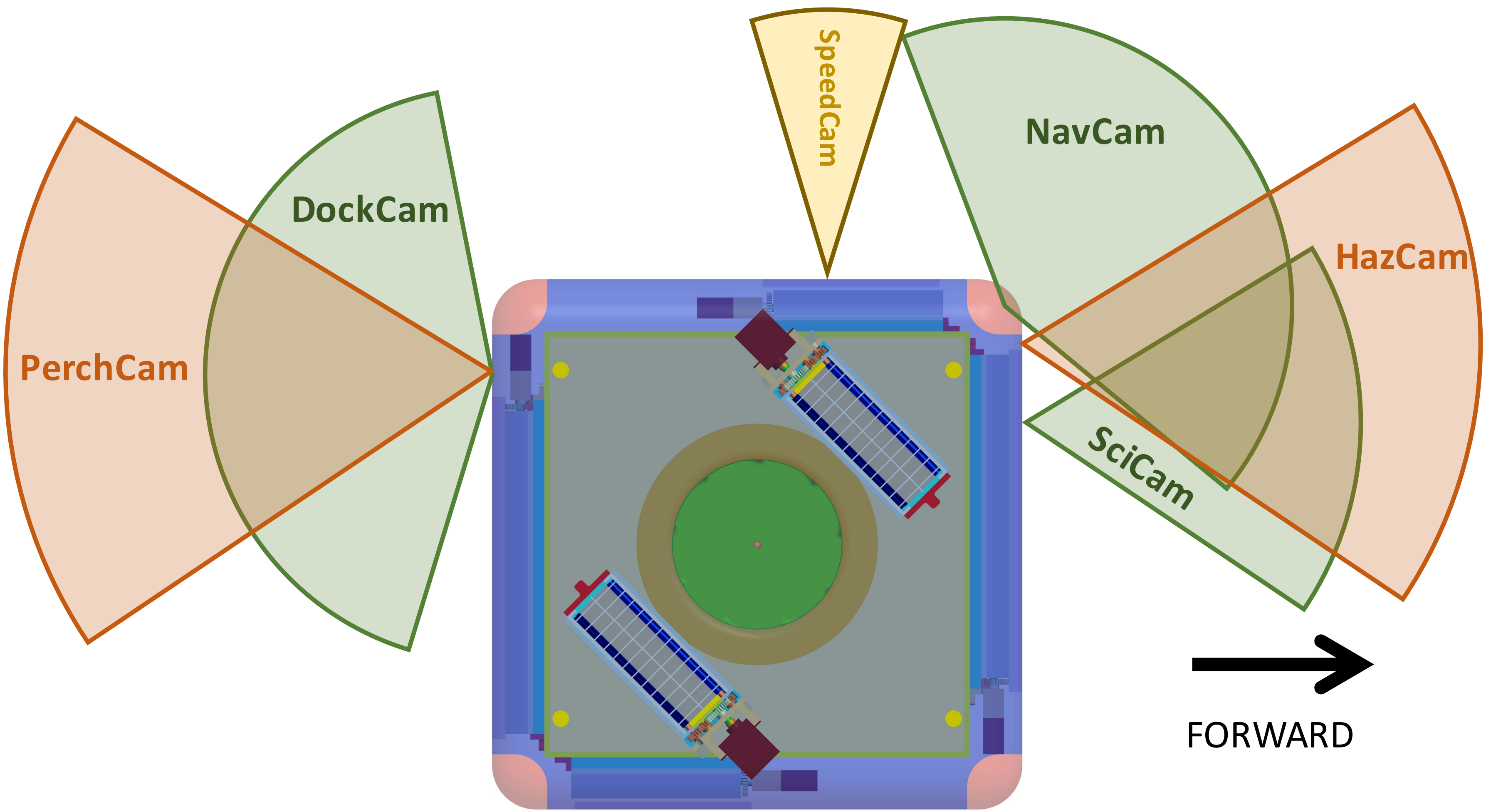
Extension hardware can be added around central module without interfering with exhaust nozzle keepouts

Holonomic Control

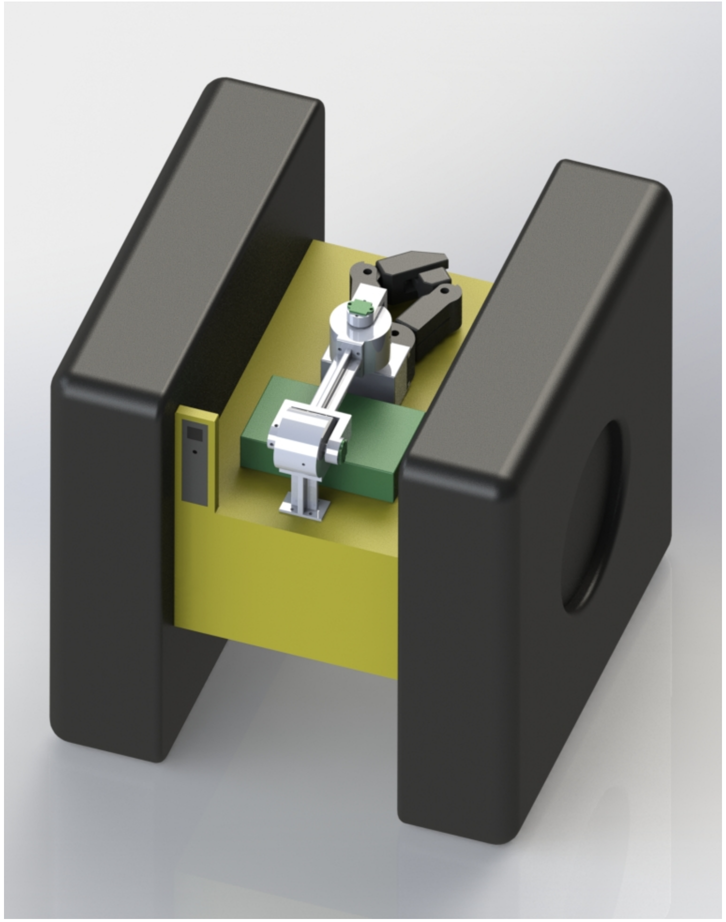


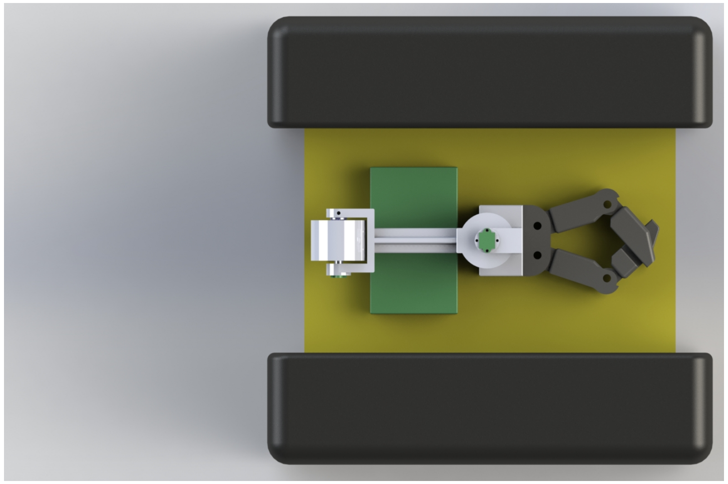
Thrust/Torque	Thrusters Used
+Fx	RX-, LX-
-Fx	RX+, LX+
+Fy	FY-, AY-
-Fy	FY+, AY+
+Fz	RZ-, LZ-
-Fz	RZ+, LZ+
+Mx	RZ-, LZ+ or AY-, AY+
-Mx	RZ+, LZ- or FY-, FY+
+My	RX+, RX- or LZ+, LZ-
-My	LX+, LX- or RZ+, RZ-
+Mz	RX+, LX- or AY+, FY-
-Mz	RX-, LX+ or AY-, FY+

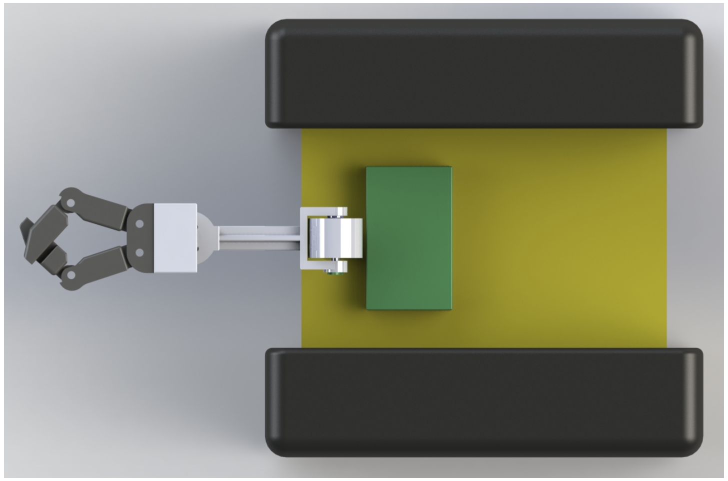
External Sensors



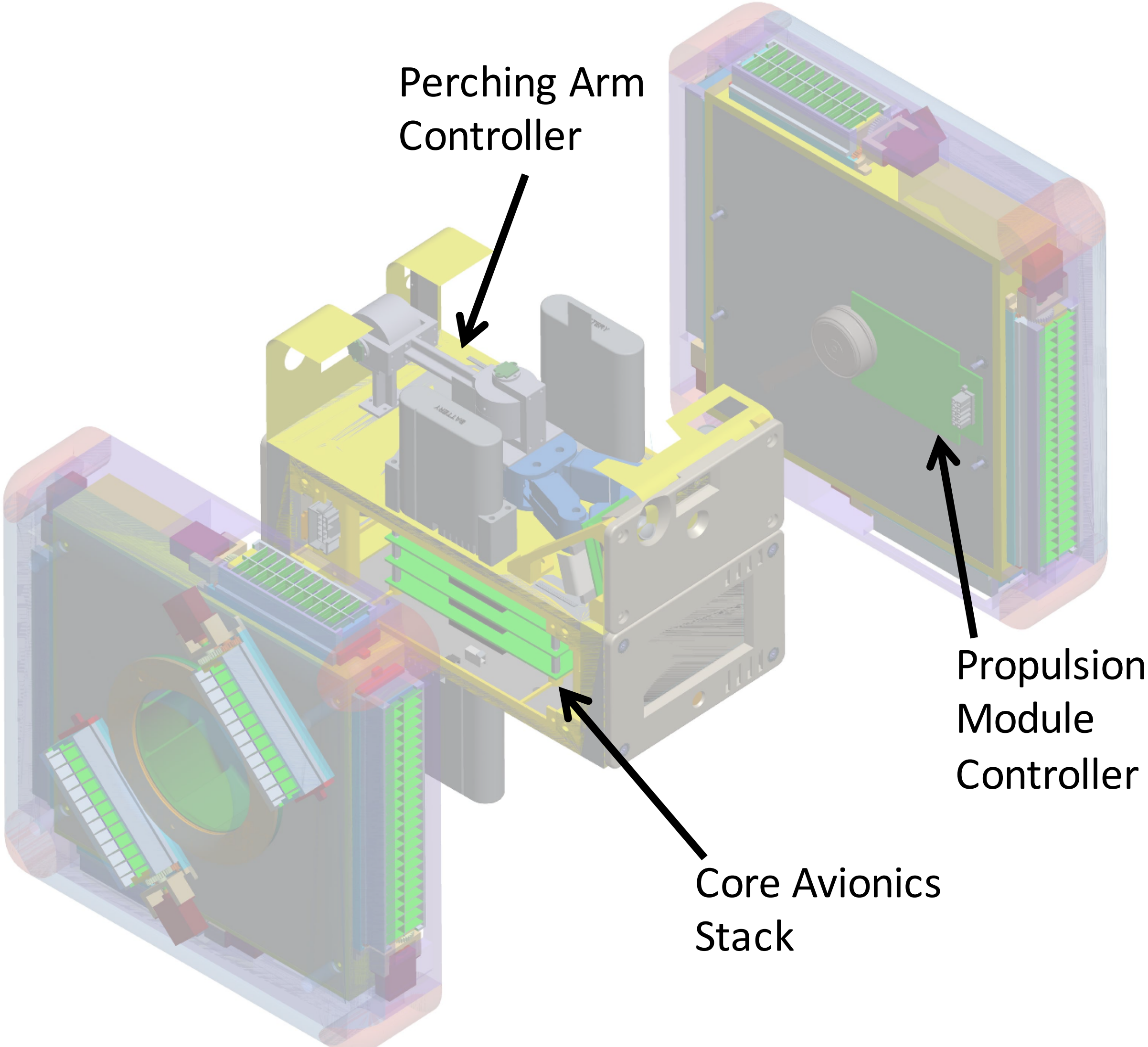
Perching Arm





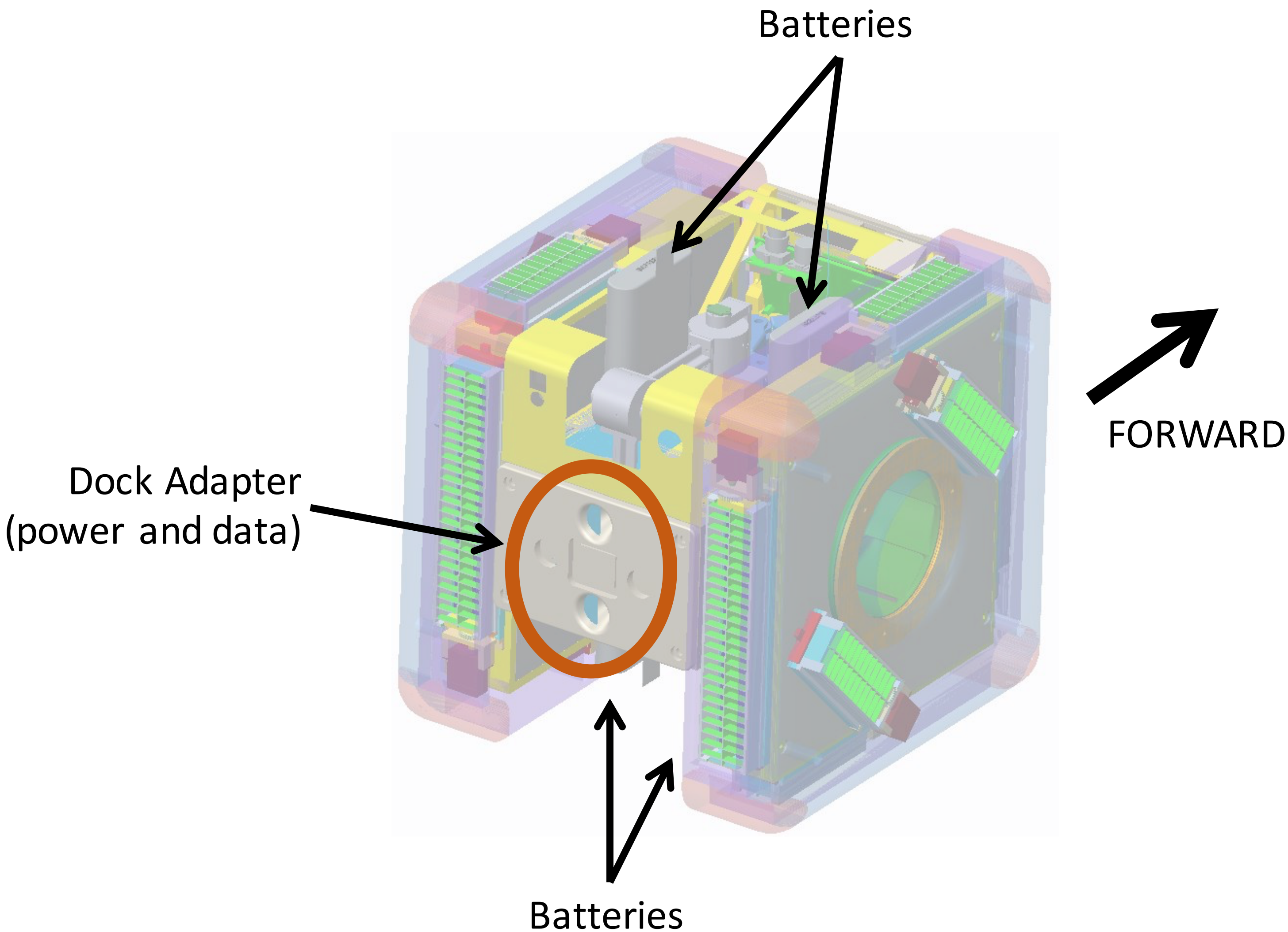


Computing

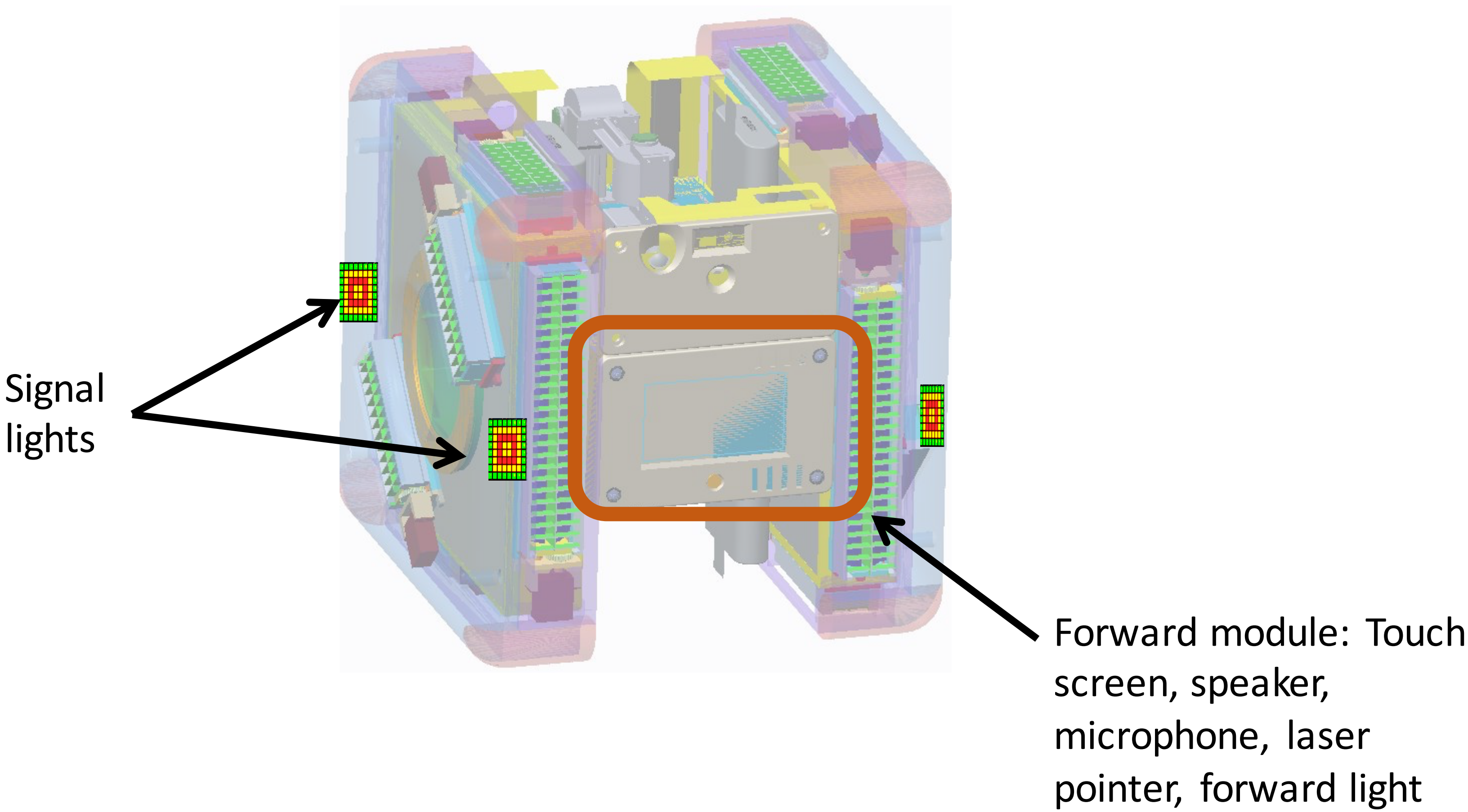


Perching Arm Controller
Propulsion Module Controller
Core Avionics Stack

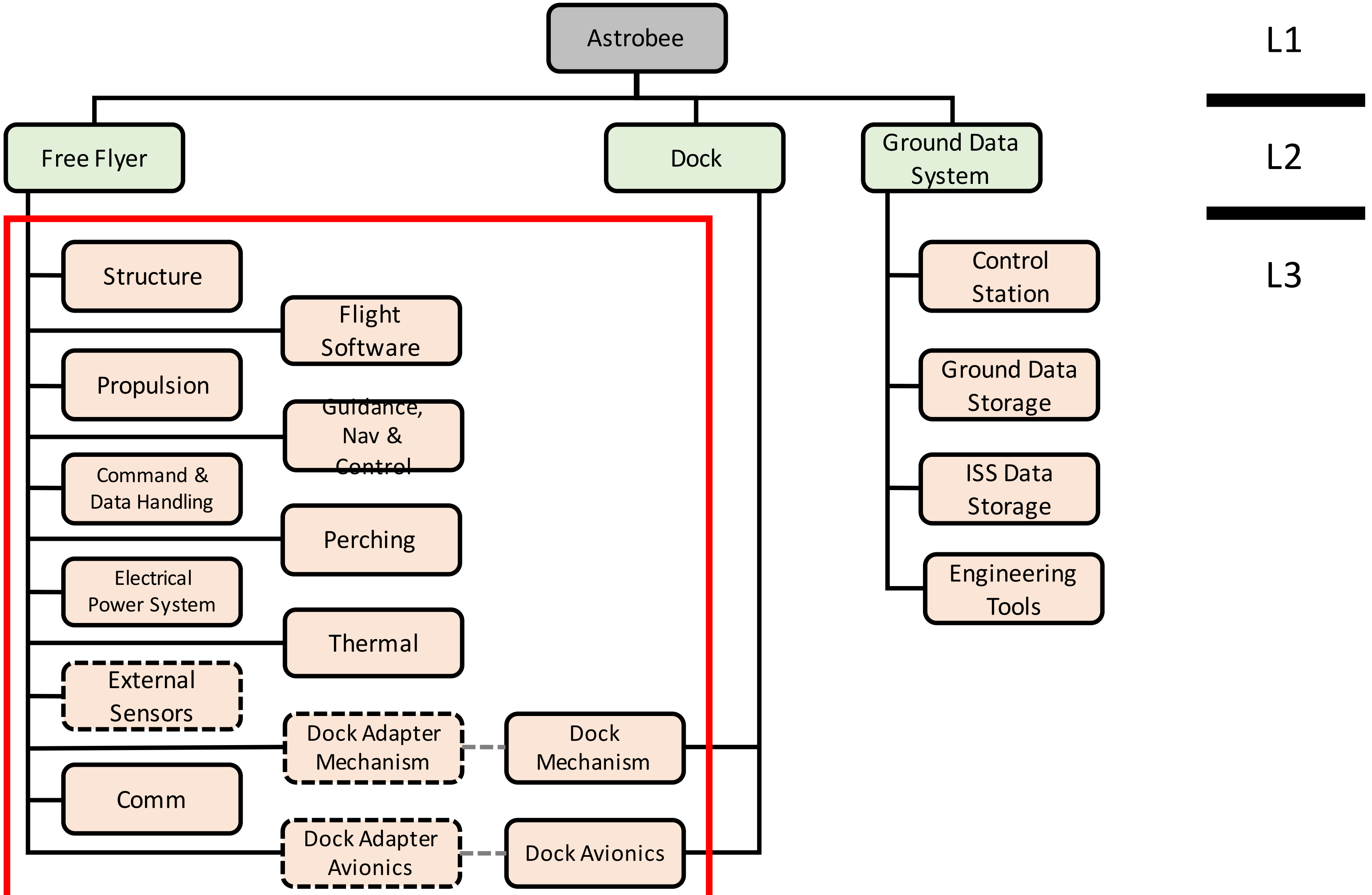
Power Systems



Crew Interaction



Subsystems



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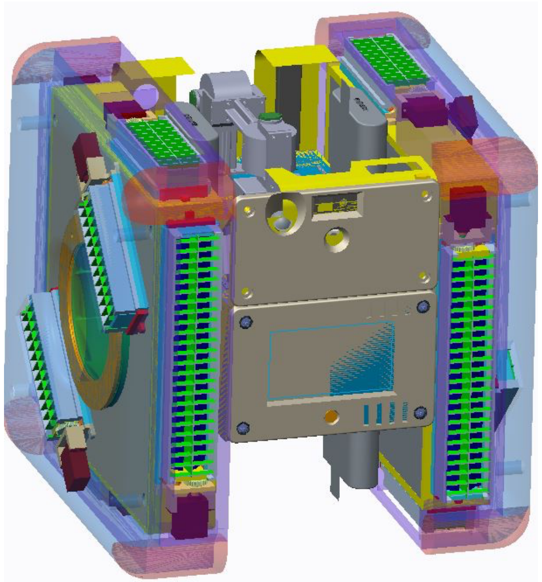
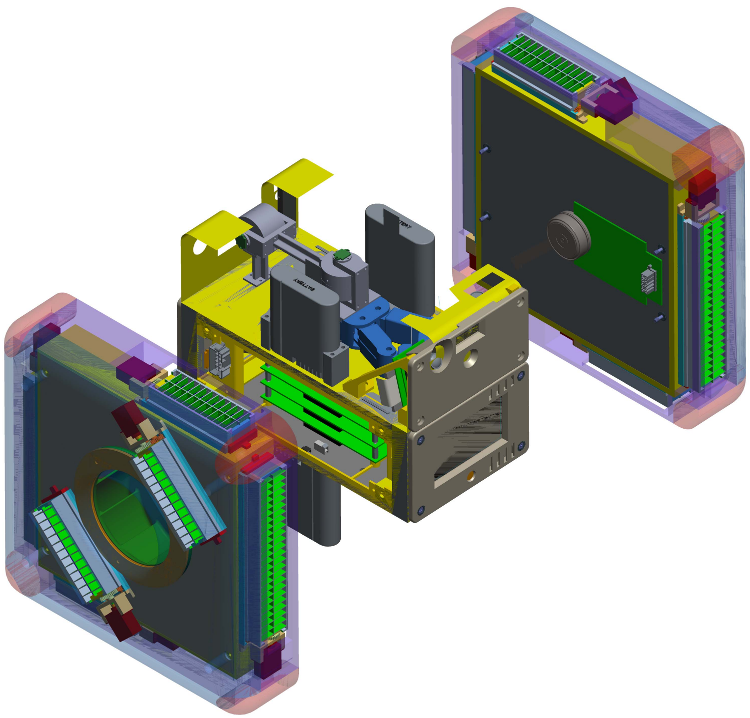
Structure

- Design Drivers
  - Safety: absorb collision energy
  - Modularity for payloads, servicing, upgrades
  - Low mass
- Design
  - Corner-mounted foam bumpers absorb impact energy in case of collision
    - Rigid hardware is recessed behind bumpers
  - Primary load-bearing structure is aluminum frame
  - Component mounting brackets 3D printed
  - Fasteners are quarter-turn or capture screws
  - Clean modular design makes crew access easy



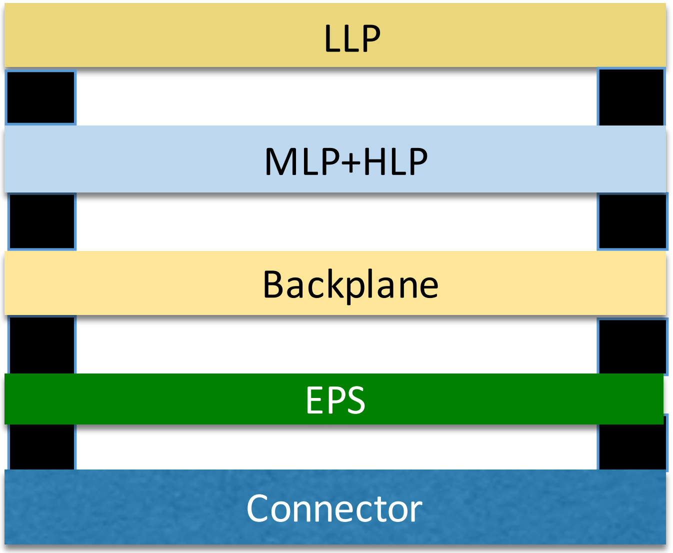
Propulsion

- Design Drivers
  - Safety: collision, hair pulling, ejected particles
  - 6 DOF holonomic control
  - Design to be simple, reliable, serviceable
  - Minimize noise, volume, power, mass
- Design
  - Two propulsion modules (left and right)
  - Each module uses an impeller to draw in cabin air and pressurize a plenum (~0.1 psi)
  - Each plenum exhausts to six nozzles with proportional control
  - Screen at impeller intake keeps hair and large particles out
  - Limit max thrust to constrain impact energy in worst-case collision



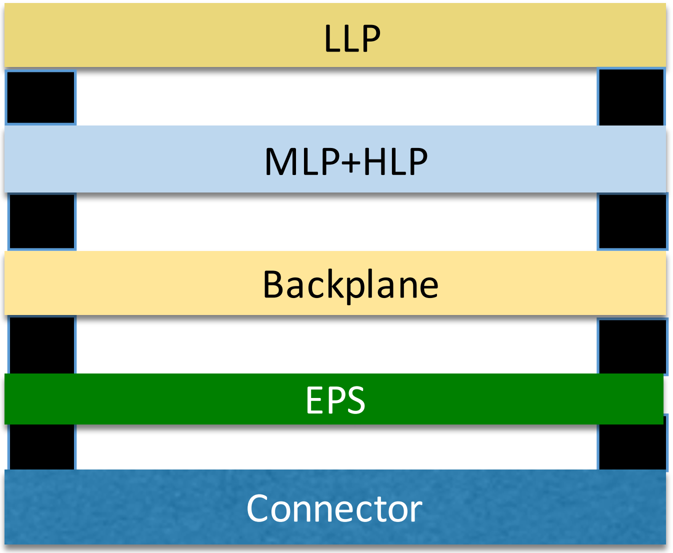
Command and Data Handling

- Design Drivers
  - Reliability: Multi-processor isolation, serviceable, upgradeable
  - Power-efficient high performance for machine vision, HD video
  - Support a variety of data buses
- Design
  - Hybrid COTS/custom approach: Integrated COTS modules on custom carrier boards
  - Power-efficient ARM processors (embedded variants of cell phone technology)
  - 3 independent processors
  - Avionics boards accessible for crew replacement or upgrade



Electrical Power System

- Design Drivers
  - Safety: fault protection
  - Provide separately switchable power to many components at multiple voltages
  - Power and thermal telemetry
- Design
  - COTS Inspired Energy Li-ion batteries at 14.4 V – ISS heritage
  - 2-4 batteries in different ops configurations
  - Most functionality provided by custom EPS board
  - Protective circuits for batteries, dock mate/demate, etc.

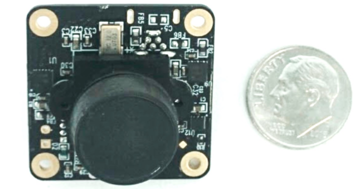


External Sensors

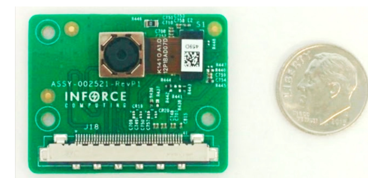
- Design Drivers
  - Reliability: Ability to stop robot motion even if sensing/computing degraded
  - Support ops scenarios: general navigation, docking, perching, crew video
  - Low power, volume, mass
- Design

Sensor	Function
NavCam	Visual pose estimation: observing ISS walls
SciCam	High-quality video of crew activities
HazCam	LIDAR obstacle detection
DockCam	Visual pose estimation: observing AR target on dock
PerchCam	LIDAR pose estimation: observing ISS handrail
SpeedCam	Sonar/optical flow velocity estimation

NavCam/DockCam

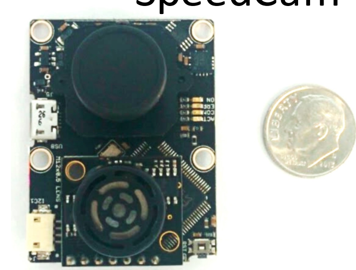


SciCam



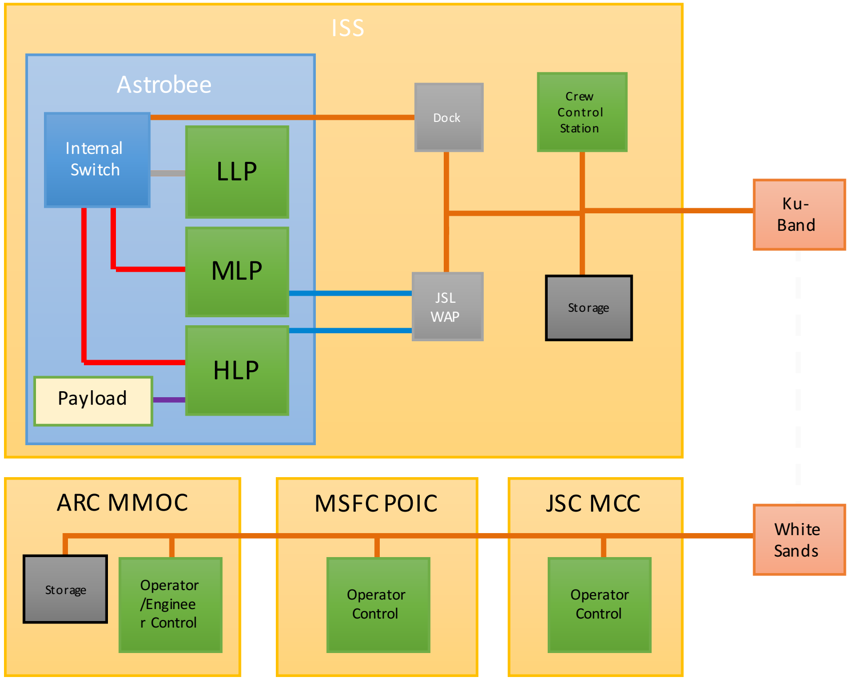
HazCam/PerchCam

SpeedCam



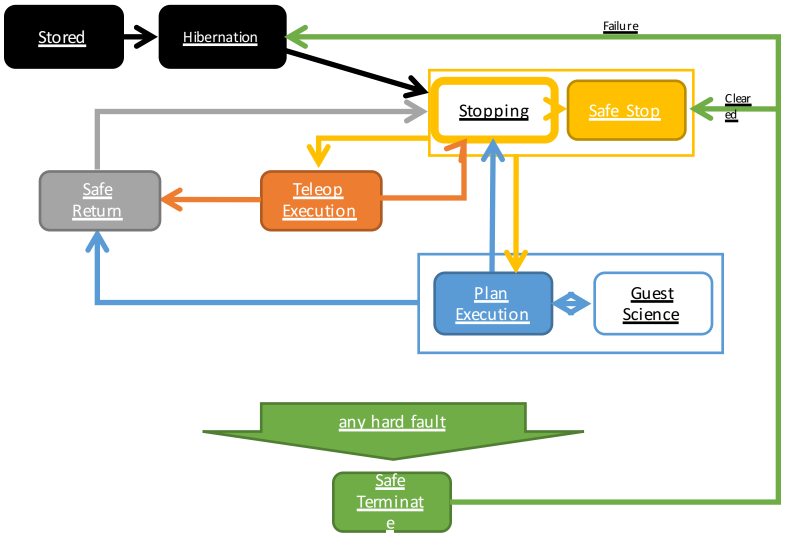
Comm

- Design Drivers
  - Reliability: Degrade gracefully with unreliable comms
  - Live HD video and telemetry
  - Downlink full logs after sortie
  - Inter-robot comms
- Design
  - Live comms through JSL WiFi / Ku-band / TReK
  - Telemetry using DDS protocol
  - Hard-wired Ethernet downlink through dock



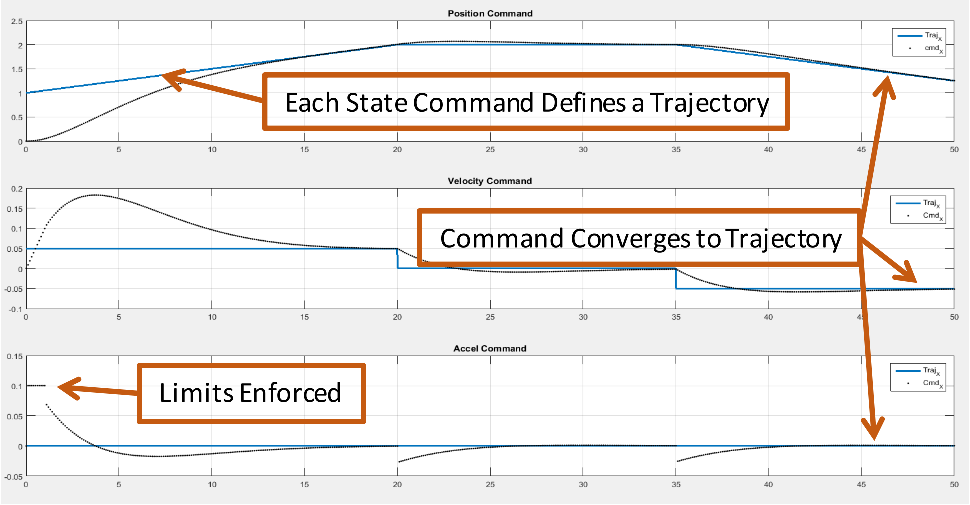
Flight Software

- Design Drivers
  - Reliability: Diagnose and recover from faults
  - Support many scenarios: general navigation, docking, perching
  - Support guest science
- Design
  - Software distributed across three processors for isolation
  - Modular architecture using ROS framework
  - Primary pose estimation with monocular vision, recognizing natural landmarks
    - Several other pose estimation inputs
  - Multiple safe modes: Safe Stop, Safe Terminate, Safe Return



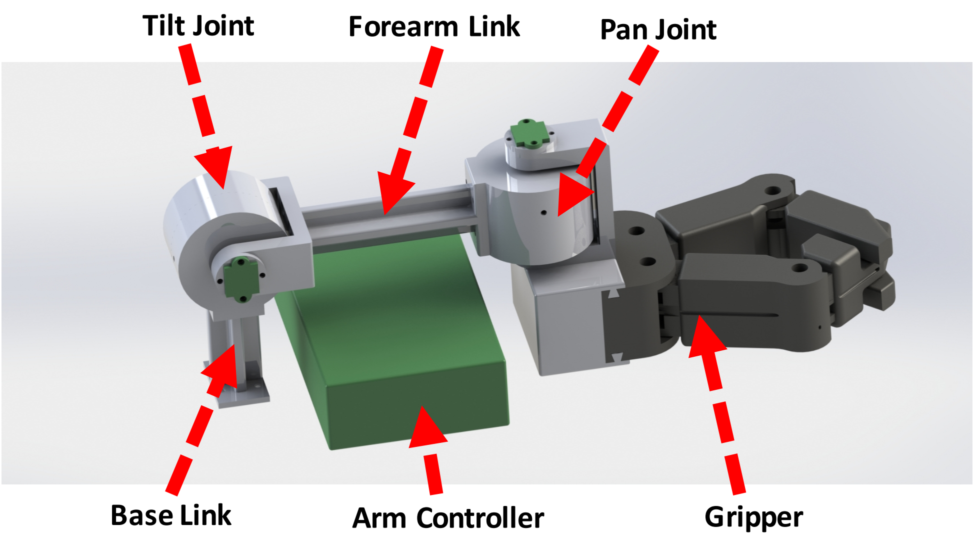
Guidance, Navigation & Control

- Design Drivers
  - Reliability: Stay on planned trajectory to avoid collisions, stop reliably
  - Support many scenarios: general navigation, docking, perching
  - Sensor data arrives asynchronously from multiple sources
- Design
  - High-quality lightweight MEMS IMU
  - Extended Kalman Filter enhancements for asynchronous sensor fusion
  - Command shaper for trajectory following
  - Develop in MATLAB/SIMULINK, auto-code to C for FSW integration
  - Adjust impeller speed to trade power efficiency vs. performance



Perching Arm

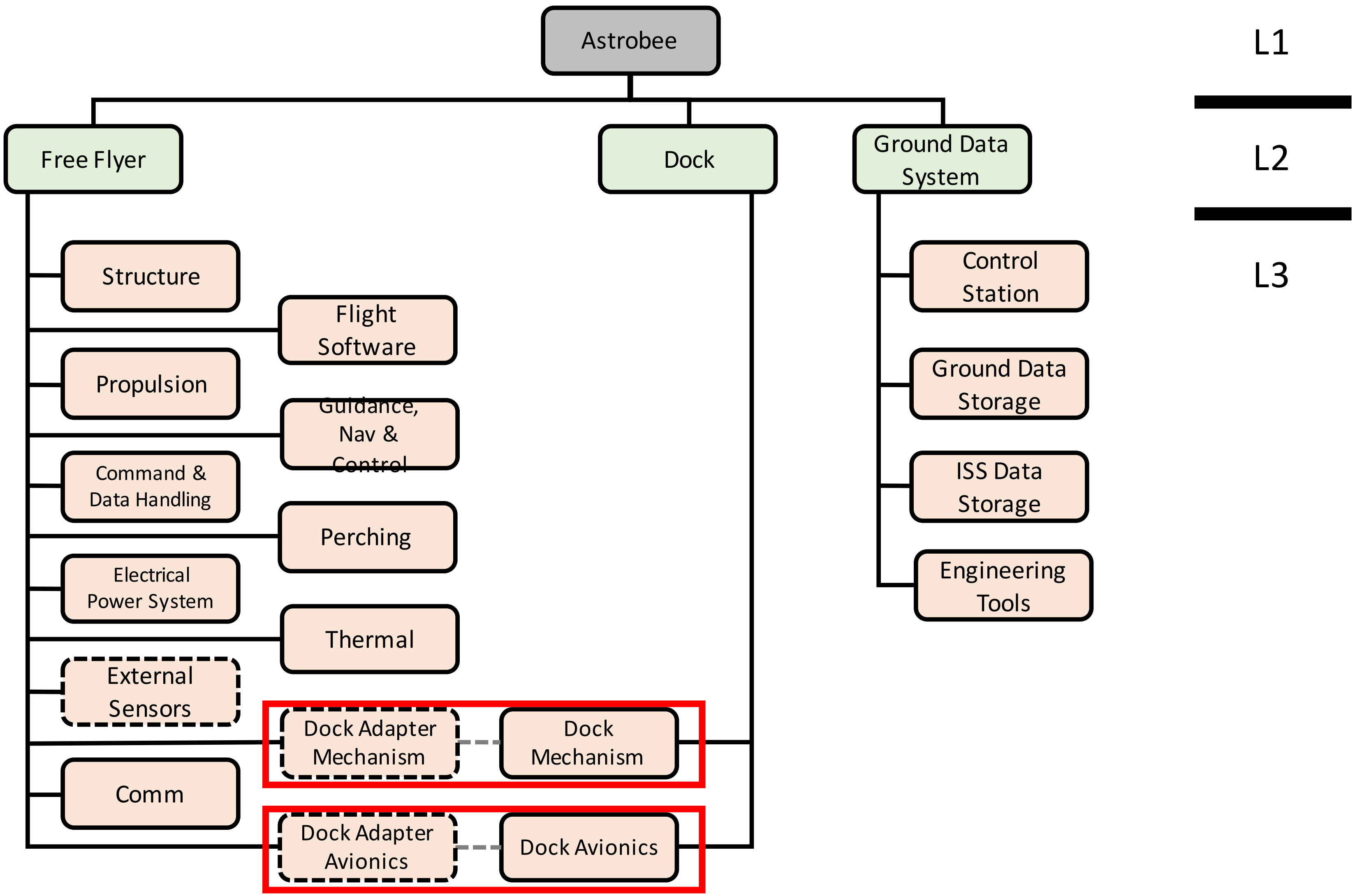
- Design Drivers
  - Safety: collision, pinch hazard, don't obstruct crew
  - Function as pan/tilt unit for SciCam
  - Stow behind bumpers when not in use
- Design
  - Grasp handrails
  - 3 DOF (tilt joint, pan joint, gripper)
  - Tendon-driven gripper, inherently compliant
  - Joint controller detects disturbance torque and shuts off to allow back-driving
  - Crew can manually perch robot on a handrail if desired



Thermal

- Design Drivers
  - Safety: Never exceed 113 F touch temperature limit (fault tolerant)
  - Reject heat produced by avionics, impeller motors
  - No gravity-driven convection
- Design
  - Heat sinks bonded to avionics board components where needed
  - Avionics box cooled by dedicated thermal fans
  - Impeller motor cooled by air flow within plenum
  - Independent over-temperature shutdown hardware

Subsystems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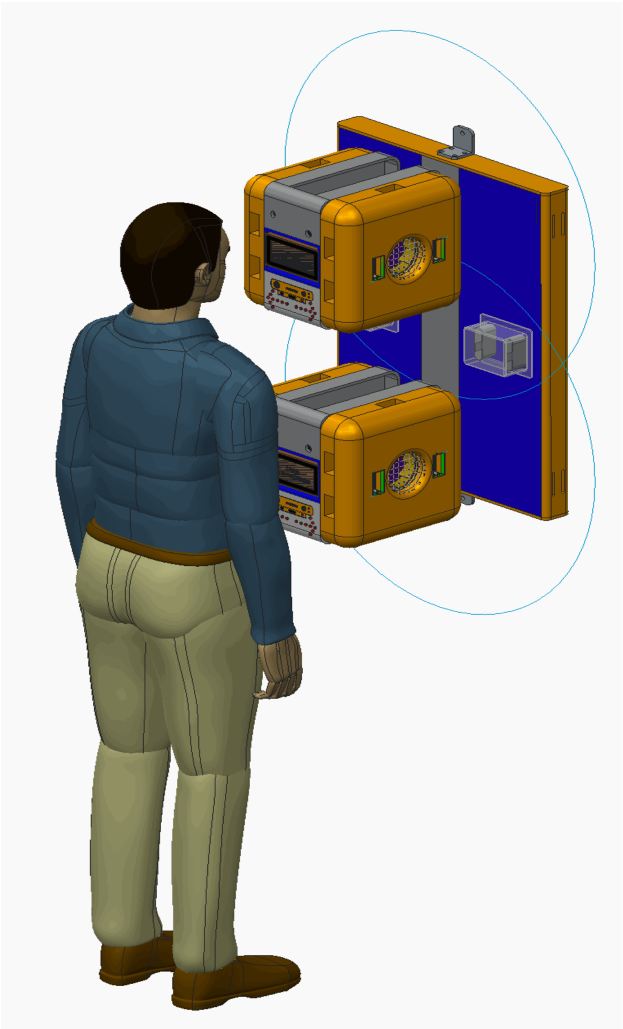
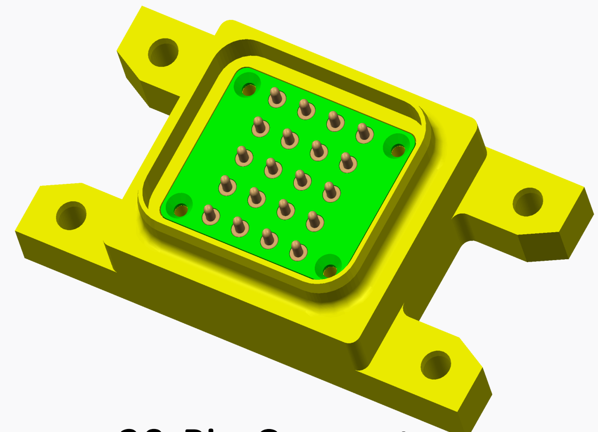
Dock+Adapter Mechanical

- Design Drivers
  - Safety: avoid obstructing crew escape paths, fire extinguishers
  - In berth, Free Flyer propulsion nozzles sufficiently far from obstructions to avoid ground effect
  - Support precision mating of data connector despite motion error
- Design
  - Dock mounts on seat track
  - “Lances and cups” mechanical guide for fine mating precision, “lances” are rounded cone shape
  - Permanent magnet retention system with electromagnet release
  - Crew can manually remove Free Flyer from dock
  - Stand-alone charging capability for spare batteries

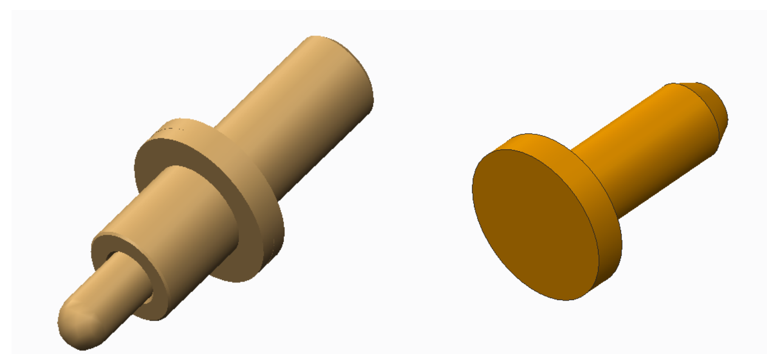


Dock+Adapter Avionics

- Design Drivers
  - Safety: fault protection
  - Provide power and high-speed data
  - Human factors: crew access for servicing
- Design
  - Minimum custom hardware, mostly COTS components
  - Pogo pins for reliable wired data connection between dock and Free Flyer with minimum insertion force
  - Thermal and power fault protection
  - Connector to Free Flyer not energized until successful mating is confirmed

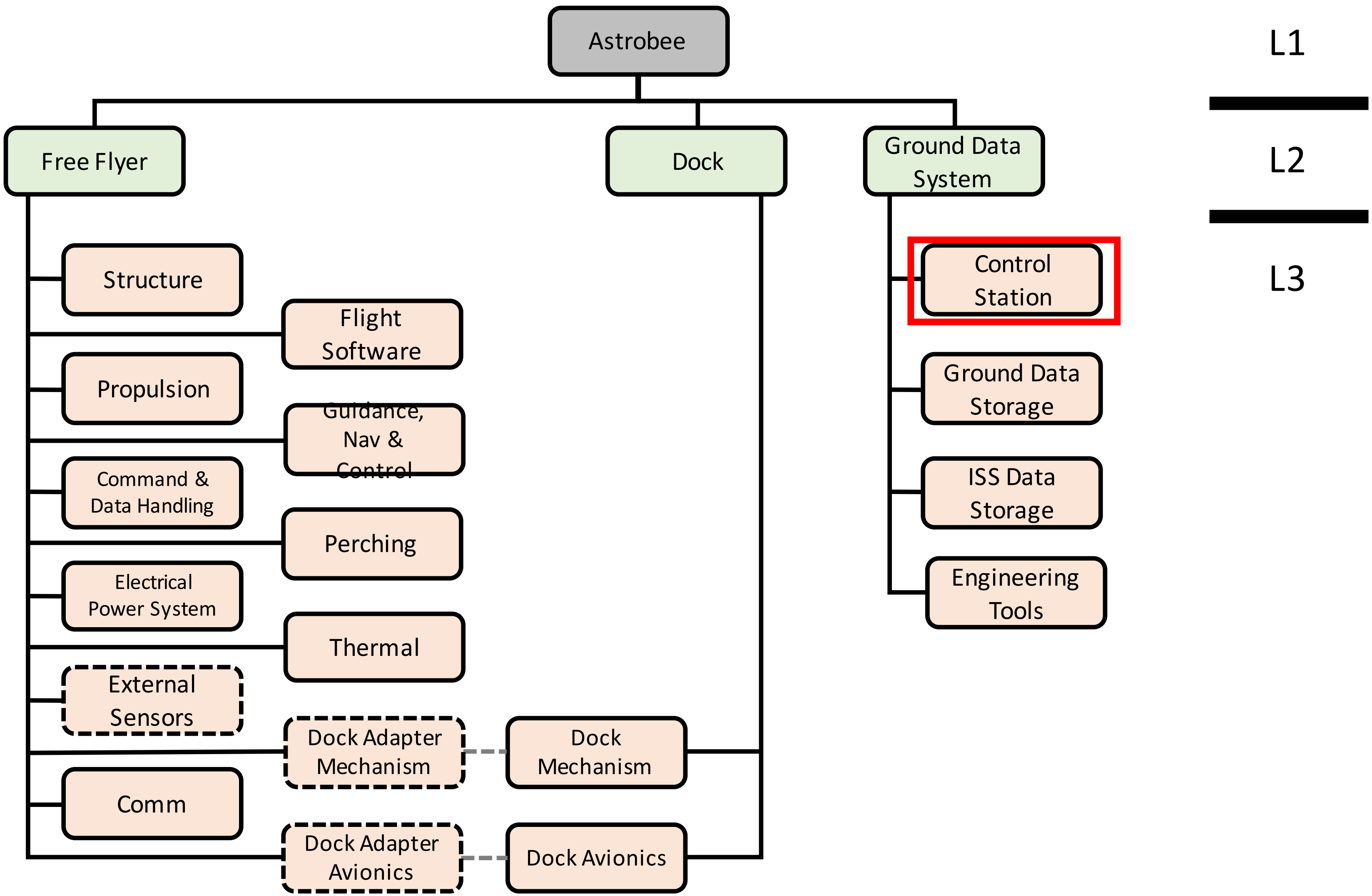


20-Pin Connector



Pogo Pin Matching Pad

Subsystems



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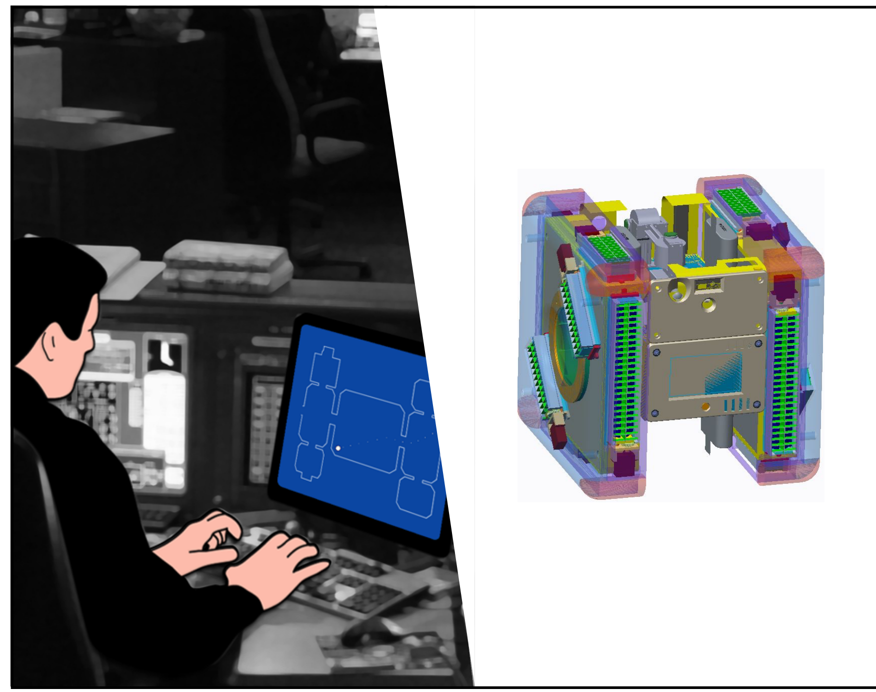
Control Station

- Design Drivers
  - Reliability: Provide operator situation awareness, report faults
  - Cover multiple ops phases: planning, live control, data archive
  - Operate with multiple users and multiple robots
- Design
  - Leverage previous Smart SPHERES control station, Eclipse RCP
  - Live telemetry through RAPID/DDS
  - Live video viewed with VLC

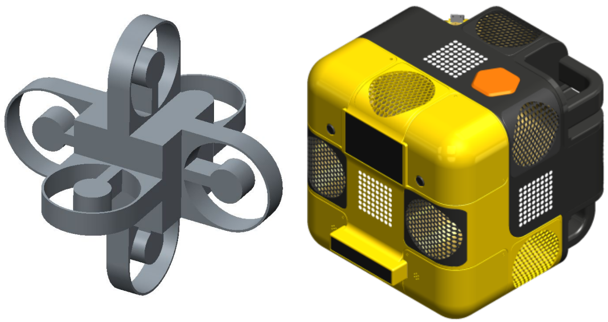


Major Changes Since PTR1

- Impeller module propulsion
- Payload bay geometry
- Thermal fans to cool avionics
- No safety-critical software
- Foam bumpers for collision

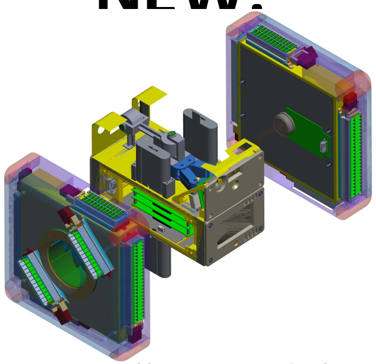
Propulsion Approach

OLD:



6 variable-pitch axial fans

NEW:

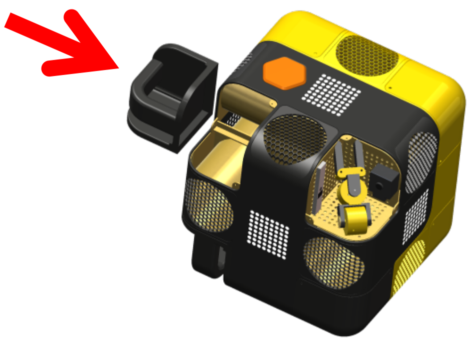


2 impeller modules;
each with 1 impeller+6 nozzles

- New pros:
  - Fewer, simpler, cheaper, more reliable fans
  - Volume down from 66% of total to 50%
  - Has space to accommodate corner bumpers
  - Compatible with intake screen to avoid hair pulling, ejected particles
- New cons:
  - Slight increase in power consumption and noise
  - 12 nozzles, not fault tolerant: poses a reliability concern
  - Late redesign has been a schedule and resource challenge

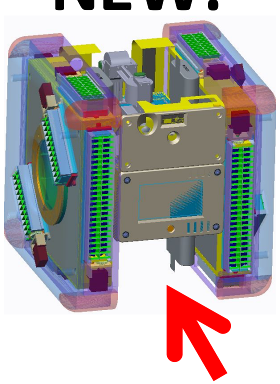
Payload Bay Geometry

OLD:



4 of 8 cube corners available for payloads

NEW:



2 payload bays at bottom of central module (forward and aft)

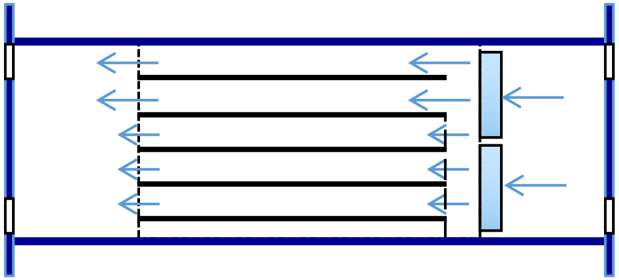
- New Pros:
  - Really necessitated by propulsion redesign
  - New bays are larger
  - The fact that the two bays are contiguous allows us to fit larger "2U" payloads within Free Flyer structure
- New Cons:
  - Total payload volume reduced by about 25%
    - But: volume estimate for original design was never realistic—no space reserved for bumpers
- In both designs, oversized payloads can fasten on to Free Flyer exterior

Thermal Approach

OLD:

[TBD, possibly passive]

NEW:



thermal fans to cool avionics

- New Pros:
  - Thermal analysis showed it was necessary
- New Cons:
  - Additional complexity
  - Power, mass
  - Active thermal control must be fault tolerant for safety

No Safety-Critical Software

OLD:

[TBD]

NEW:

[no safety-critical software]

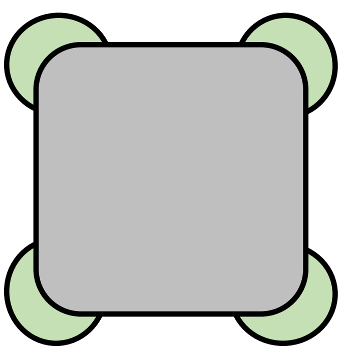
- New Pros:
  - Simplifies C&DH hardware (redundant processors not needed)
  - Massive reduction in software approval process
- New Cons:
  - Risk that hardware alone can't mitigate all hazards

Collision Hazard Approach

OLD:

[TBD]

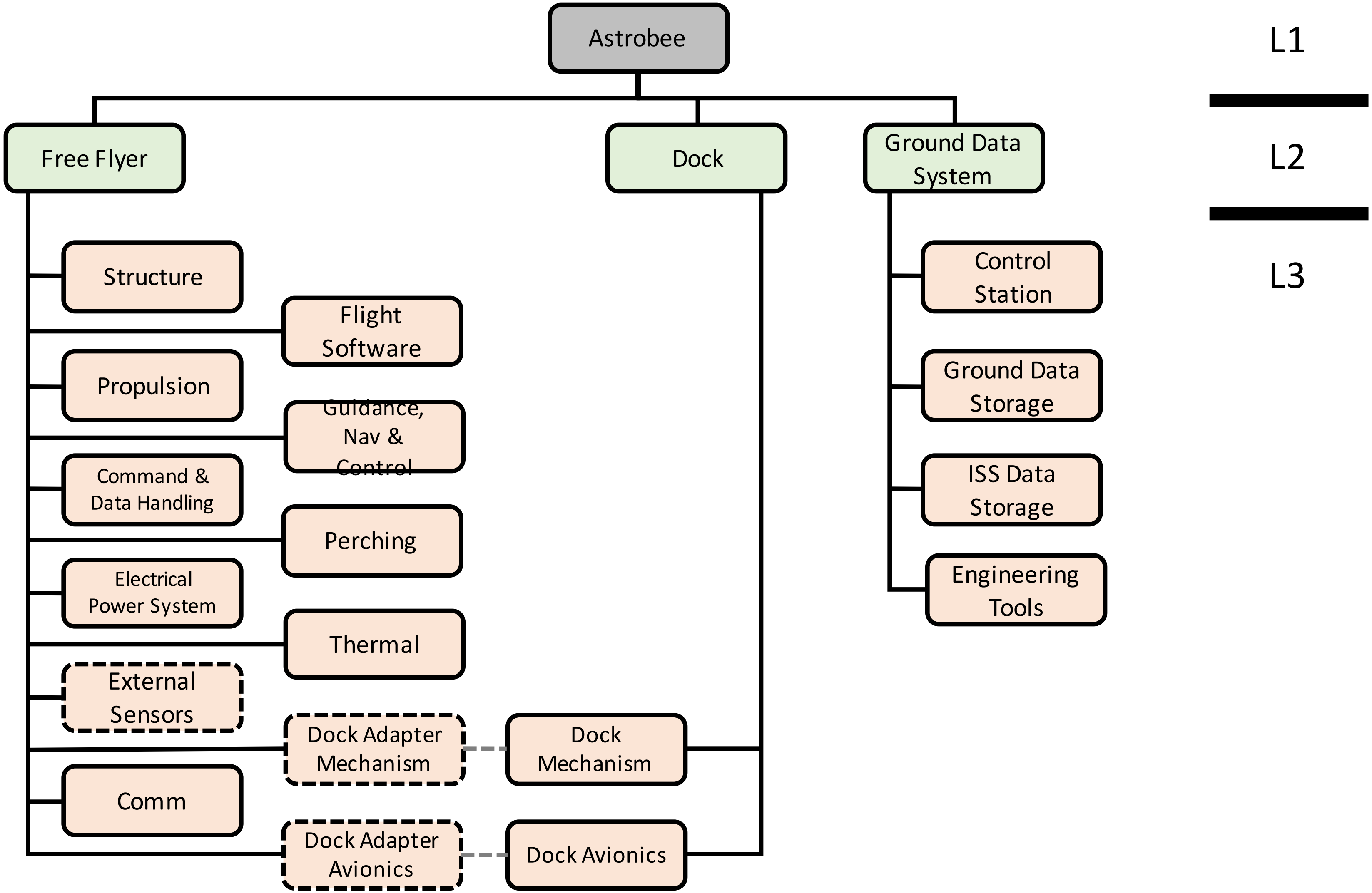
NEW:



corner-mounted foam bumpers

- New Pros:
  - Mitigates need for software hazard controls
- New Cons:
  - Bumpers occupy corner volume
  - Bumpers need inspection / replacement after significant collision

Next Up: Subsystem Presentations



Subsystem Overview Agenda

- Structure
- Propulsion
- C&DH
- EPS
- External sensors
- Comm
- FSW
- GN&C
- Perching Arm
- Thermal
- Dock Mechanical
- Dock Avionics
- GDS

Astrobee Structure Subsystem

Design Overview

Subsystem Team

- Earl Daley (ARC-RE, Lead)
- Jeff Blair (ARC-RE)
- Alex Langford (ARC-RE)
- Hugo Sanchez (ARC-RE)

- Troy Shilt (ARC-RE, Intern)

Design Drivers

- Mass
  - 6kg for entire system
- Modularity
- Sensor geometry
- Loads
  - Launch
  - Max velocity impact
  - Crew kick
- Volume

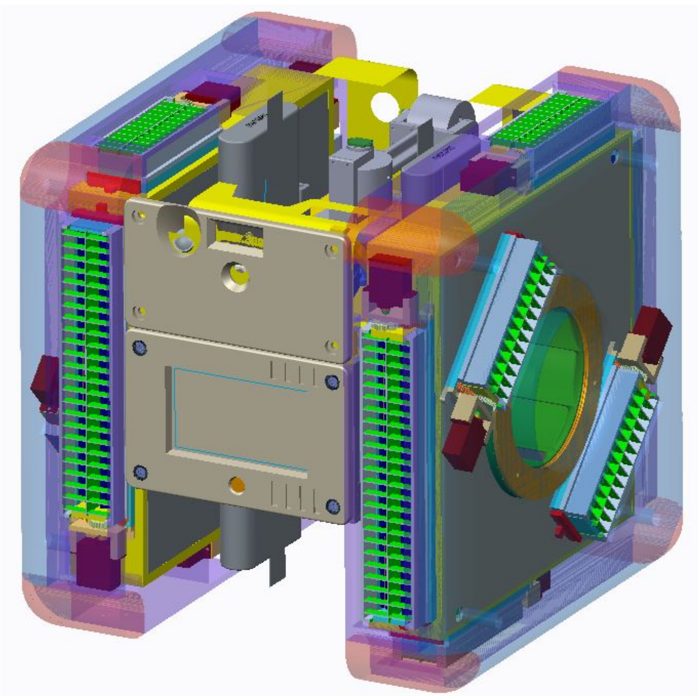
Trade Study

Attributes	Options
Fastening mechanism (TBD)	• Capture screws • Latches • Hinge pins
Material	• Aluminum • Ultem 9085 • Sandwich-structured composite

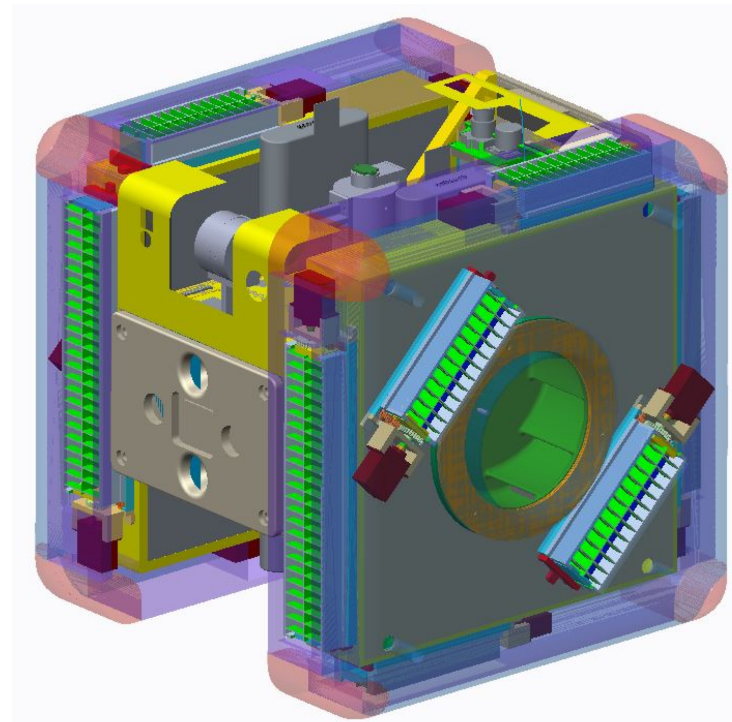
Selected Design

- Aluminum structure
  - Pros: strong
  - Cons: requires machining
- Capture Screws (majority of location)
  - Pros: can be used at all module levels
  - Cons: requires tools
- ¼ Turn D-ring Fasters (payload)
  - Pros: no tools required
  - Cons: too large for many locations

Drawing

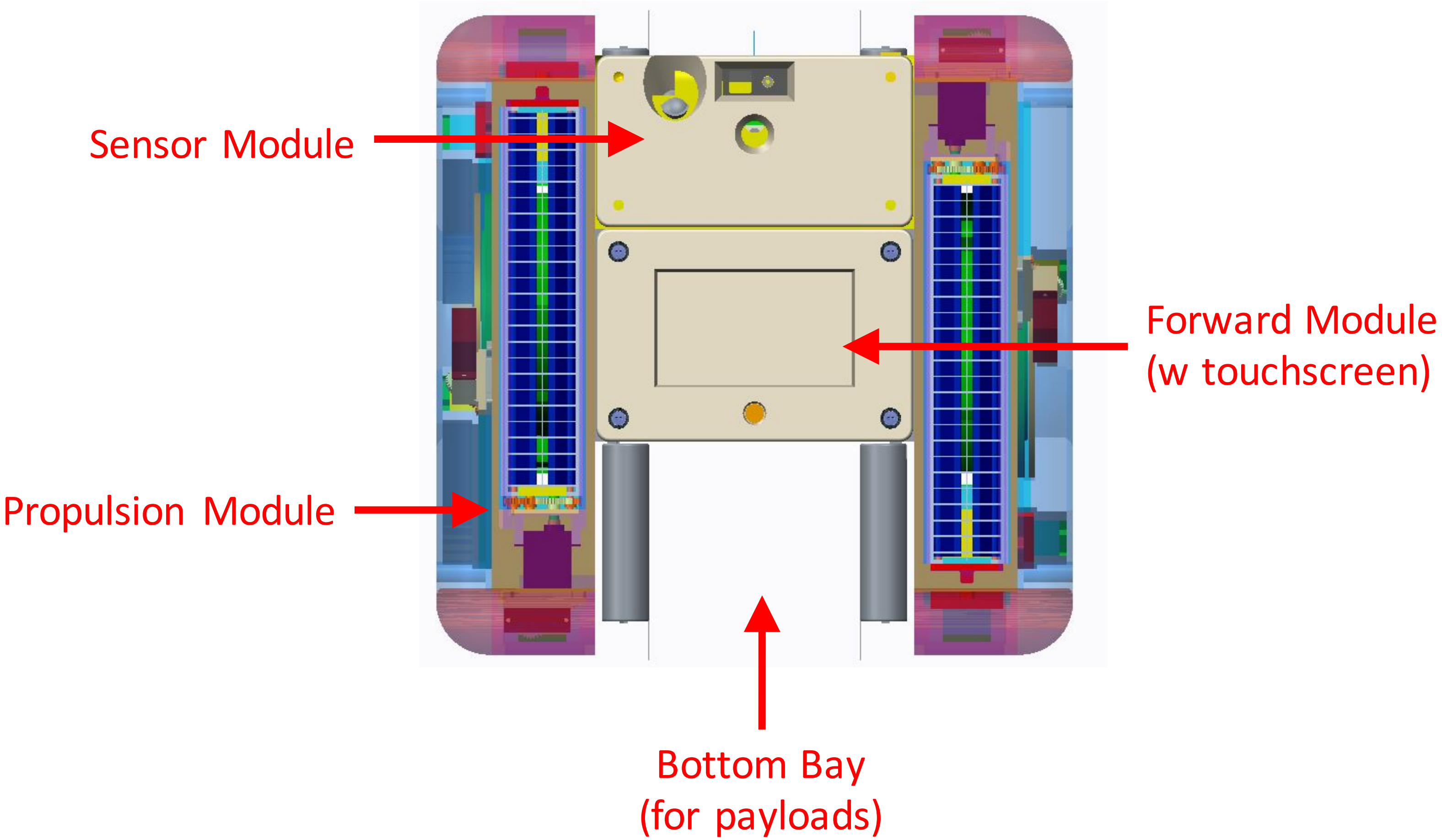


Forward Top

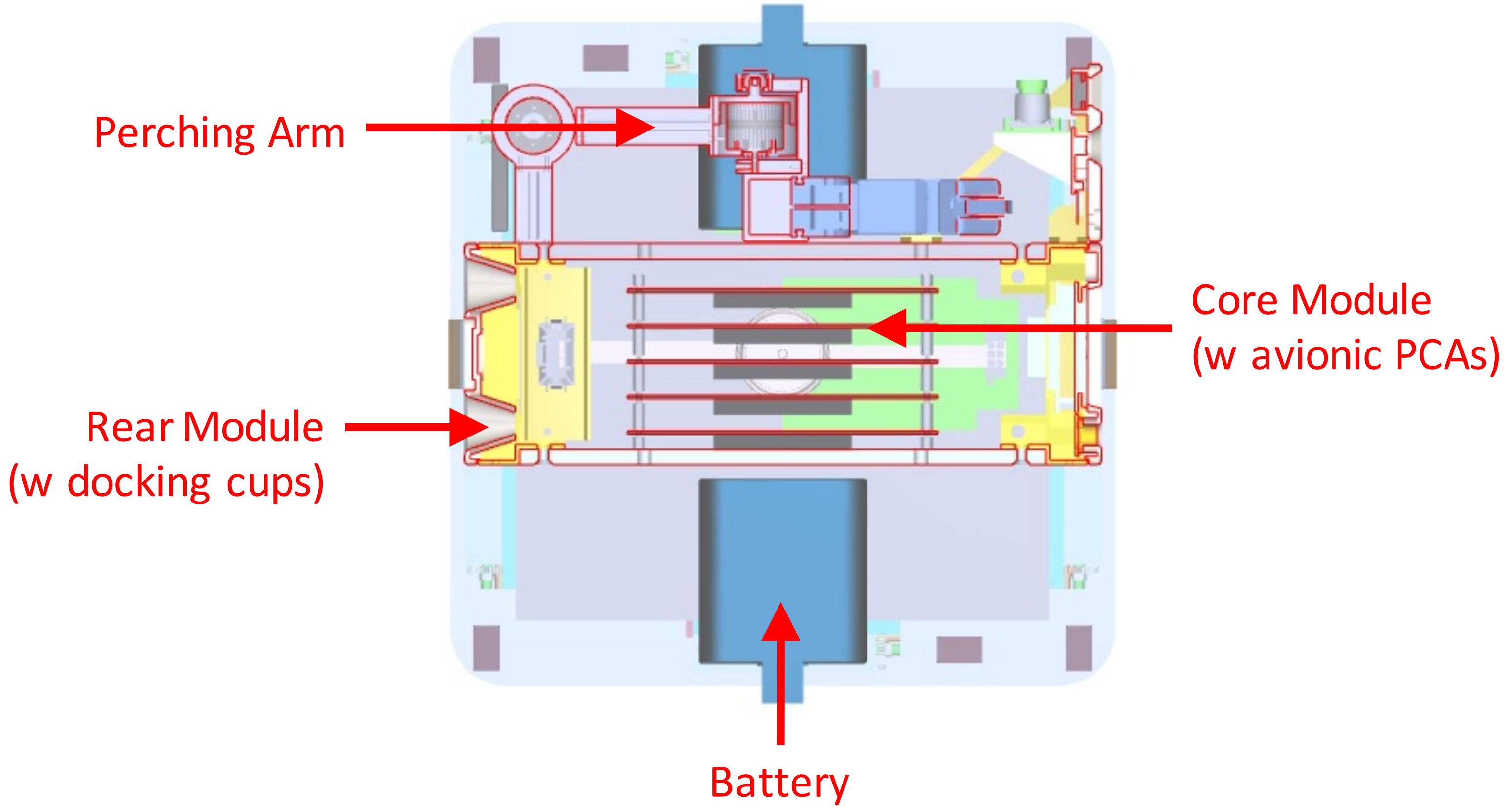


Aft Top

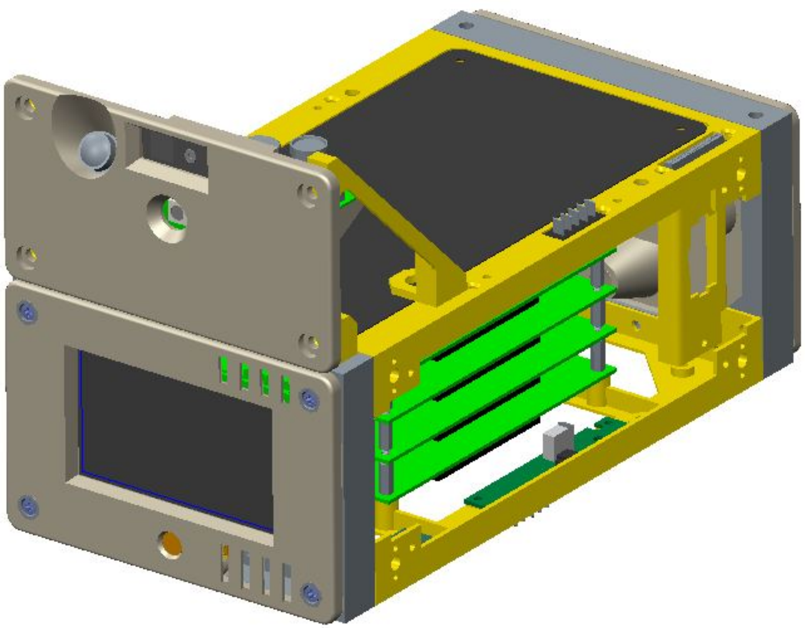
Front Layout

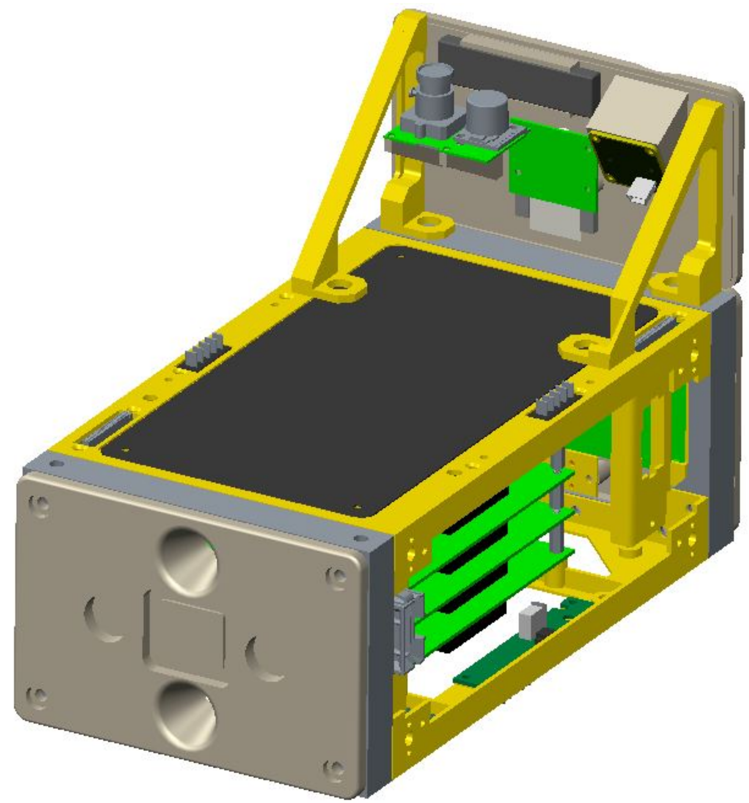


Cross-section Layout

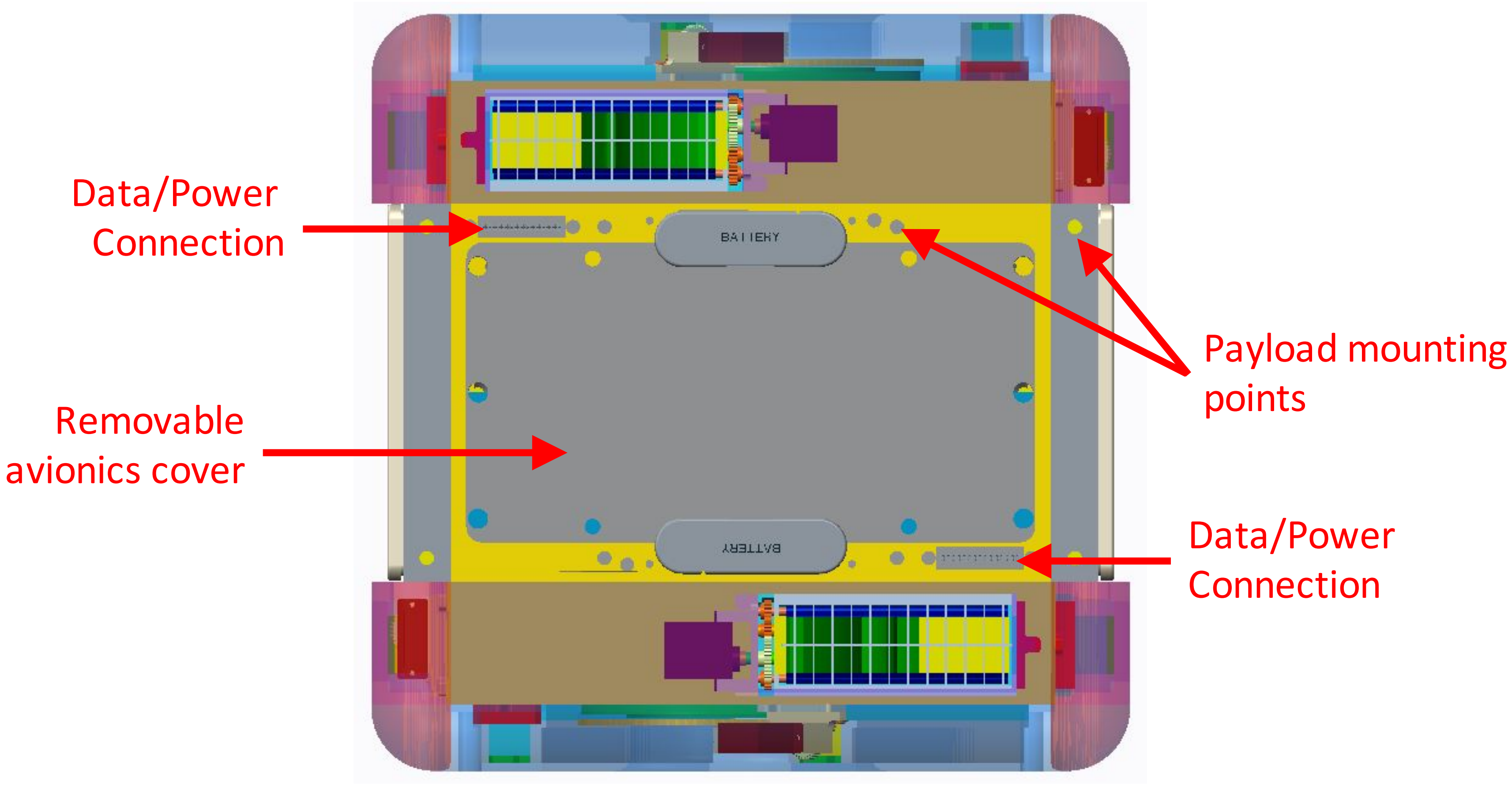


Core Module





Payload Bay



Data/Power Connection
Removable avionics cover
Payload mounting points
Data/Power Connection

Astrobee Propulsion Subsystem

Design Overview

Subsystem Team

- Blair Mclachlan (ARC-AOX, Aero Lead)
- Mike Mcintyre (ARC-RE, GNC Lead)
- Jesse Fusco (ARC-RE)
- Earl Daley (ARC-RE)
- Jeff Blair (ARC-RE)
- Brian Koss (ARC-RE)
- John Love (ARC-RD)
- Hugo Sanchez (ARC-RE)

- Travis Mendoza (ARC-RE, Intern)
- Troy Shilt (ARC-RE, Intern)

Design Drivers

- Thrust
  - 0.3 Newtons on all axes
  - 0.6 Newtons on one axis
- Noise
  - 65dBA maximum
  - <60dBA preferred
- Volume
  - 3inch module thickness
- Power
- Mass

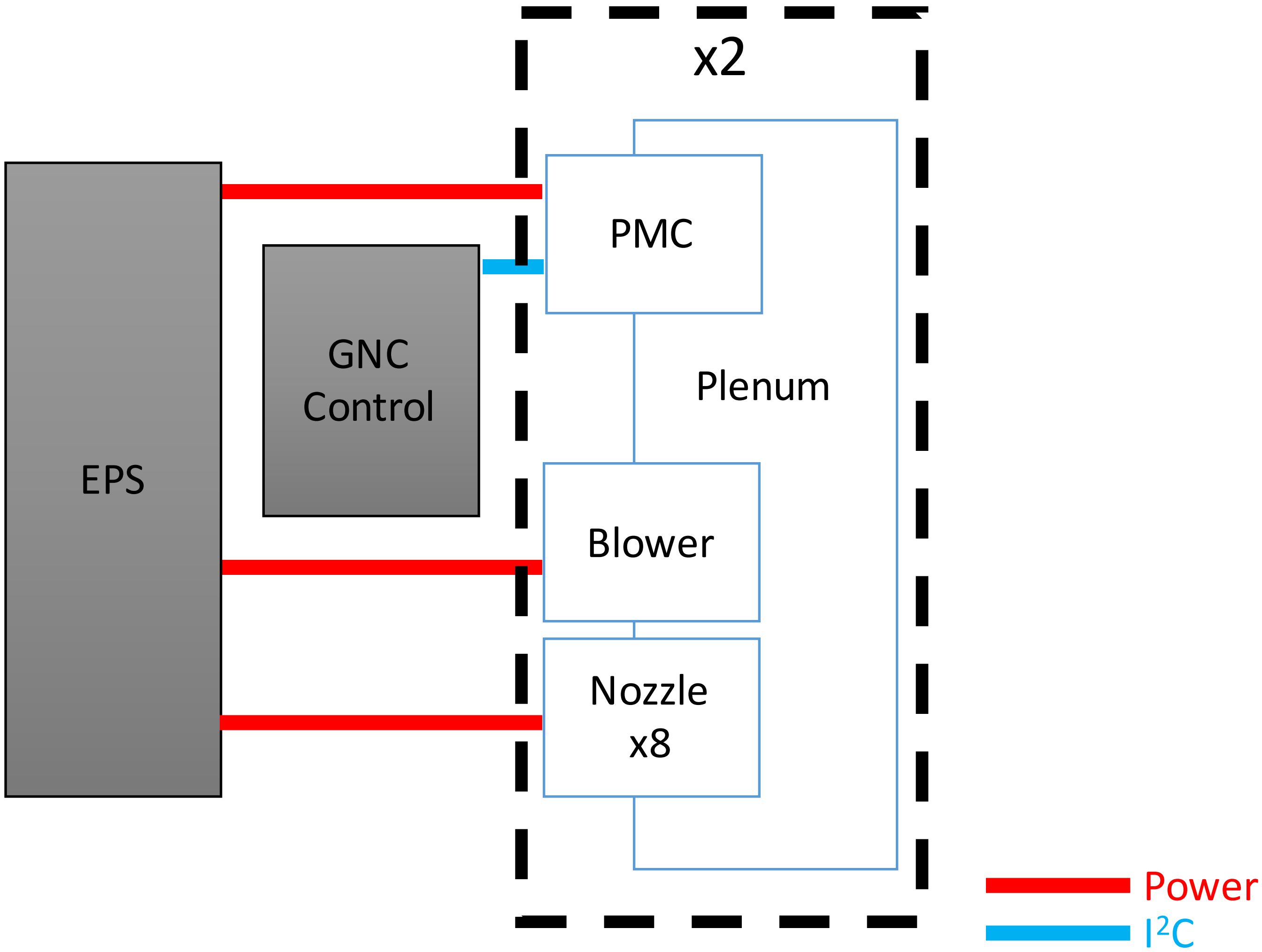
Trade Study

Attributes	Options
Propulsion type	• Axial fan • Compressed air • Blower system
Blower diameter	• 4, 4.4, 4.6, and 5 inch
Blower height	• 2 inch • 1 5/8 inch
Nozzle flapper	• Single flapper • Double flapper
Nozzle open area	• 2 cm^2 • 4 cm^2
Nozzle efficiency	• Guillotine • Flapper
Material	• Aluminum • Ultem 9085 • Windform XT 2.0

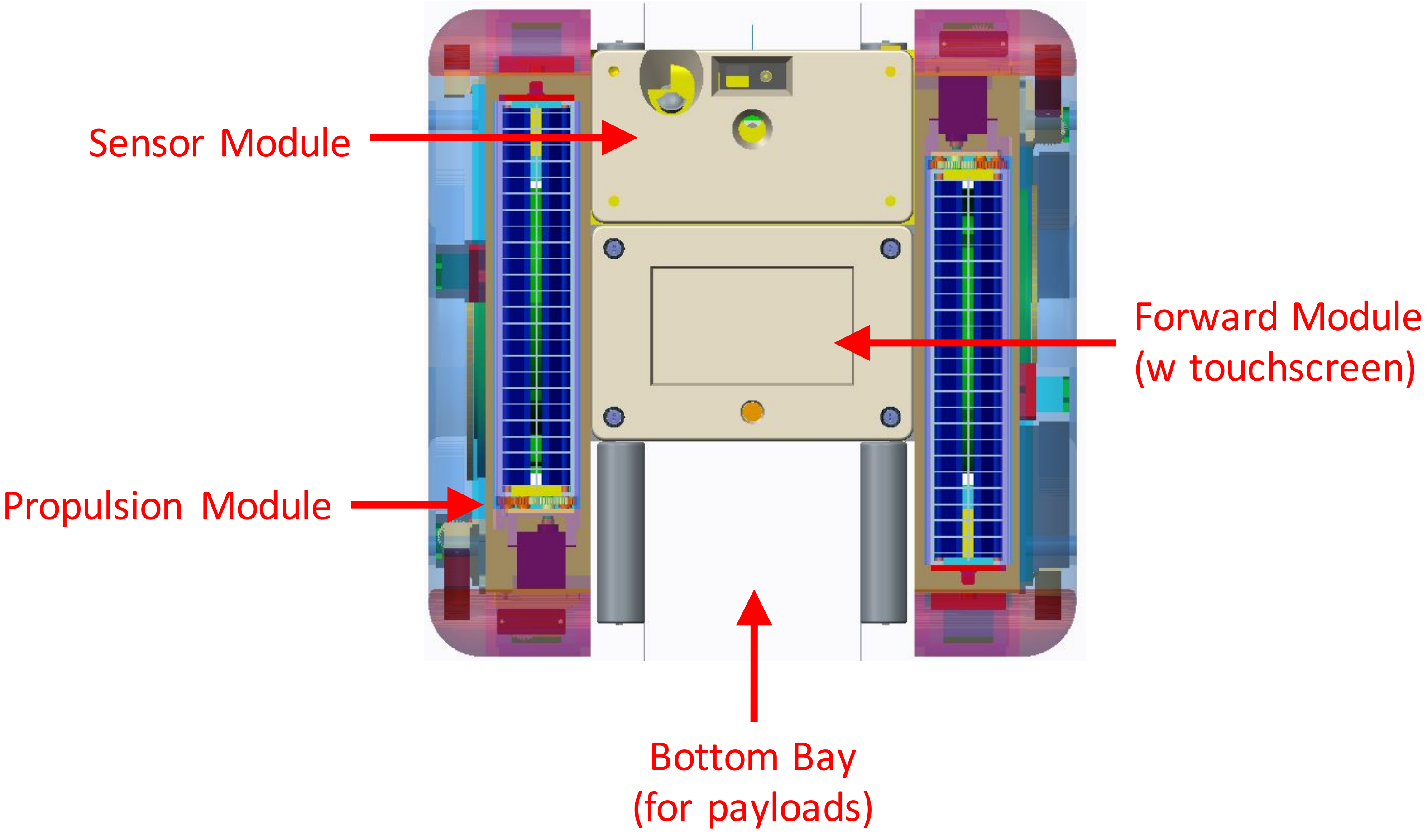
Selected Design

- Two blower propulsion modules
  - Pro: Packaging is more simple than axial fan design
  - Con: Blower noise is expected to be higher than axial fans
- Blower with 5” Diameter and 1 5/8” Height
  - Pro: Larger blower allows RPM and SPL
  - Con: None known - limited by volume constraints
- Dual Flapper Nozzle
  - Pro: Shorter in height and >0.9 efficiency
  - Con: More complex gearing for single servo
- 6 nozzle design
  - Pro: Few nozzles (and servos) and more space for impeller
  - Con: Single nozzle for primary thrust vector is inefficient
- Windform impeller
  - Pros: easy to manufacture and light
  - Cons: more brittle than aluminum

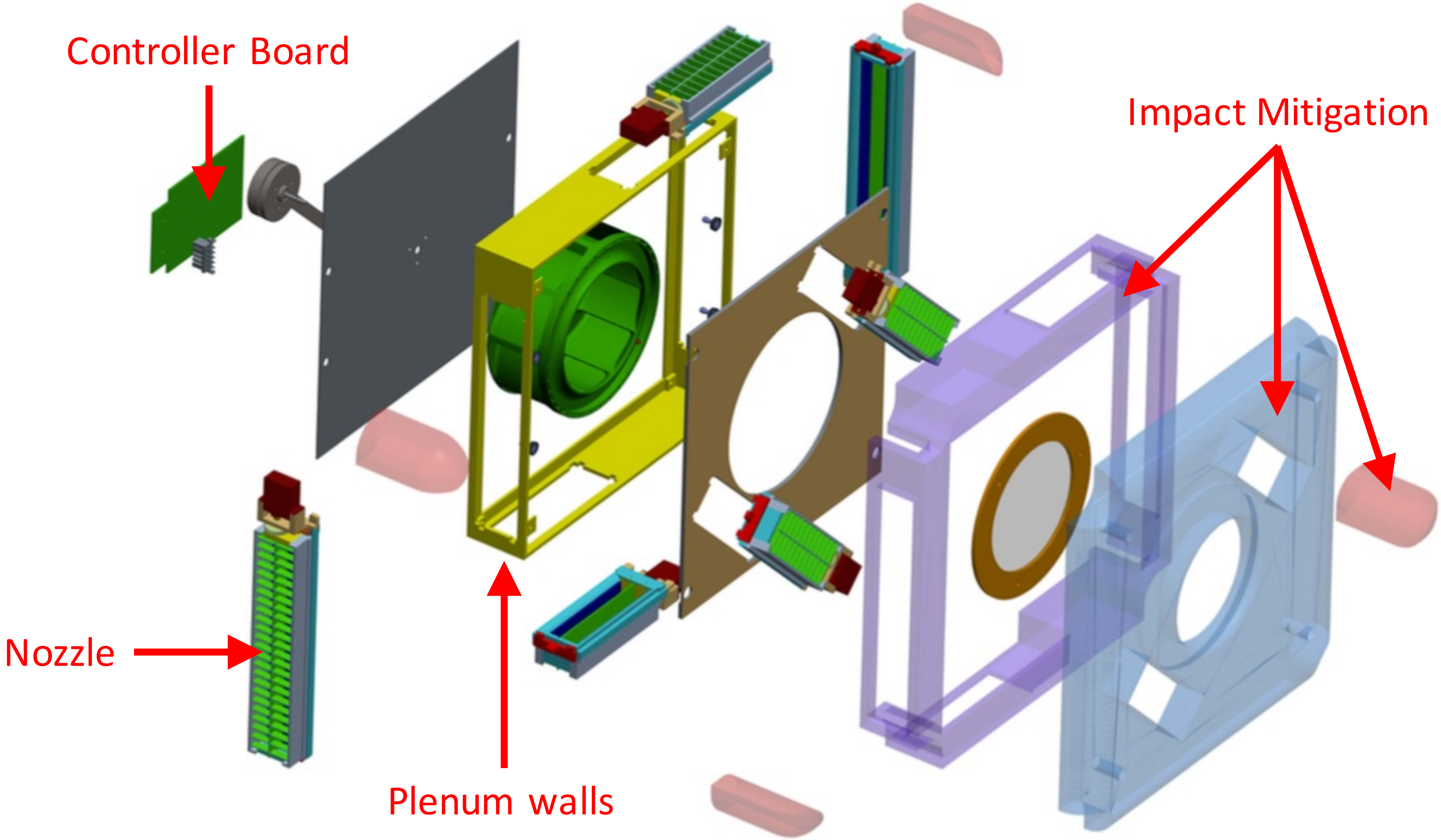
Architecture Diagram



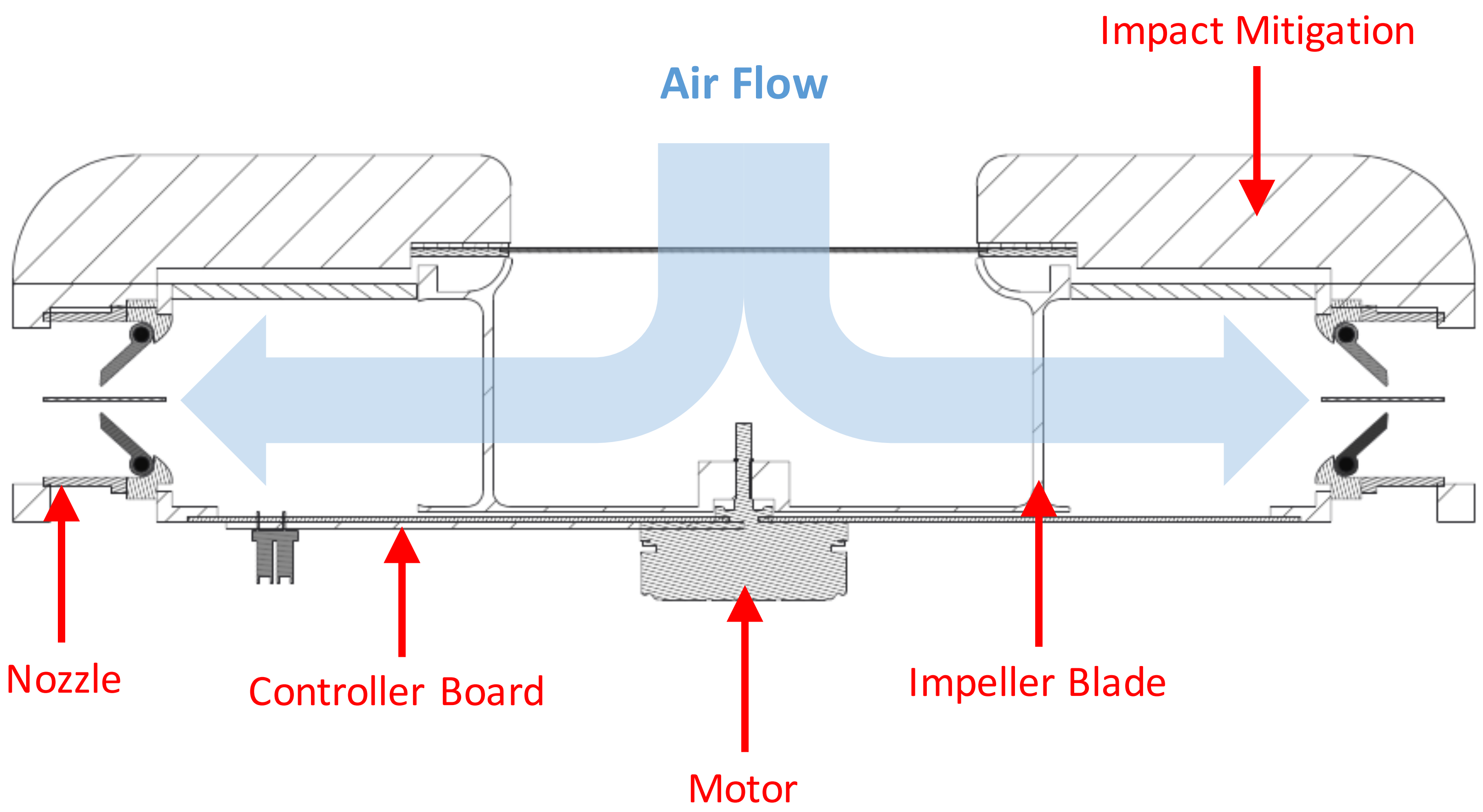
Free Flyer Layout



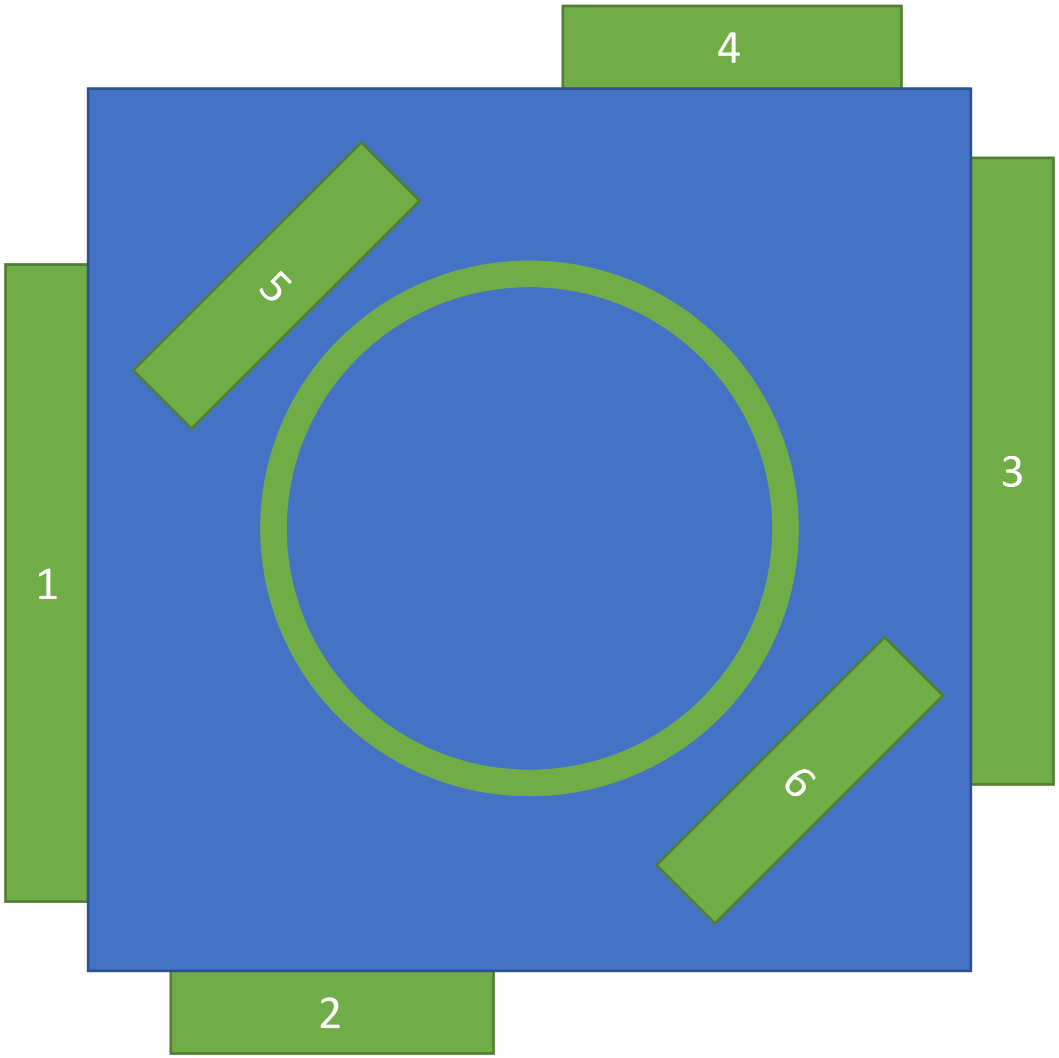
Prop Module Components



Prop Module Cross-section

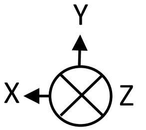


6 Nozzle Layout



2.5 and 5 inch^2 nozzles

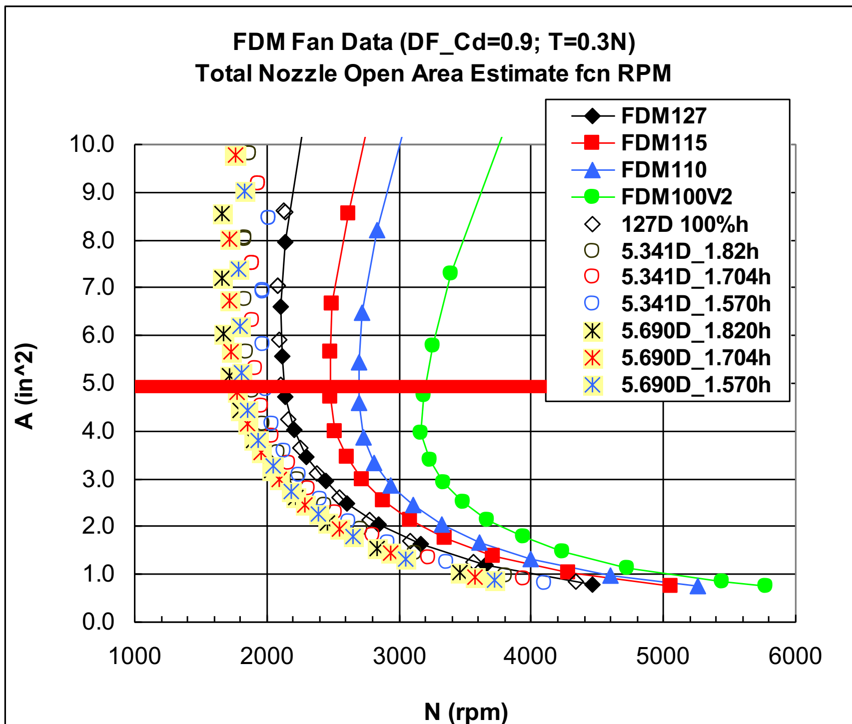
Pure Force or Moment Axis	Nozzles Required
+Fx	3
-Fx	1
+Fy	2
-Fy	4
+Fz	5,6
-Fz	NA
+Mx	2
-Mx	4
+My	1
-My	3
+Mz	1,3
-Mz	2,4

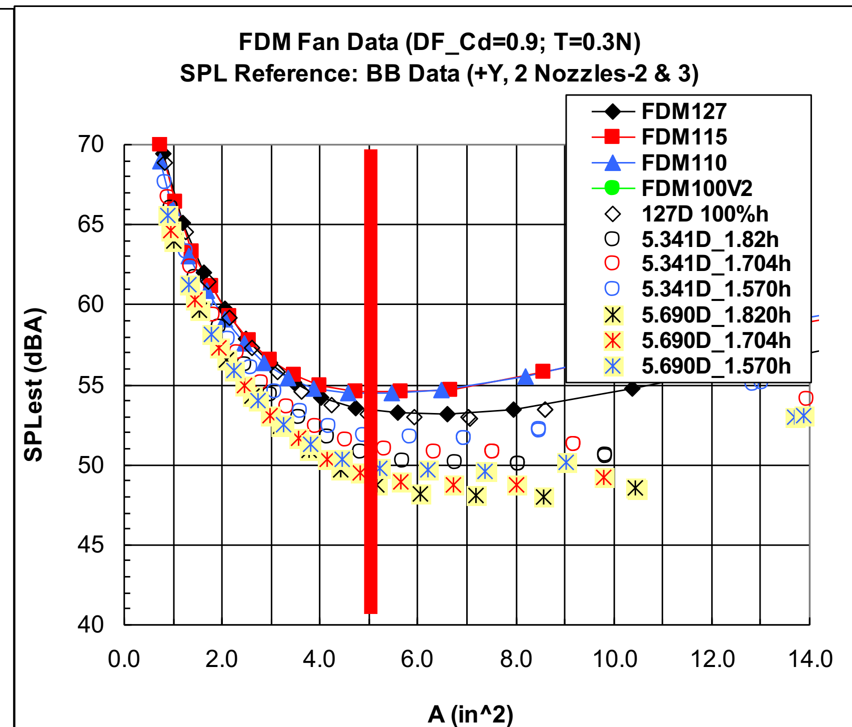


Nozzle Sizing

Total Nozzle Open Area Estimate

Dual Flap (DF) Nozzle (Cd=0.9); Constant Thrust (T=0.3N)





5 inch^2 nozzle minimizes impeller RPM and noise

Astrobee CDH Subsystem

Design Overview

Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
- Jason Lum (ARC-TI)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)
- Vinh To (ARC-TI)

Design Drivers

- Low power consumption
- High computing power
- Multiple processors
- Small form factor
- Low mass
- Support multiple payloads
- Modular

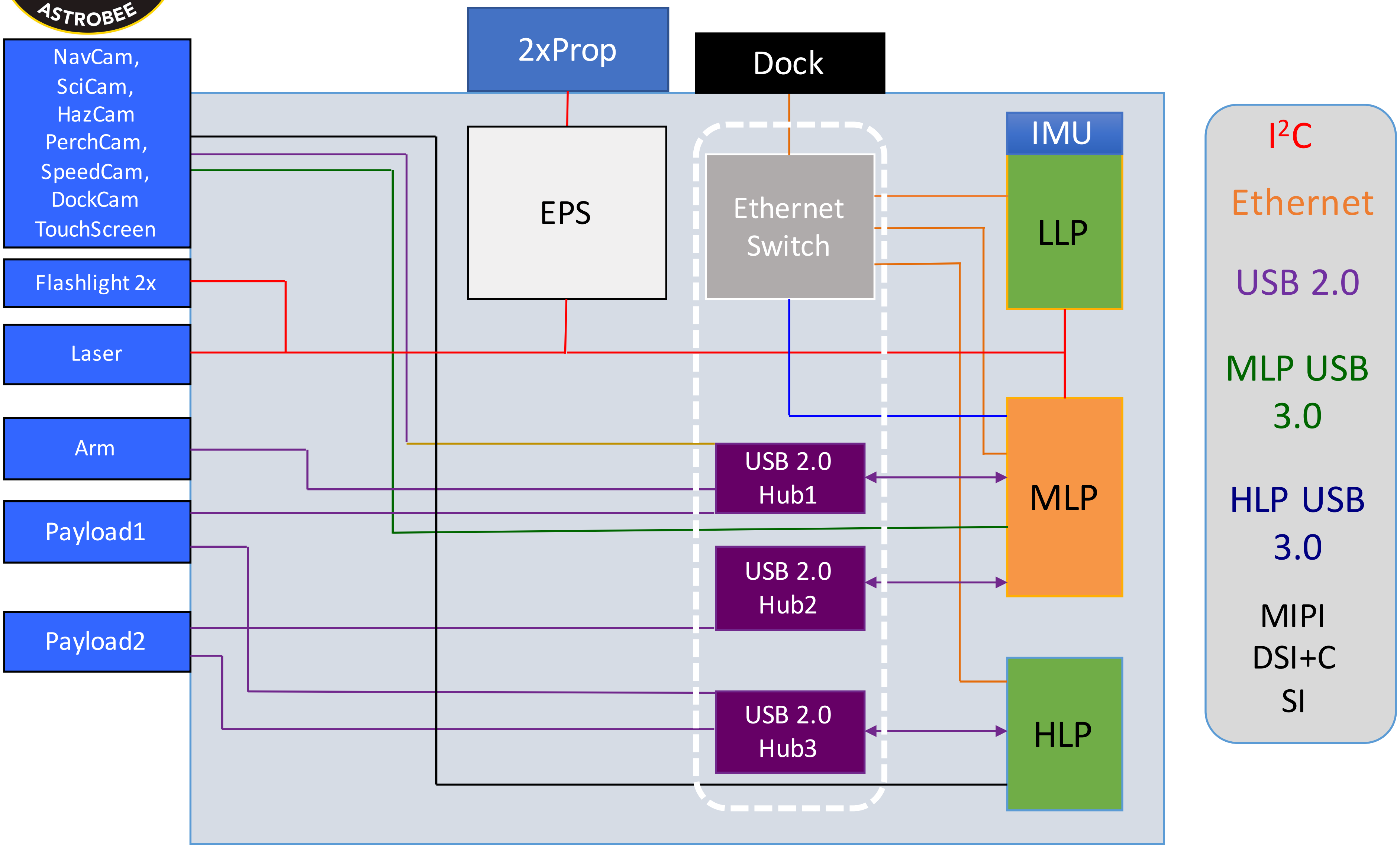
Trade Study

- Arm vs x86
- Exynos vs OMAP vs i.MX6 vs SnapDragon
- Single vs dual vs quad cores
- SOM and SBC HW
- Wide variety of comm support
- Custom carrier boards

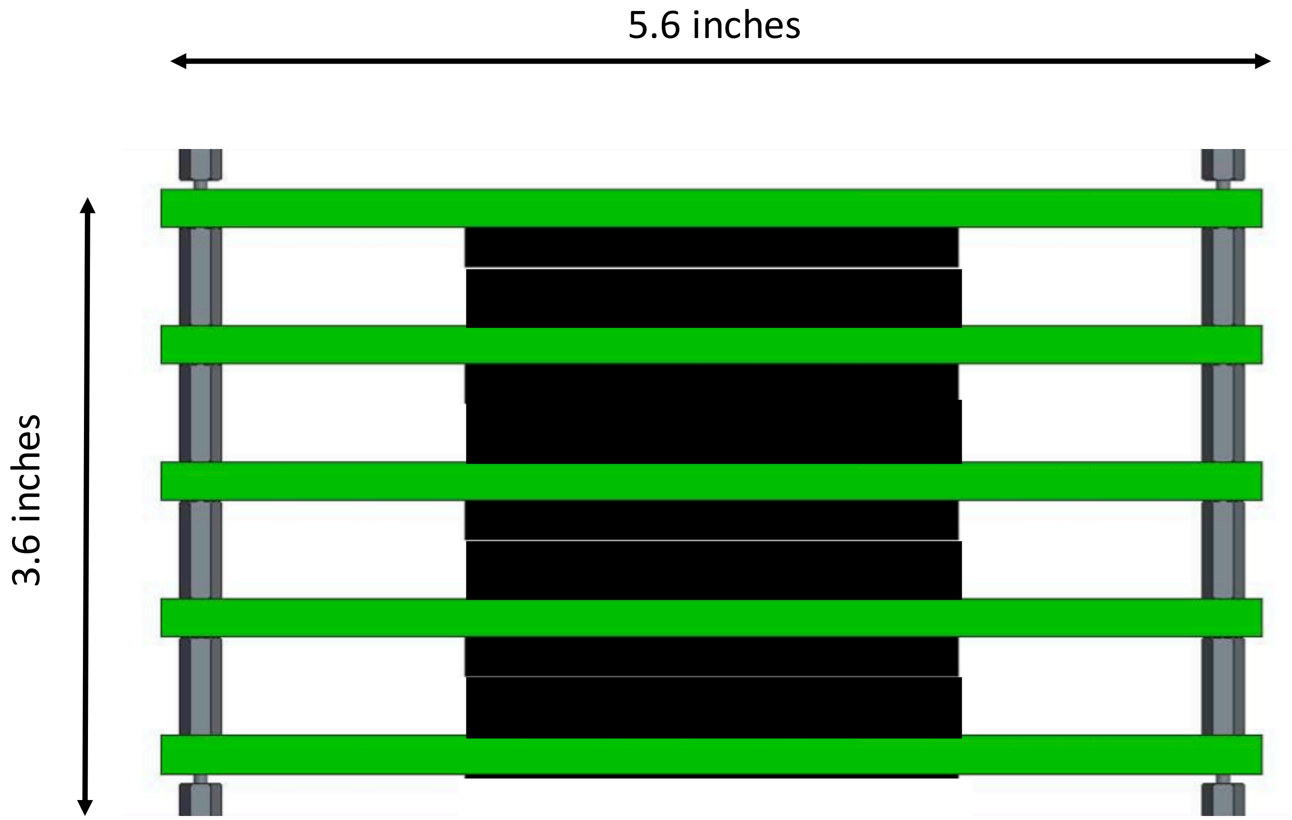
Selected Design

- Low Level Processor (LLP) – ***Wandboard Dual***
  - Dual core i.MX6 (ARM Cortex-A9, ARMv7 32-bit)
  - 1 GB RAM
  - 3 x I^2C bus
  - SPI
  - GPIO
- Middle Level Processor (MLP) & High Level Processor (HLP) – ***IFC6501***
  - Quad core Snapdragon 805 (ARM Cortex-A15 class, ARMv7 32-bit)
  - 2GB RAM
  - 2 x I^2C bus
  - 1 x USB 3.0
  - 2 x USB 2.0
  - MIPI DSI + CSI
  - GPIO

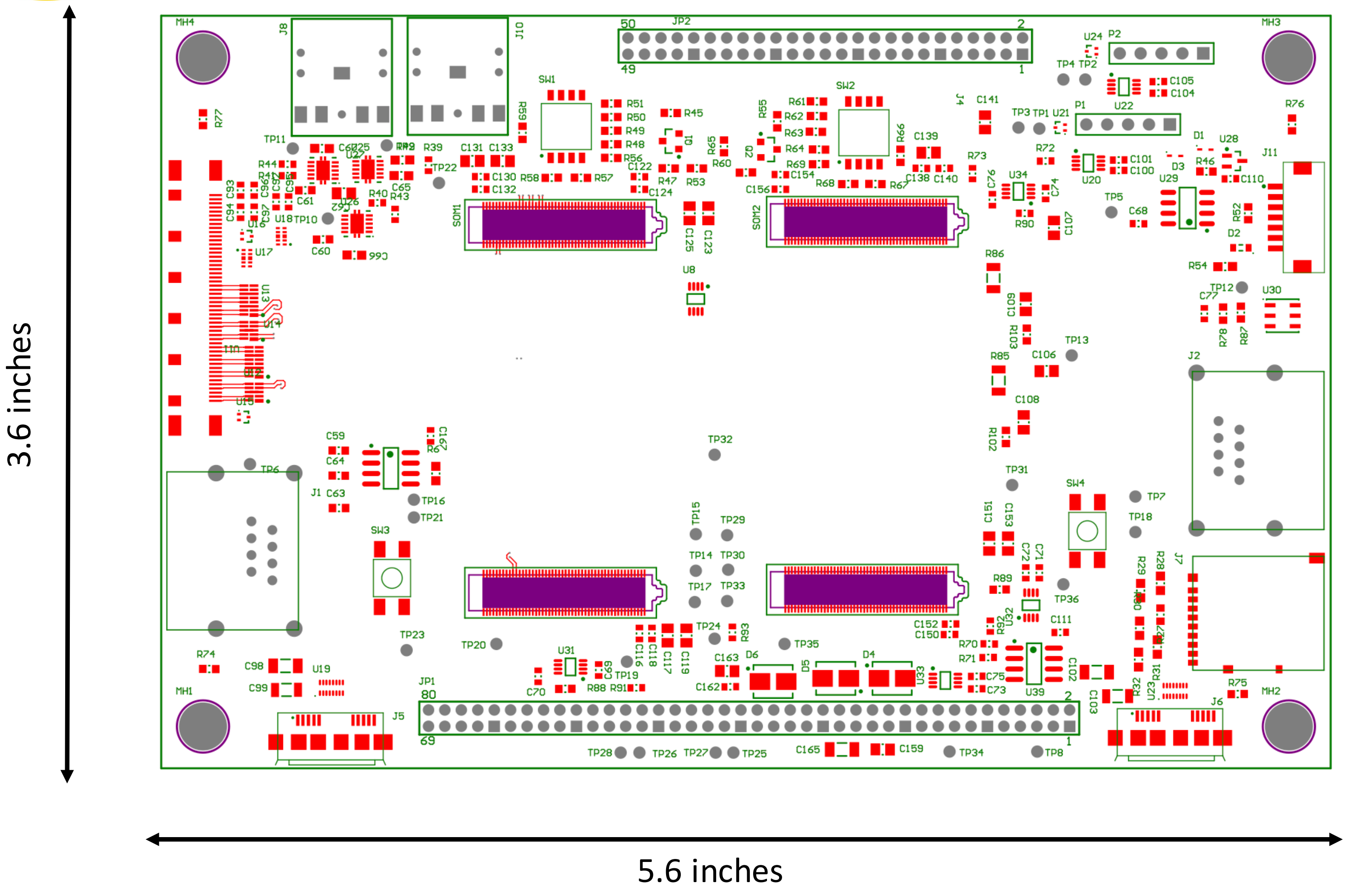
Architecture Diagram



Avionics Stack – Side View



MLP+HLP Carrier Board



Component List

- Backplane
- LLP carrier board
- MLP + HLP carrier board
- Touchscreen
- Peripheral Bay Connector
- LED signal indicator
- Laser pointer
- LED flashlight

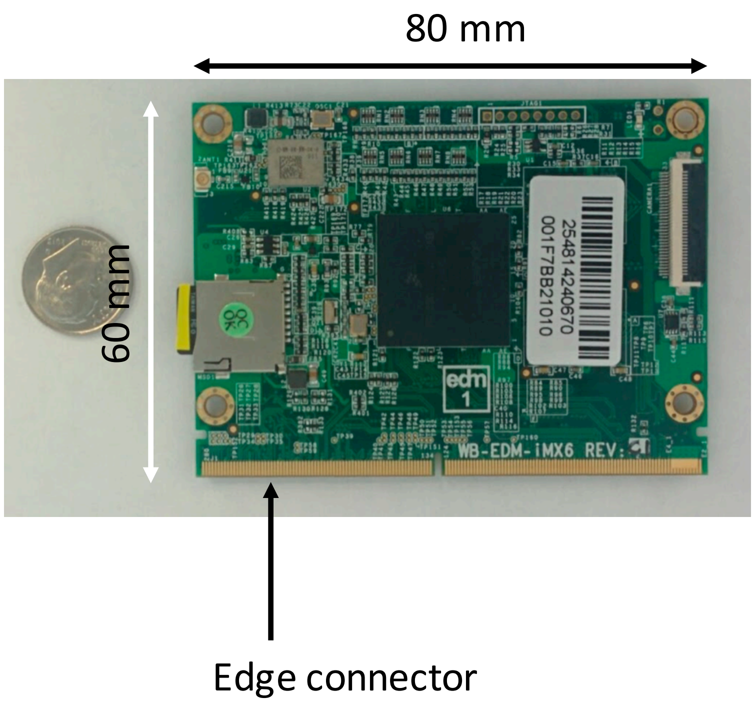
Backplane Board

- Connect EPS, LLP, MLP, and HLP
- 5-port 100 Mbit network switch
- 1 x 4-port USB 2.0 hub and 1 x 7-port USB 2.0 hub for MLP
- 1 x 4-port USB 2.0 hub for HLP

LLP Trade Study

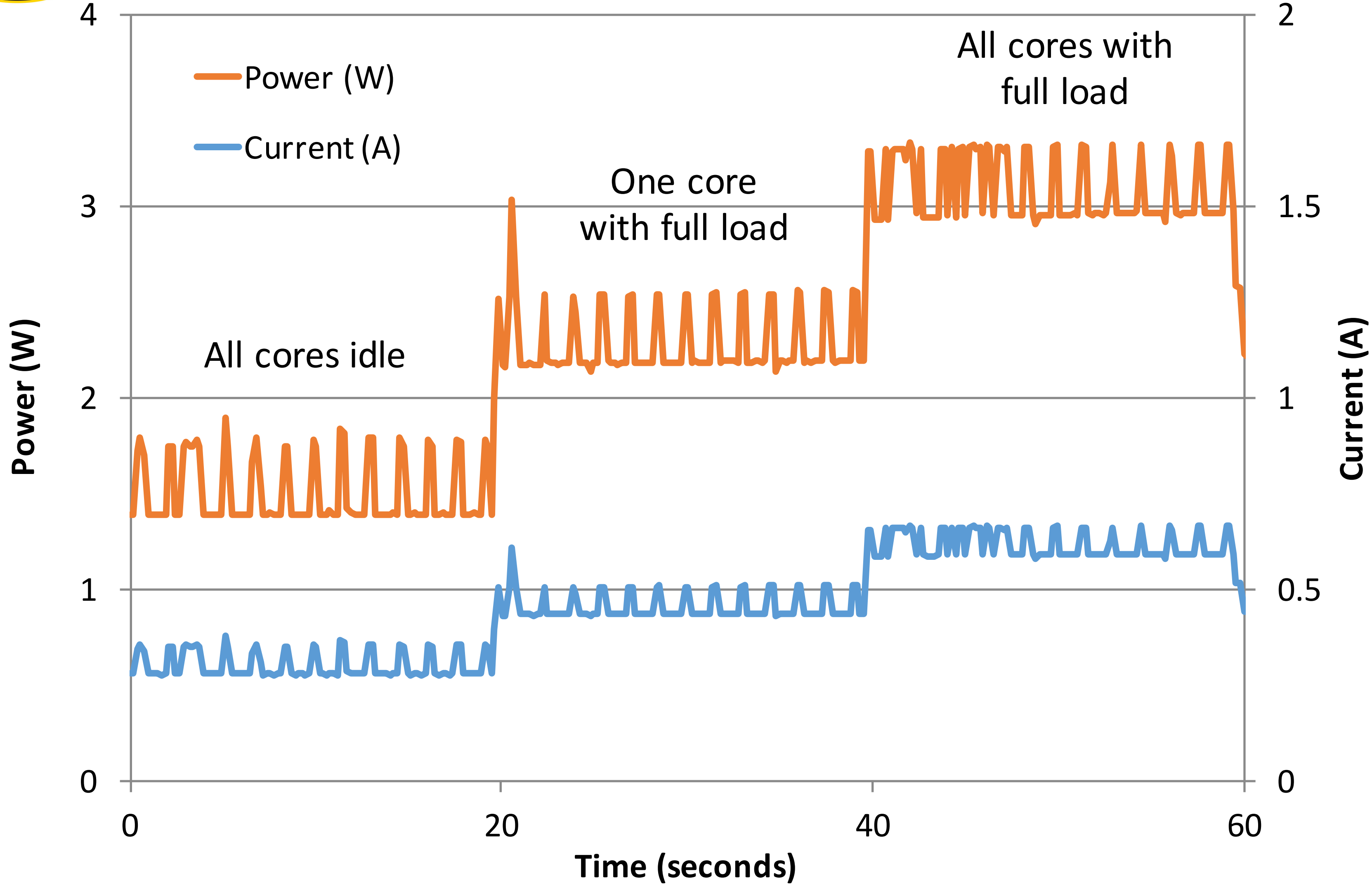
	Overall	Power Consumption	Computational Power	Comms	Development Cost (SW)	Development Cost (HW)	Modular
Priority		1	2	1	2	2	1
CM-T54	**3.95**	3	5	5	4	4	5
CM-FX6	**3.55**	3	4	5	2	4	5
BeagleBone Black	**2.69**	5	1	5	5	5	1
COMe-mBTi10	**3.85**	4	5	3	4	4	5
SMARC-xSBTi	**3.51**	2	5	5	4	4	5
Nitrogen6x-SOM Q	**3.89**	3	4	5	4	4	5
Nitrogen6x-SOM D	**3.75**	3	3	5	4	4	5
Nitrogen6x-SOM S	**4.06**	4	3	5	4	4	5
Wandboard Dual	**4.42**	4	4	5	5	5	5

LLP – *Wandboard Dual*



- i.MX6 Dual Cortex-A9
- 1 GB RAM
- Edge connector with carrier board
- 80mm x 60mm
- Ubuntu support

Power Consumption

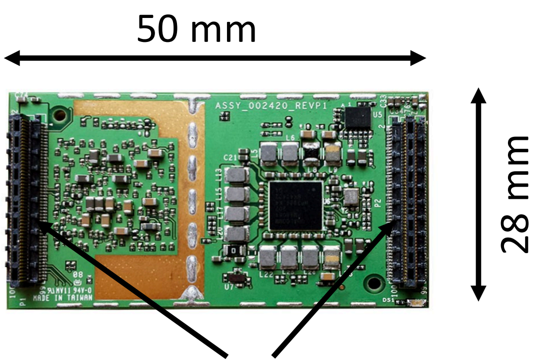


MLP & HLP Trade Study

	Overall	Power Consumption	Computational Power	Comms	Software Development Cost	Hardware Development Cost	Modularity
Priority		2	1	1	2	3	1
Odroid-XU3	**2.74**	2	5	4	5	4	1
CM-FX6	**2.90**	3	2	3	4	2	4
VAR-SOM-OM54	**3.12**	3	3	5	1	3	5
phyCORE-OMAP5430	**3.12**	3	3	5	1	3	5
OMAP5430 Pico ITX	**2.61**	3	3	5	3	4	1
DragonBoard 8074	**3.04**	1	5	5	1	4	5
DragonBoard 8084	**3.04**	1	5	5	1	4	5
IFC6410	**2.31**	2	4	2	5	4	1
IFC6540	**2.59**	1	5	5	4	4	1
IFC6400	**3.03**	2	4	2	5	3	4
IFC6501	**3.14**	1	5	3	4	2	5
COMe-mBT10	**3.11**	1	5	3	3	4	4

MLP & HLP – *IFC6501*

Top

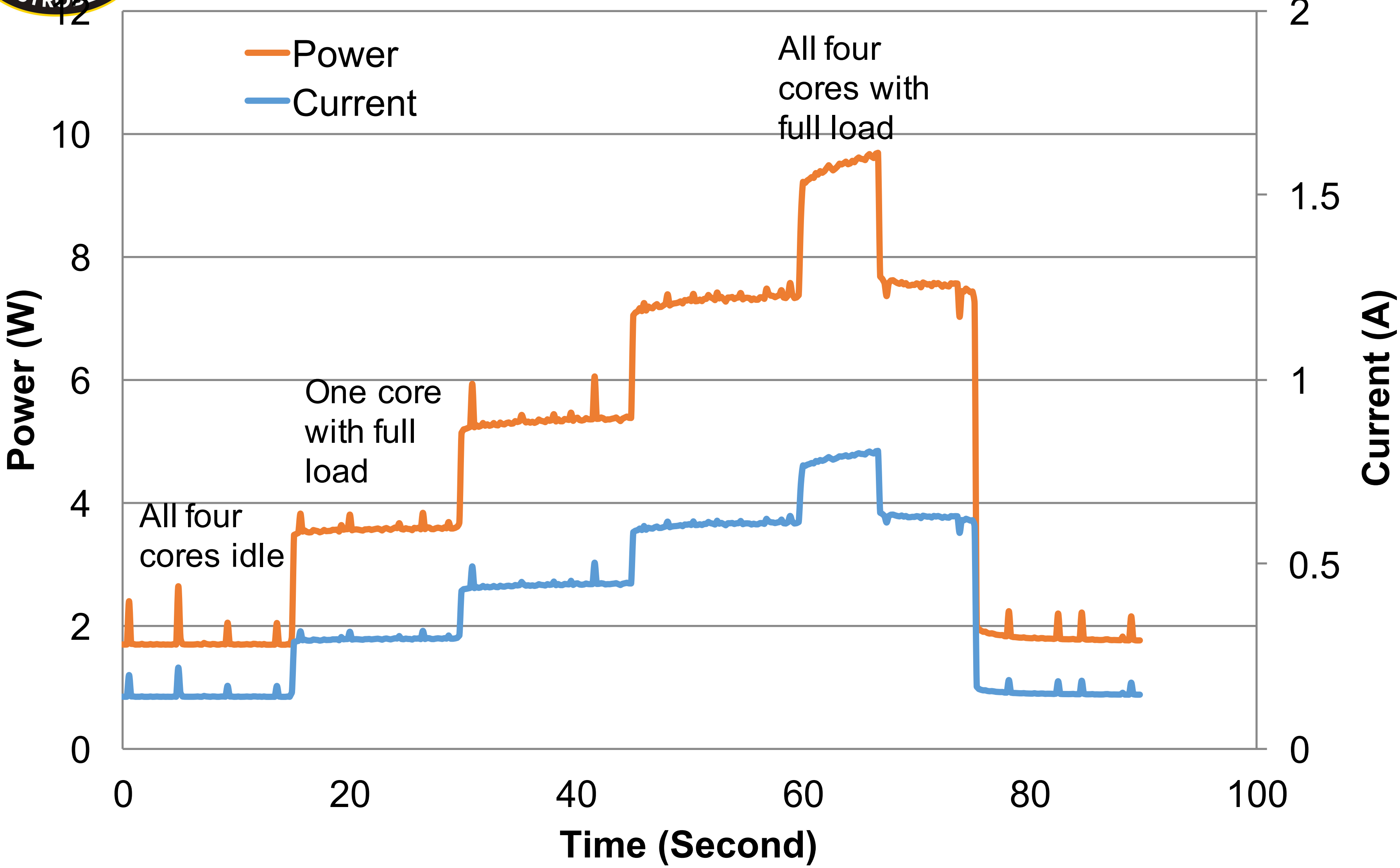


Bottom

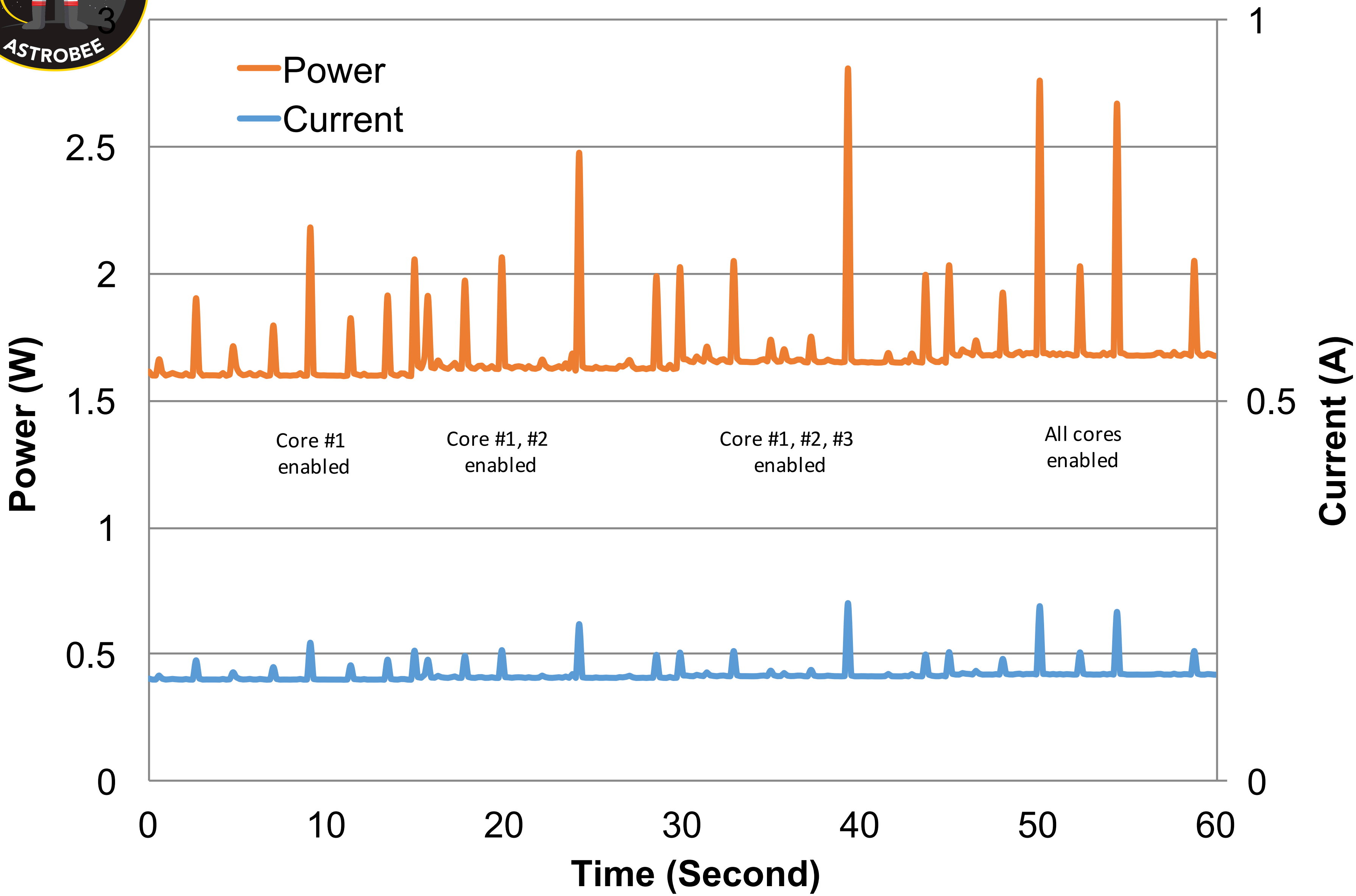
- Inforce Computing's System-on-Module (SoM)
- Qualcomm SnapDragon 805
  - Cortex-A15 class (ARMv7 32-bit)
  - 2 GB RAM
- 28mm x 50mm, 8 g
- Ubuntu and Android support

Active Power Consumption

ISS ROBOTIC FREE FLYER
ASTROBEE



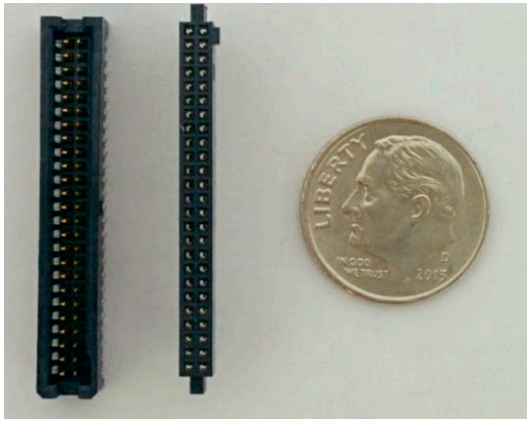
Idle Power Consumption



Touch Screen

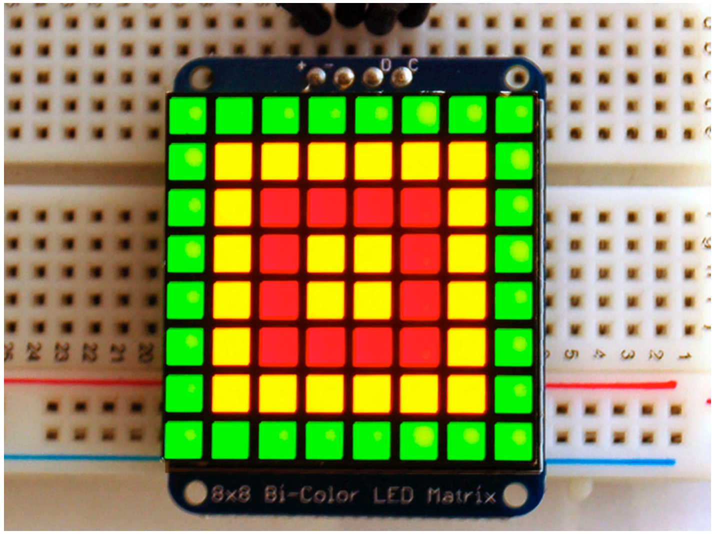
- 4” 800x480
- MIPI DSI
- Capacitive touch screen
- 60mm x 40mm x 1.8mm

Peripheral Bay Connector



- Samtec 0.05” TFM/SFM connector
- 50 pin connector
- V_{batt}, GND
- USB 2.0

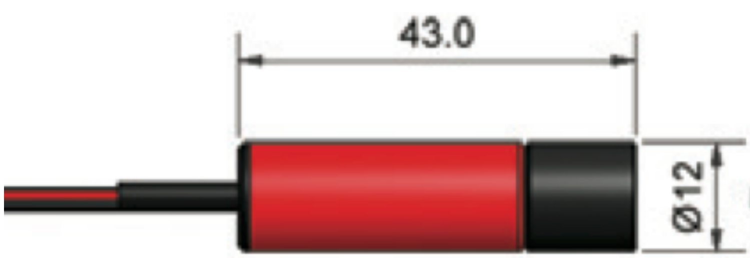
LED Signal Indicator



- 8x8 bi-color LED matrix
- I2C control
- 33mm x 41mm x 4mm
- Maximum power consumption: 120 mA @ 3.3V

Laser Pointer

- Direct Emission Green Laser
- 520 nm
- 0.9 mw



LED Flashlight

- 3.3 V @ 1 A
- 216 lm
- 45^{o} viewing angle
- 127^{o}C at full power

Astrobee EPS Subsystem

Design Overview

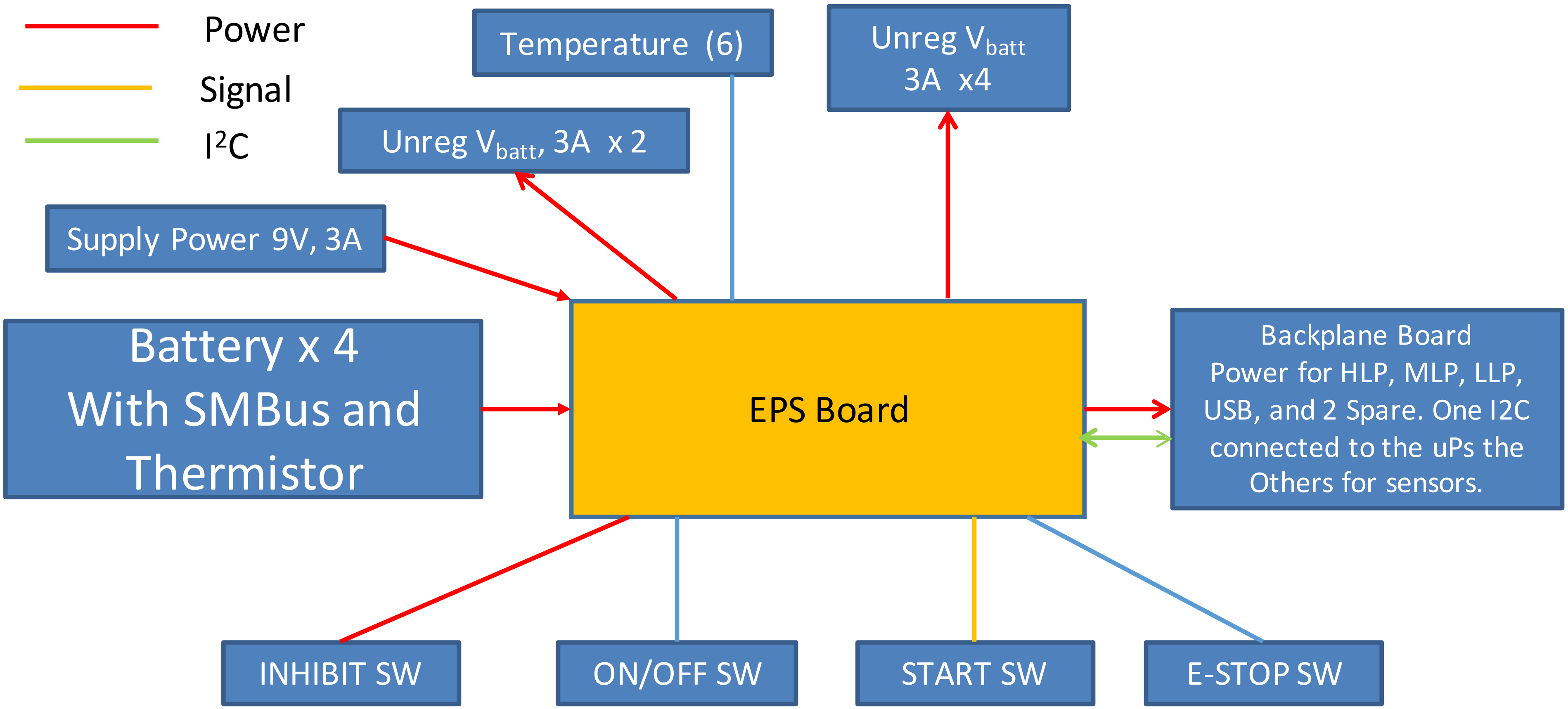
Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
- Jason Lum (ARC-TI)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)
- Vinh To (ARC-TI)

Design Drivers

- Provide power to Astrobee
- Recharge through dock adapter
- Support up to 4 batteries
- Monitor system voltage, current, and temperature

Architecture Diagram



Functions

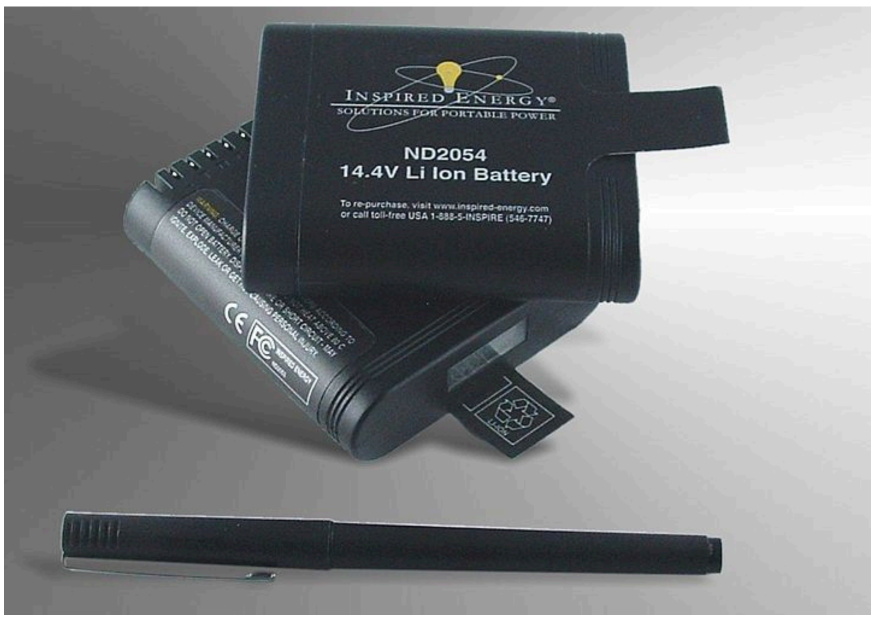
- Provide power to:
  - LLP, MLP, & HLP
  - Prop modules
  - Payloads
- Monitor:
  - Voltage
  - Current
  - Temperature
- Protection
  - E-stop
  - Thermal
  - Power

Power

- Input Power:
  - 9 V to 28 V input (Default at 24V) @ 3A.
- Output Power
  - 2 power lines with Unreg V_{batt} @ 3A MAX.
  - 4 power lines with Unreg V_{batt} @ 3A MAX.
- Storage Power: Can connect up to 4 batteries (Power = 196 Wh)
- EPS Board Power Consumption: <0.4W idle

Battery

- Battery pack should be < 80 Wh
- Inspired Energy Battery 14.4V option
- Older version of battery on Station



Cell Array	4S1P
Voltage	V_{max}=16.8V, V_{nom}=14.4V, V_{cutoff}=9.6V
Max Discharge Current	4A
Max Continuous Power	40W
Weight	234 g
Comm	SMBus
Dimension	23mm x 87mm x 79mm

Monitor

- Battery Voltage
- Input V & I
- System V & I
- Temperature
  - 2 on board & 6 external
  - Battery
- Battery State (SMBus)

Protection

- Low Battery Voltage Protection: Turn system OFF when Batteries get down to 9.6 V and Will not turn on until Battery voltage back up to 10 V
- Hardware Current limit, EPS 3.3V and EPS 5V
- Software Current limit: All System and Sub-systems current can set to the safe current level through software
- On Board E-STOP
- Thermal protection for the Batteries, Motors, and Boards set in software to turn OFF

Others Function

- One wire EEPROM: Used for board ID. Might add in Board burn-in time tracking on the next rev. if space available
- 6 LEDS arrays for error or debug purpose.
- 45 LEDS and 54 Test points: Use for Power and communication indicators to support hardware test and soft debug.

Astrobee External Sensors

Design Overview

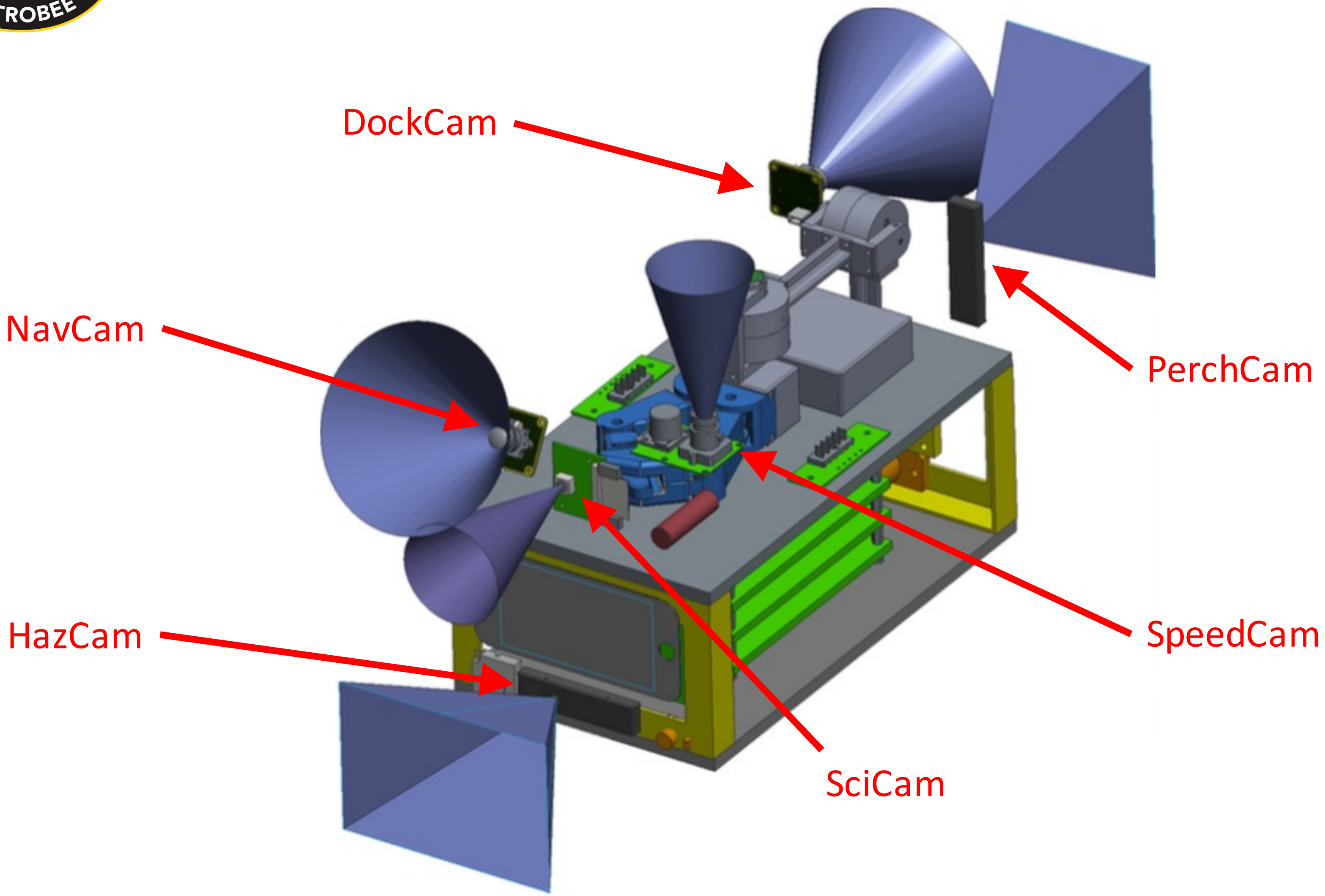
Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
- Jason Lum (ARC-TI)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)
- Vinh To (ARC-TI)

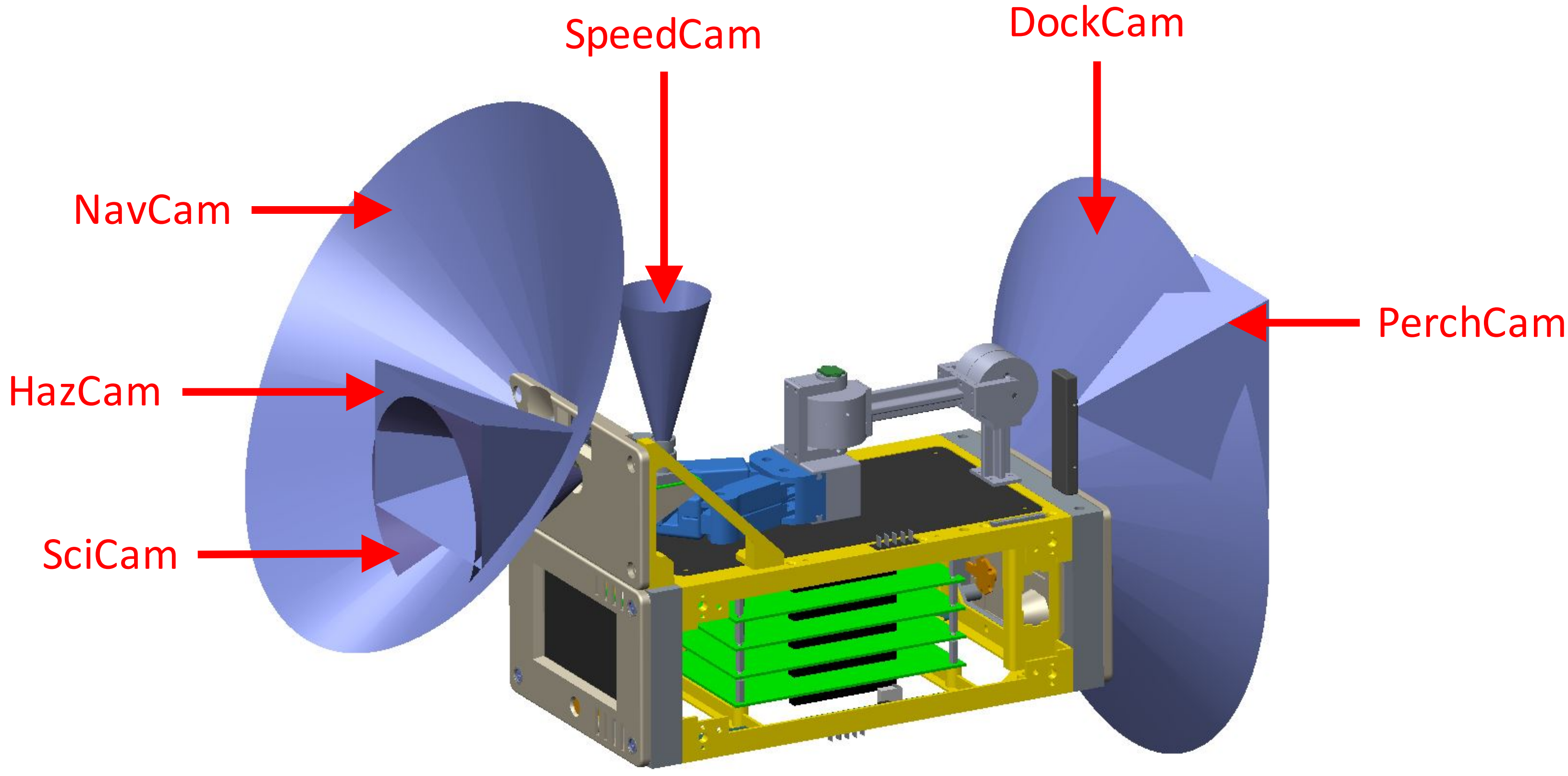
Component List

Sensor	Purpose	Direction
NavCam	Localization – Optical flow, Sparse Mapping	Forward
DockCam	Localization – AR tag extraction	Aft
SciCam	HD video streaming and recording	Forward
SpeedCam	Localization – Optical flow	Up
HazCam	Obstacle avoidance	Forward
PerchCam	Handrail detection	Aft

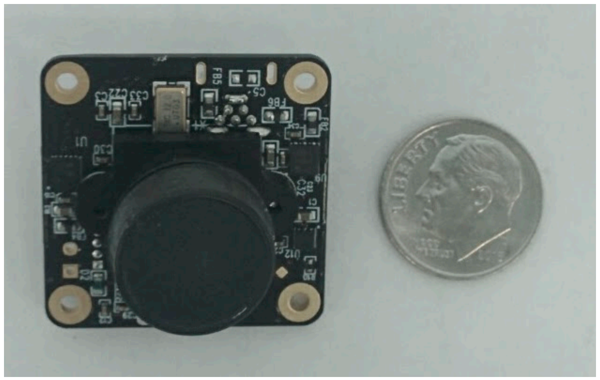
Sensor Layout



Sensor Layout



NavCam & DockCam

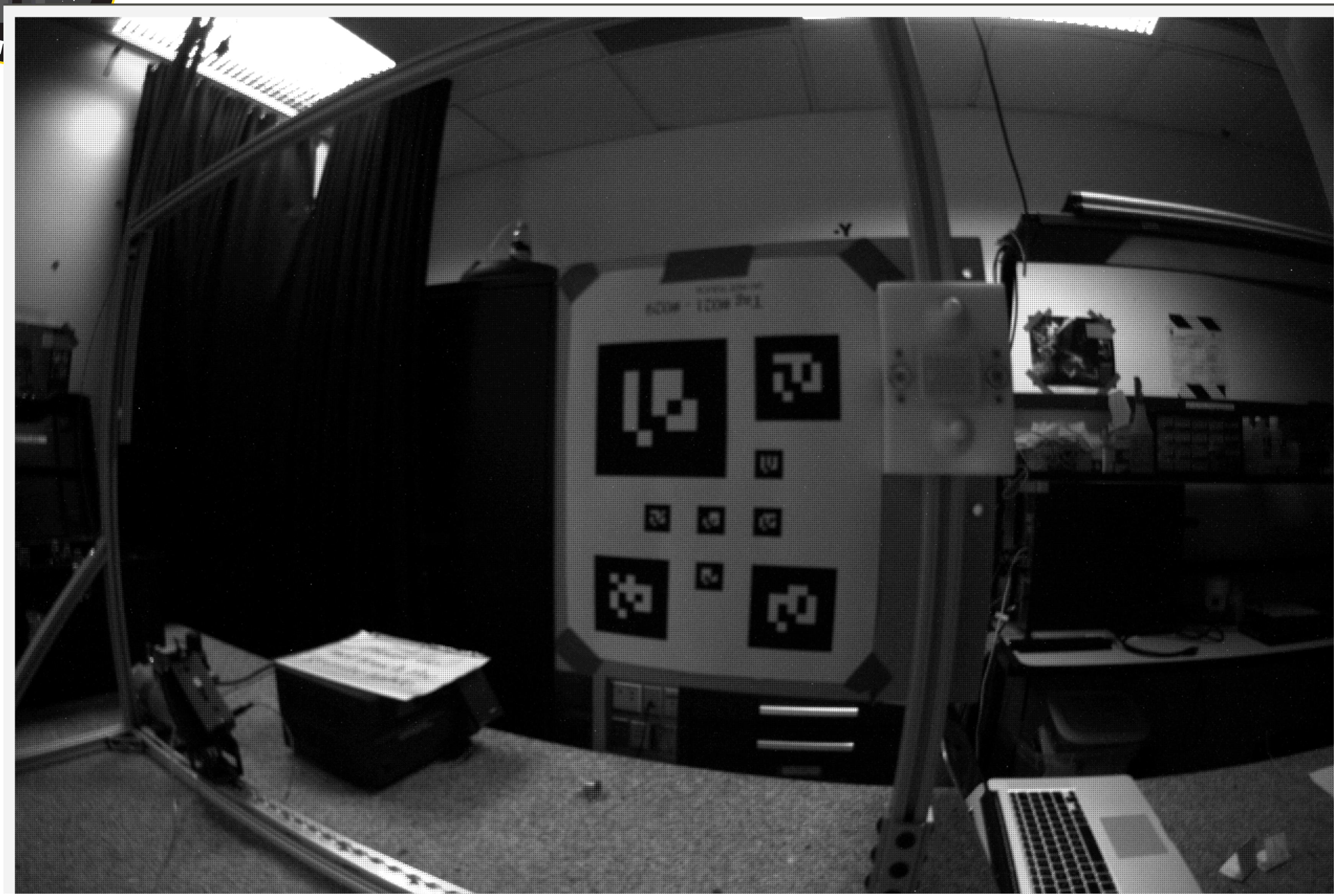


DFM 42BUC03-ML

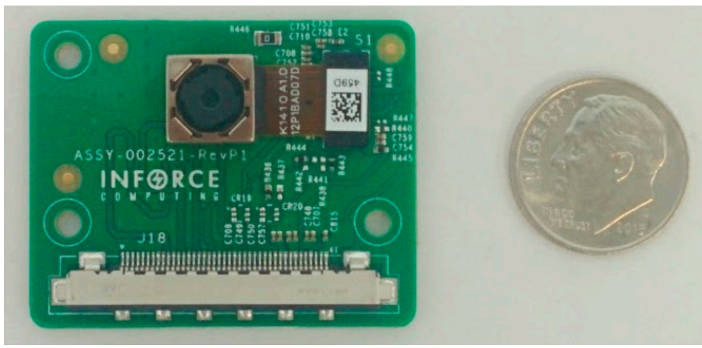
Fisheye lens

- The Imaging Source DFM 42BUC03-ML, 1/3”
- USB 2.0
- 1280x960 pixels @ 25 FPS
- Wide angle lens: FOV D 130
- 30 mm x 30 mm x 15 mm, 7 g
- 1.25 watts

NavCam & DockCam

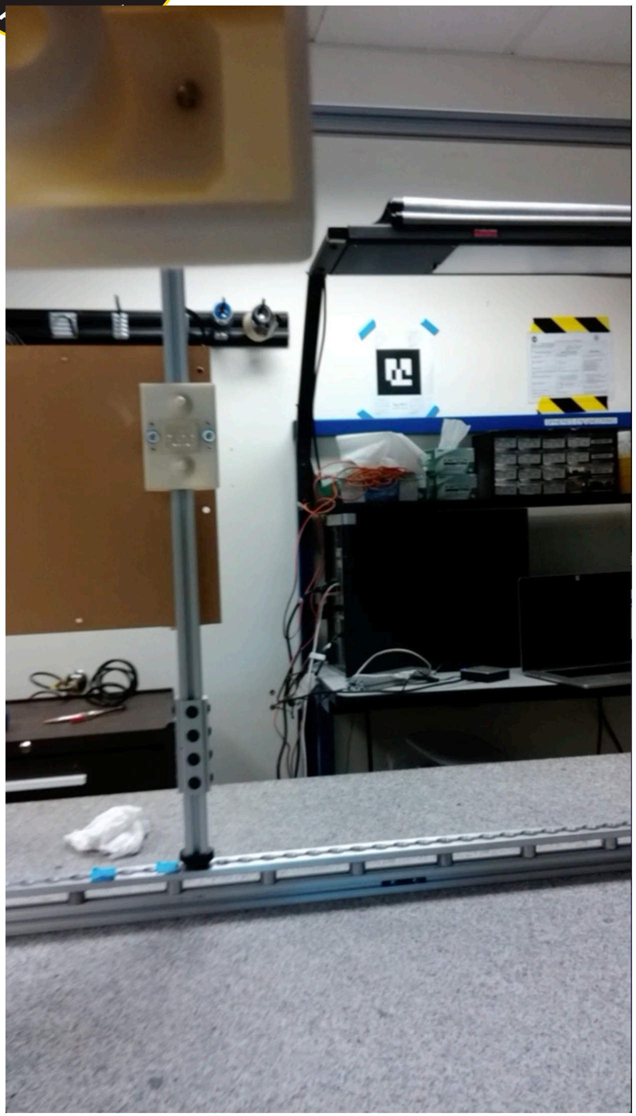


SciCam



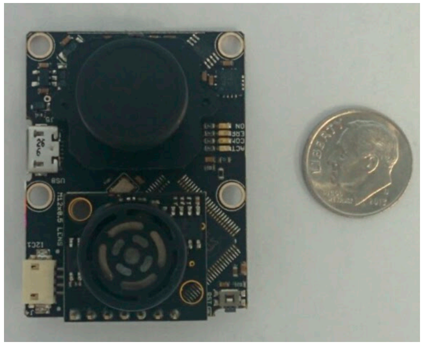
- Sony IMX135
- 13 Mega Pixel
- MIPI-CSI
- Auto focus support
- FOV: 54.8^0 H x 42.5^0 V
- 38.1 x 30.5 x 1.5 mm, 5 g

SciCam



- Resolutions & Frame Rates
  - Full resolution @ 24 FPS
  - Half resolution @ 48 FPS
  - 1080p @ 30 FPS
  - 1080p @ 60 FPS
- CPU & Disk Usage for Recording
  - 1080p @ 30 FPS → 40 % of a core, 150 MB/min
  - 720p @ 30 FPS → 35 % of a core, 100 MB/min
  - 480p @ 30 FPS → 30 % of a core, 17 MB/min

SpeedCam



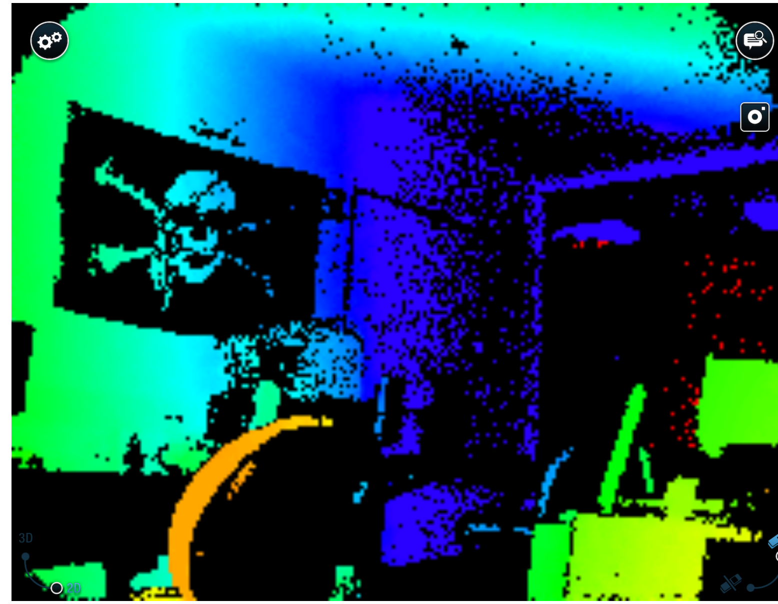
- PX4Flow
- Optical flow processing on 4x4 binned image at 400 Hz
- On board gyro and sonar
- USB, I2C support
- 0.6 W

HazCam & PerchCam

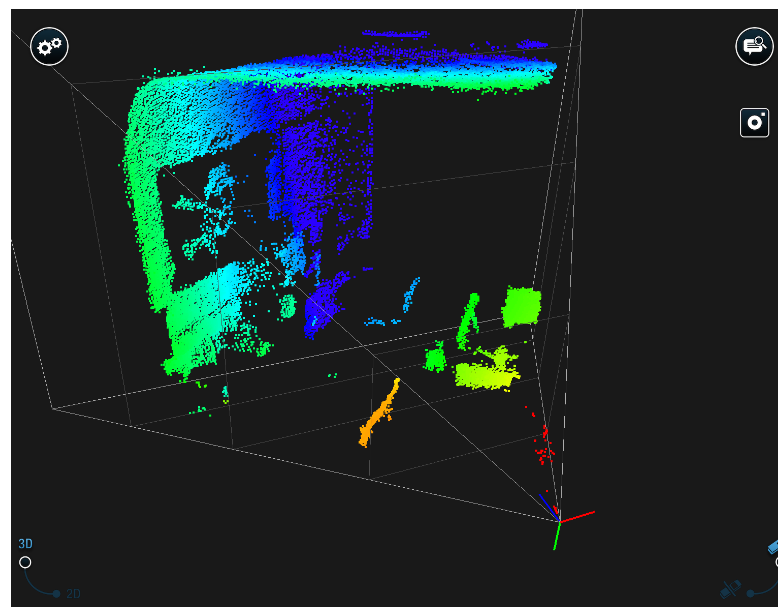
- CamBoard pico flexx
- 0.1 – 4 m range
- USB 2.0, 300 mW average
- 68mm x 17mm x 7.25mm
- 62^{o} x 45^{o}, 224 x 172 pixels

HazCam & PerchCam

2D Projection



3D Depth

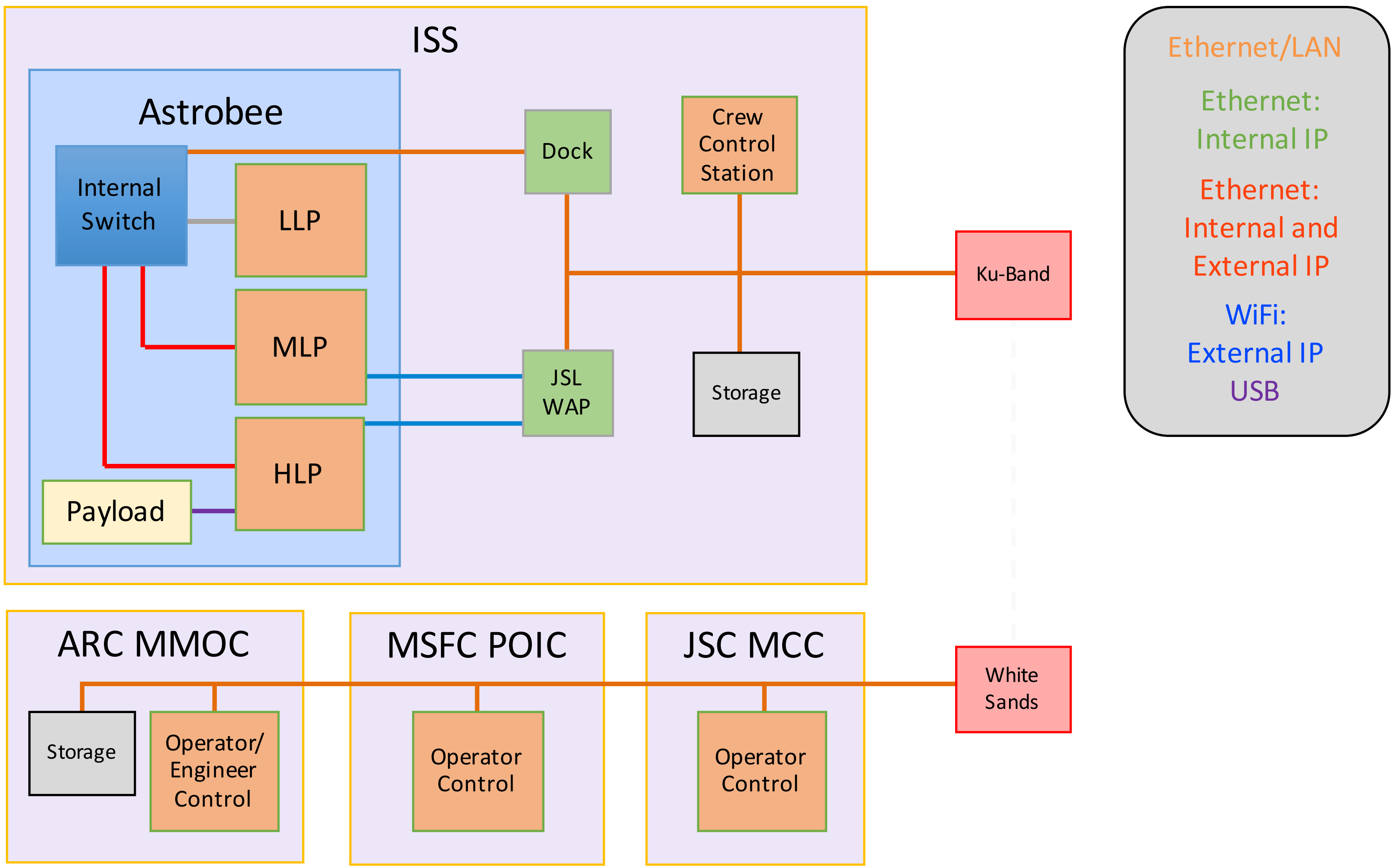


Comms

Team

- Ted Morse
- Vinh To
- Jason Lum (alum)

Comms Block Diagram

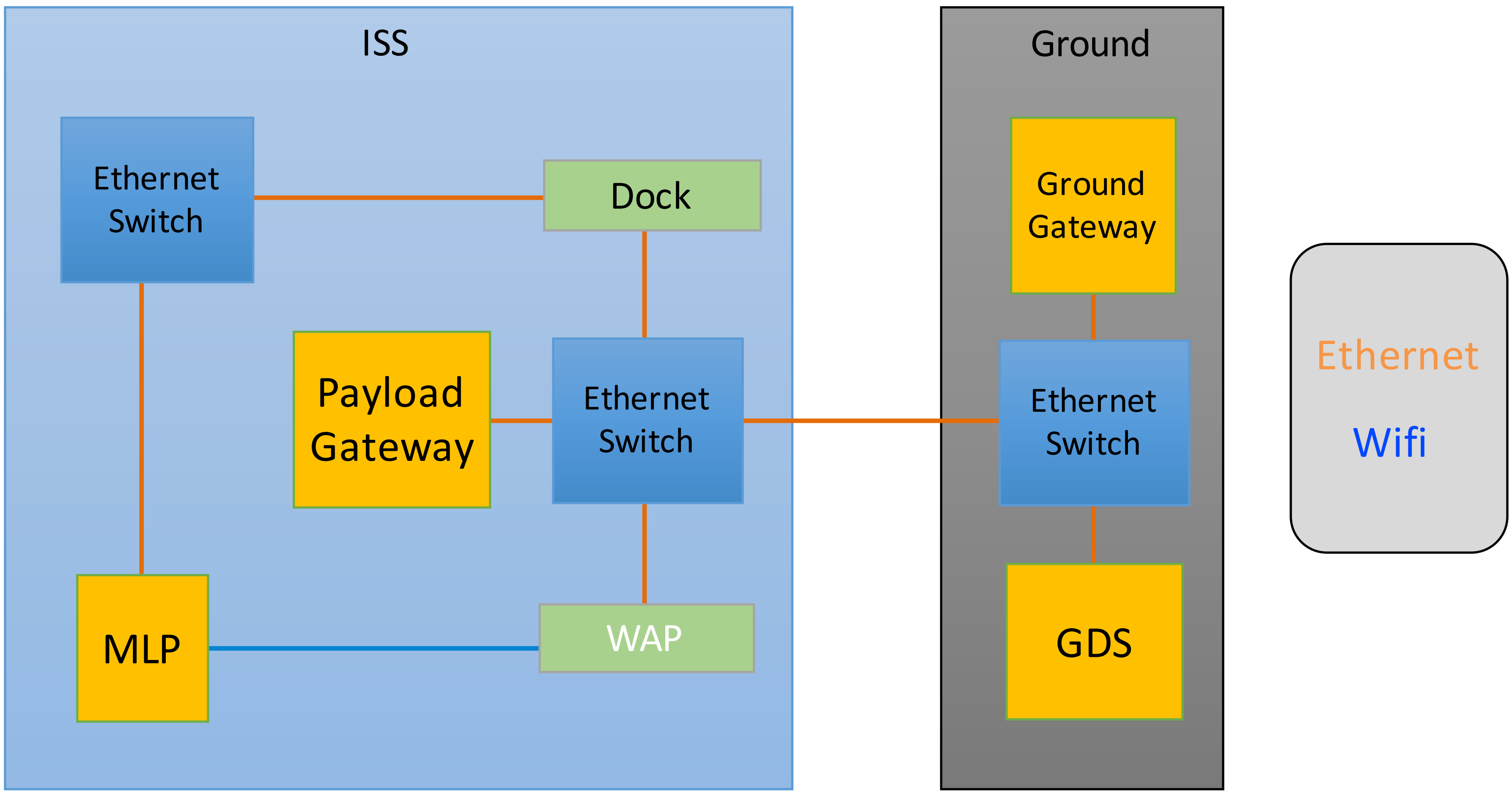


Comms Setup

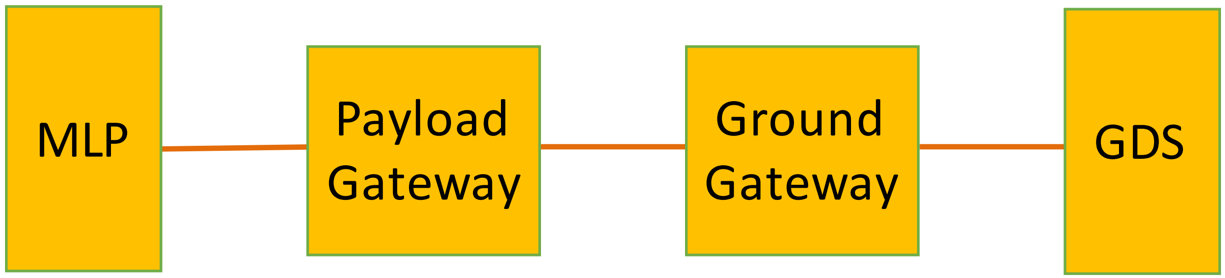
- MLP Wifi is used for comms to GDS, including video. (and possibly Astrobee-to-Astrobee.)*
- Internal IPs are used for FSW messaging.*
- External wired IPs are generally used for large file transfers, upgrades, etc.
- HLP not actively used, but enabled.

*Actual protocols defined by FSW & FSW/GDS ICD – but we all know it's DDS & ROS.

TReK CFDP DTN Diagram



TReK CFDP DTN Setup



- TReK CFDP DTN is a reliable file transfer protocol.
- Data is sent serially through each node.
- The KU Forward connection is between the gateways.
- Data is stored at the gateways during a LOS.

Antenna

- 2.4 GHz/5.8 GHz Wifi antenna
- ~3dBi/5dBi gain
- Adhesive tape mounting
- Paper thin

Astrobee Flight Software Subsystem

Design Overview

FSW Subsystem Team

- Staff
  - Brian Coltin
  - Lorenzo Flückiger (lead)
  - Ted Morse
- Postdoc
  - Dong-Hyun Lee
- Intern
  - Mike Watterson
- Alumni
  - Oleg Alexandrov
  - Ravi Gogna
  - Zack Moratto

Agenda

- Overview and system architecture of Astrobee Flight Software
- Trades studies for main components:
  - Communication Framework
  - Localization
- Details of key components

Astrobee FSW Features

- Manage Astrobee sensing and actuation
- Navigate and localize within the ISS
- Perform autonomous perching
- Perform autonomous docking (+ return to dock)
- Manage multisensory interaction with the crew
- Support “Guest Science” operations
- Support plan based automated tasks
- Support remote control from ground

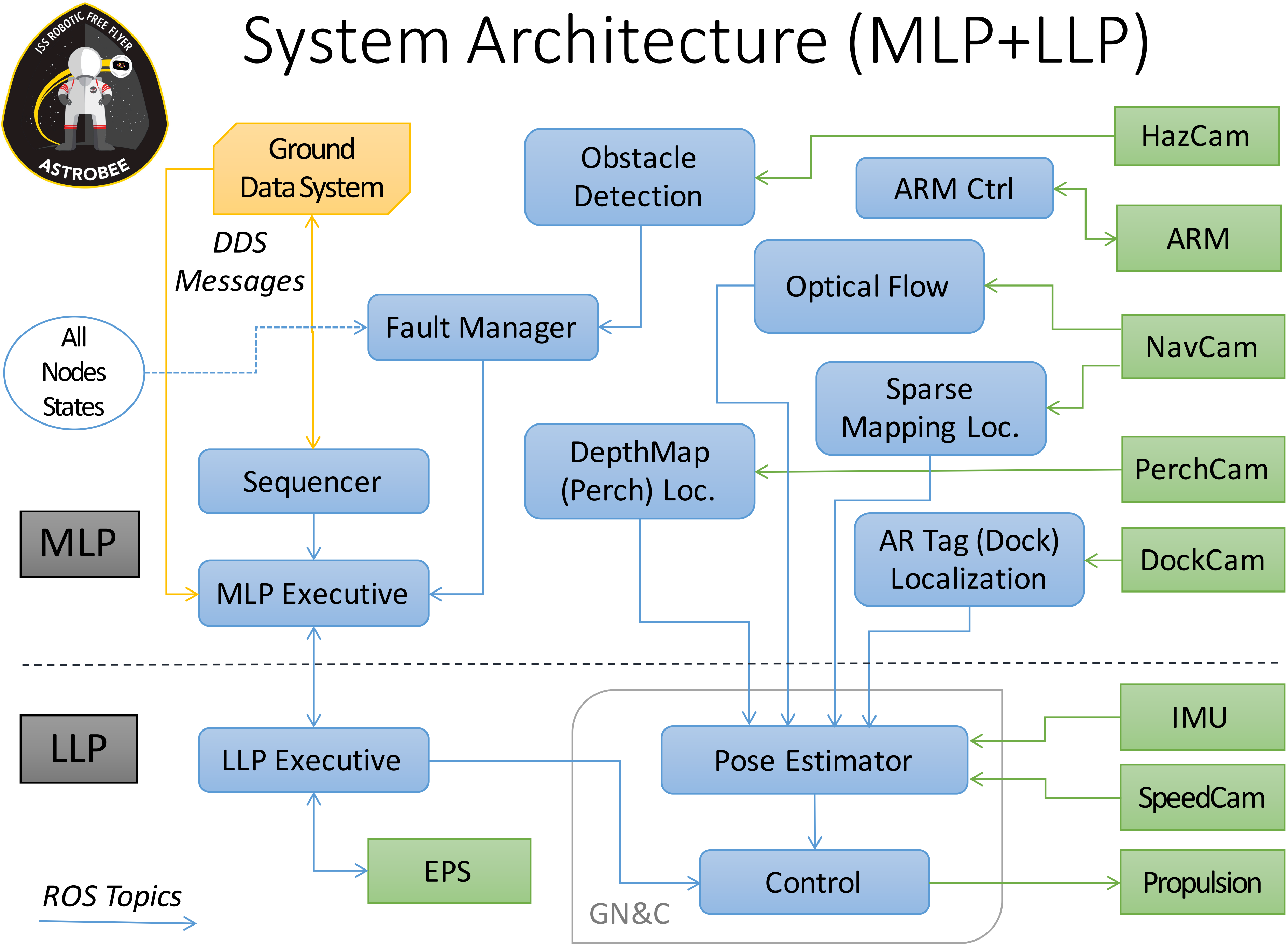
Risk Reduction

Vision-Based

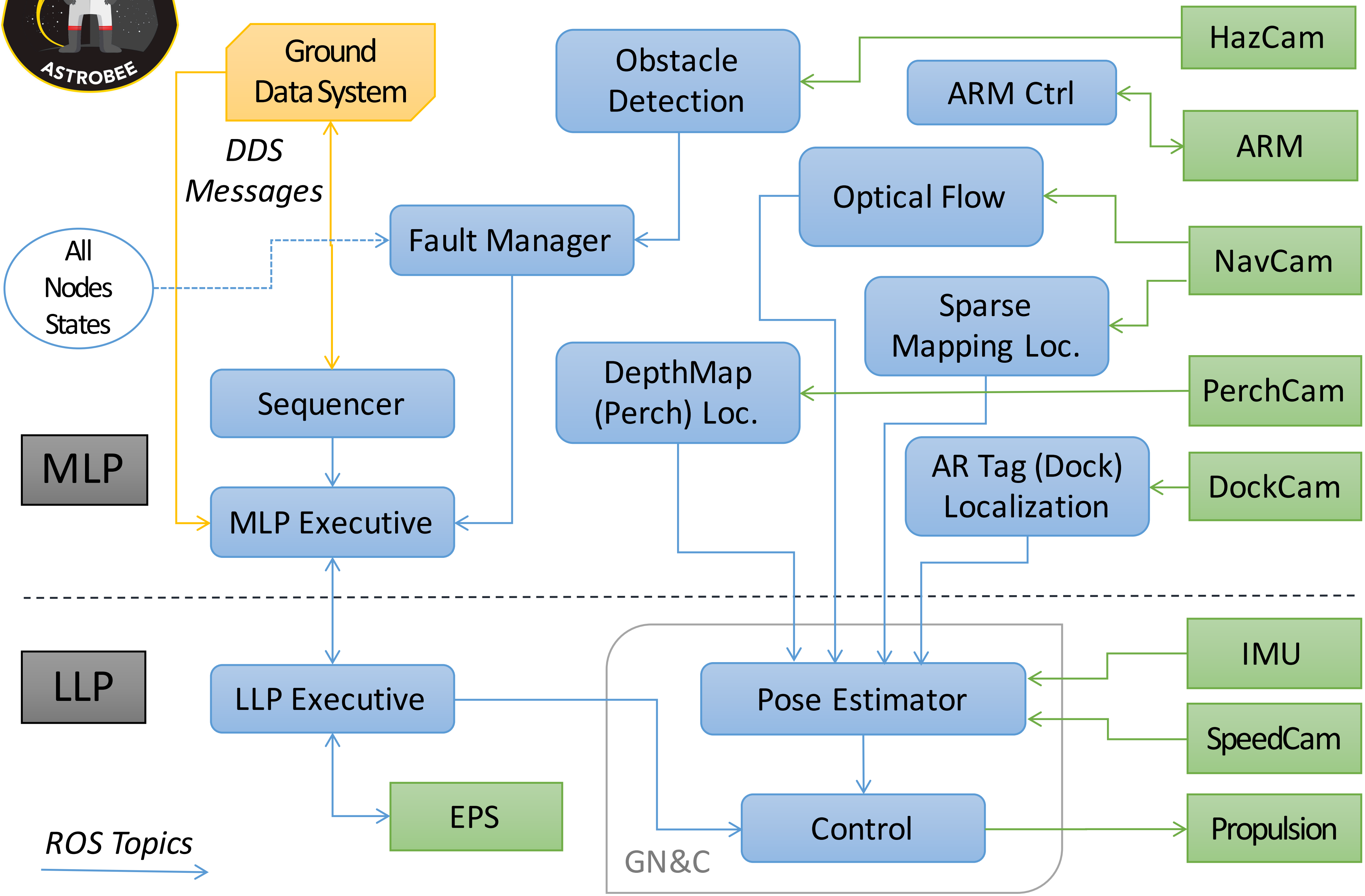
Selected HW Architecture

- *Three ARM processors to isolate guest code, vision based navigation and 100 Hz control loop*
- **Low Level Processor** (LLP) – Linux, Dual core
  - Runs pose estimator and propulsion control loop
- **Mid Level Processor** (MLP) – Linux, Quad core
  - Runs absolute localization algorithms, obstacle detection, sequencer, communications
  - Heavy processing power used by vision
- **High Level Processor** (HLP) – Android, Quad core
  - Interface with Science Camera and Display
  - Encodes video with dedicated hardware
  - Runs Guest Science code

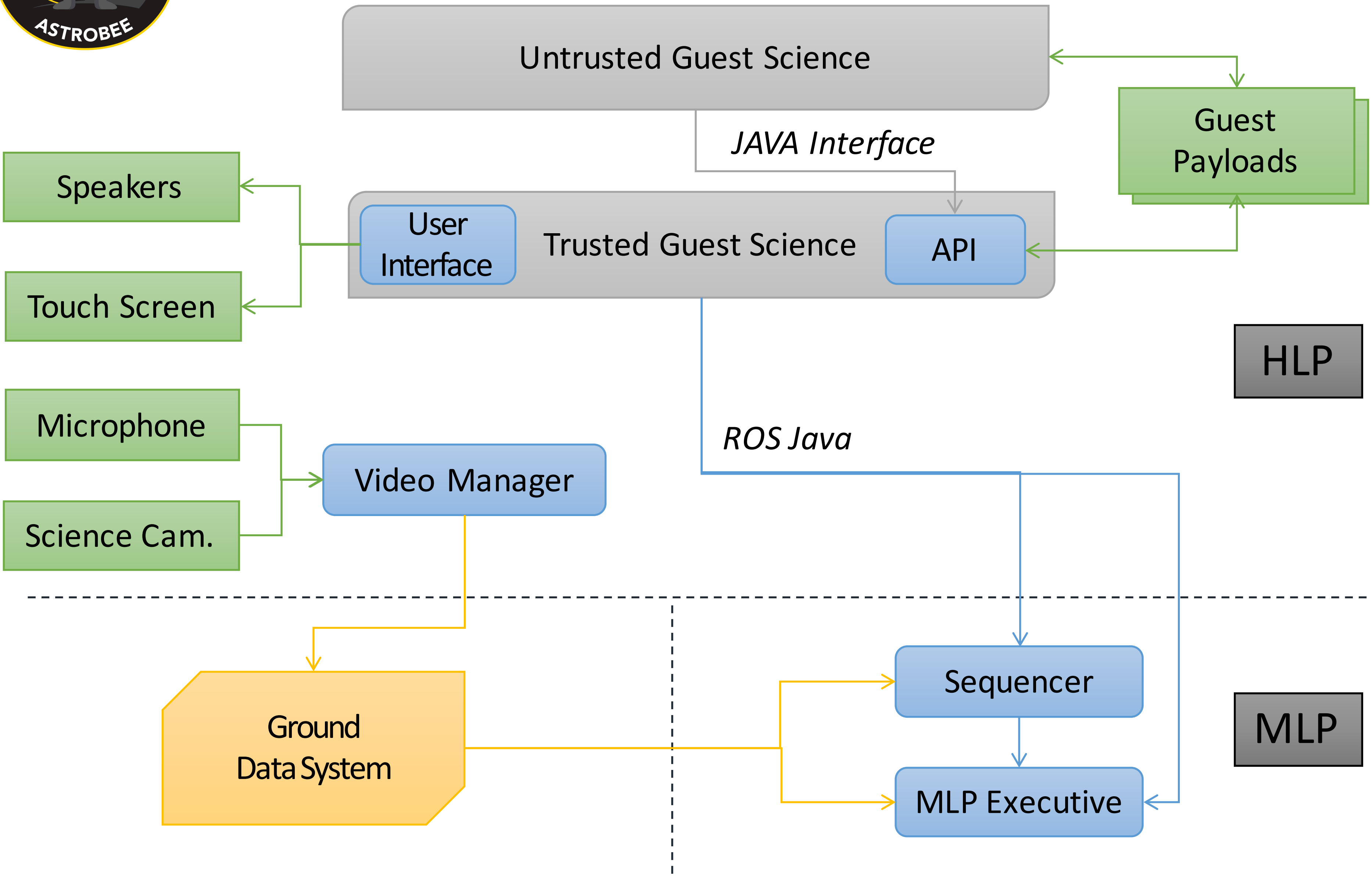
System Architecture (MLP+LLP)



System Architecture (MLP+LLP)



System Architecture (HLP)



FSW Components

- OS (Communication Framework)
- *Pose Estimation + Propulsion Control*
- Offline mapping for localization
- Online localization (inputs for absolute pose)
  - Navigation
  - Docking
  - Perching
- Fault Management
- Executive (Mode Manager)
- Sequencer (Plan Execution)
- User Interfaces
- Guest Science

Agenda

- Overview and high level architecture of Astrobee Flight Software
- Trades studies for main components:
  - Communication Framework
  - Localization
- Details of key components

Communication Framework

Candidates
Common Flight Executive (CFE)
Robotic Operating System (ROS)
Mobile Robot Programing Toolkit (MRPT)
Joint Architecture for Unmanned Systems (JAUS)
IRG RoverSW (SORA + **RAPID**)
Data Distribution Service (DDS)

Selected solution is hybrid of:

- ROS for onboard messaging
- DDS for remote comm.

- Key factors for ROS selection (vs. CFE):
  - Messages definition and serialization support
  - Better service isolation
  - Documentation & Support
  - Library of Robotics Algorithms Available
- Key factors for DDS + RAPID
  - Multiple Configurable Quality Of Service (QoS)
  - ISS Tested + Heritage from SmartSpheres

Localization Design Drivers

	Localization Options	
Infrastructure + External Maps	ISS Wifi	Does not provide desired accuracy
	Beacons (passive/active)	Modifications to ISS / change dependent
Robot Builds Maps	Stereo Vision	"Metric" (shape) maps makes matching difficult
	3D sensors (LIDAR, ...)	
	Monocular Vision	"Features" maps efficient to filter

Requirements
Localize anywhere on ISS US segment
Minimize modifications to ISS
Cope with changing environment

Selected Solution (hybrid):

- Build and update maps offline
- Match visual features online (3 modes) for localization

Agenda

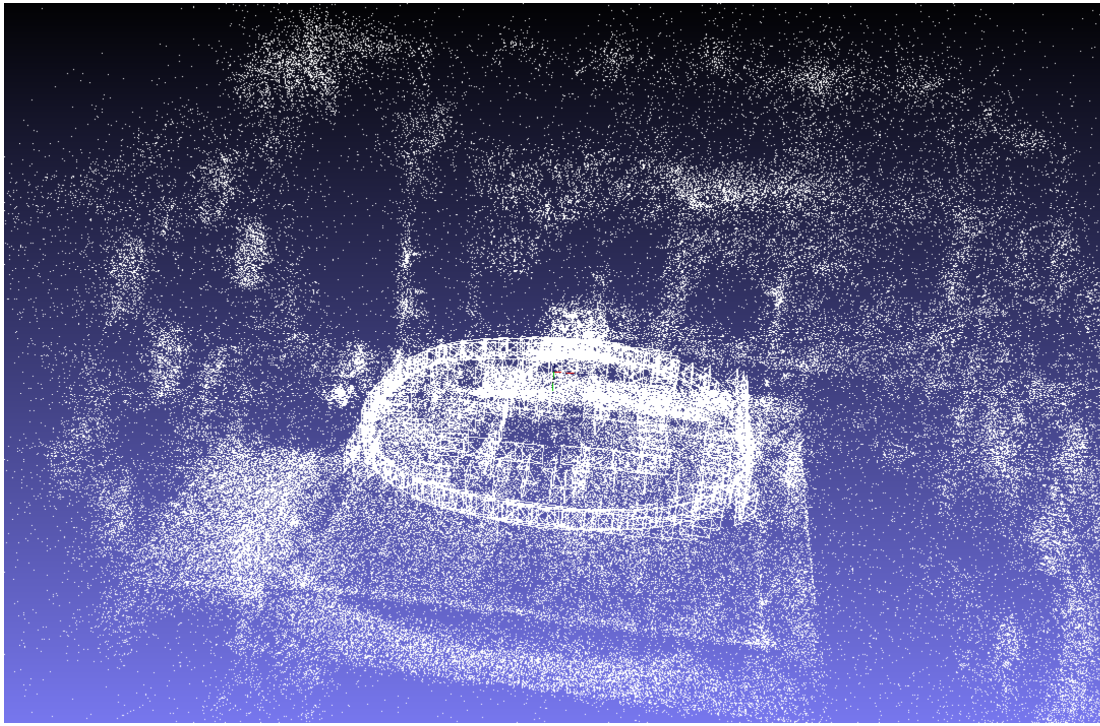
- Overview and high level architecture of Astrobee Flight Software
- Trades studies for main components:
  - Communication Framework
  - Localization
- Details of key components

Vision Algorithms

- Four MLP vision nodes send observations to the Pose Estimator:
  - Sparse Mapping : runs for regular navigation, provides absolute position within the ISS map
  - Optical Flow : always run,provides velocities
  - Handrail Detector : only runs for perching
  - AR Tags : only runs for docking

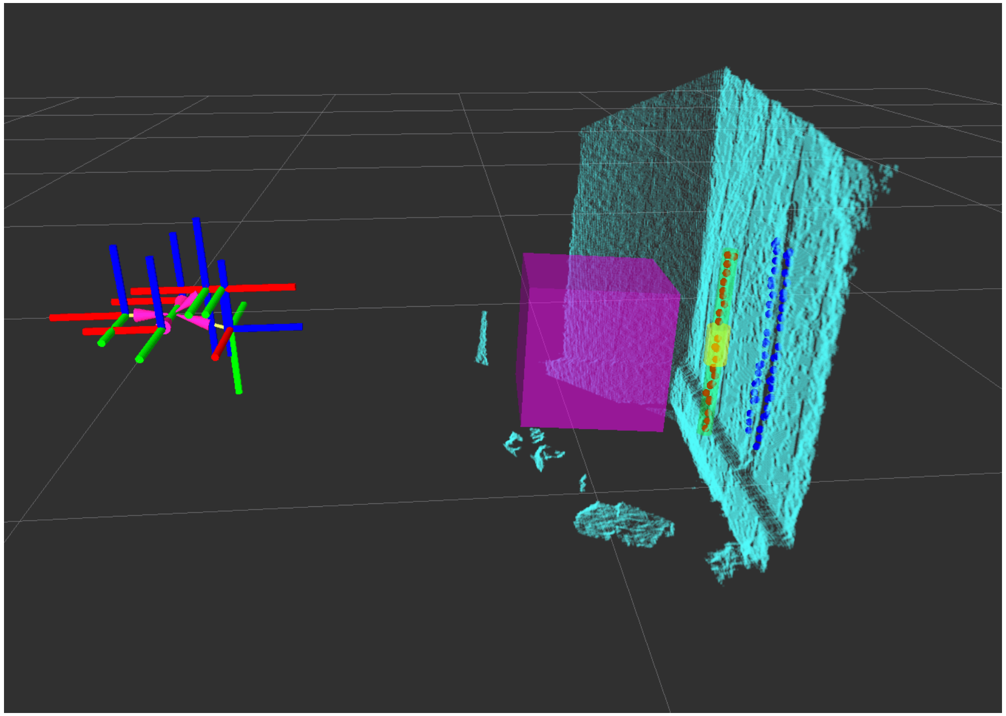
Sparse Mapping

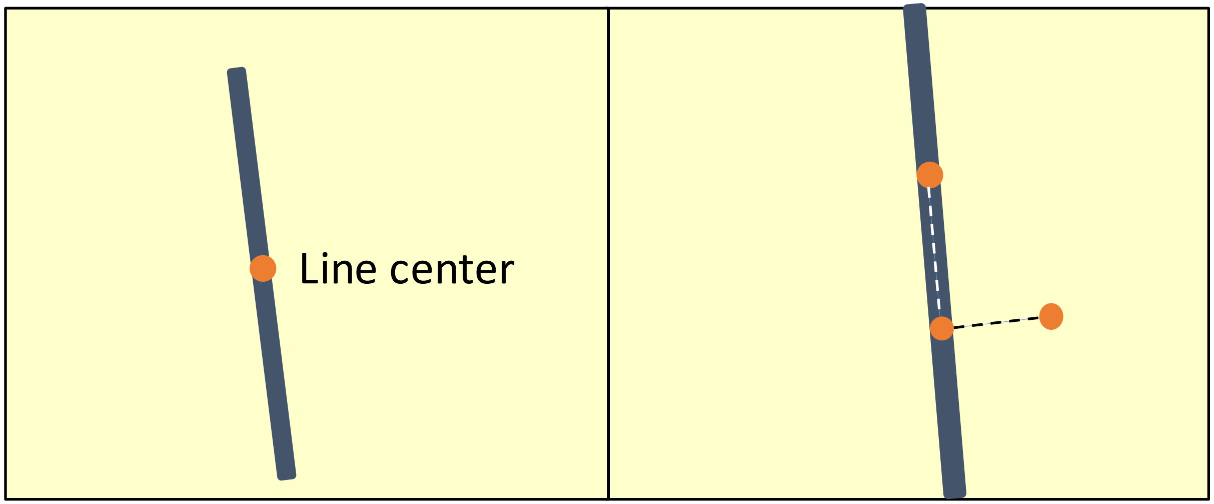
- Build maps from ISS imagery on ground
- Match BRISK features from images to features in reference map to determine robot pose
- AR tags send similar information to Pose Estimator from AR tags



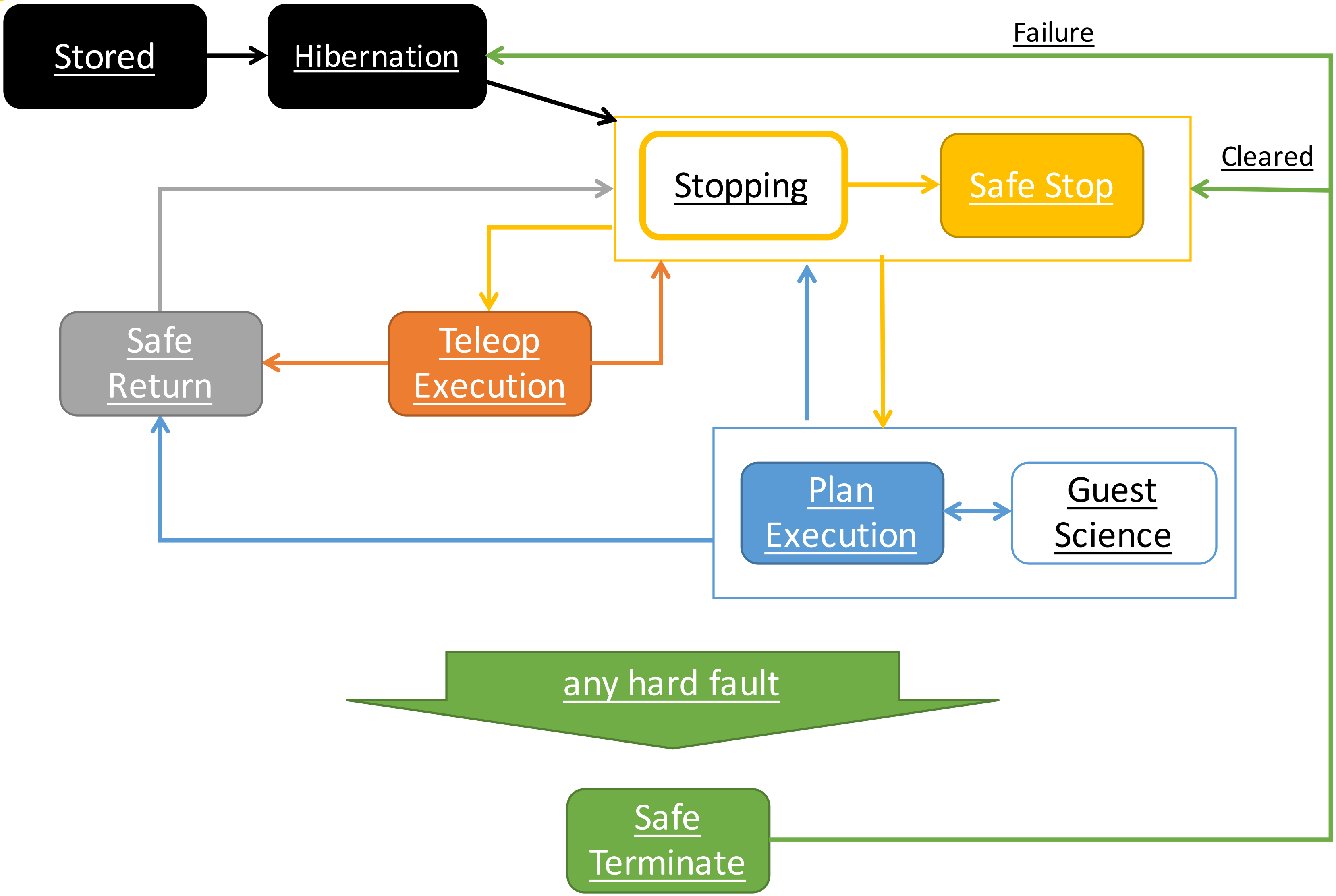
Handrail Detection

- Uses PerchCam depth sensor
- Fit plane to wall behind handrail, line to handrail
- When perching, send points from handrail to EKF
- Uncertainty in direction along handrail when close



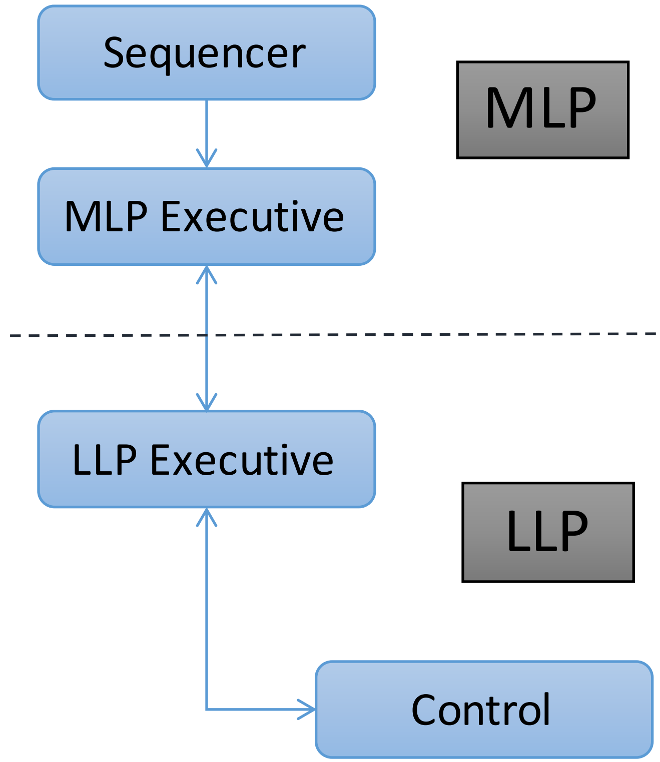


Operating Modes



Executive Nodes

- Executive Nodes are responsible for keeping track of all states.
- There are Executives on both MLP and LLP so that the operating mode is preserved in the event of a processor shutdown.
- Trajectory commands flow through Executives so that in case of an emergency, an Executive can execute a safe stop.
- Executives maintain operating mode through a finite state machine.

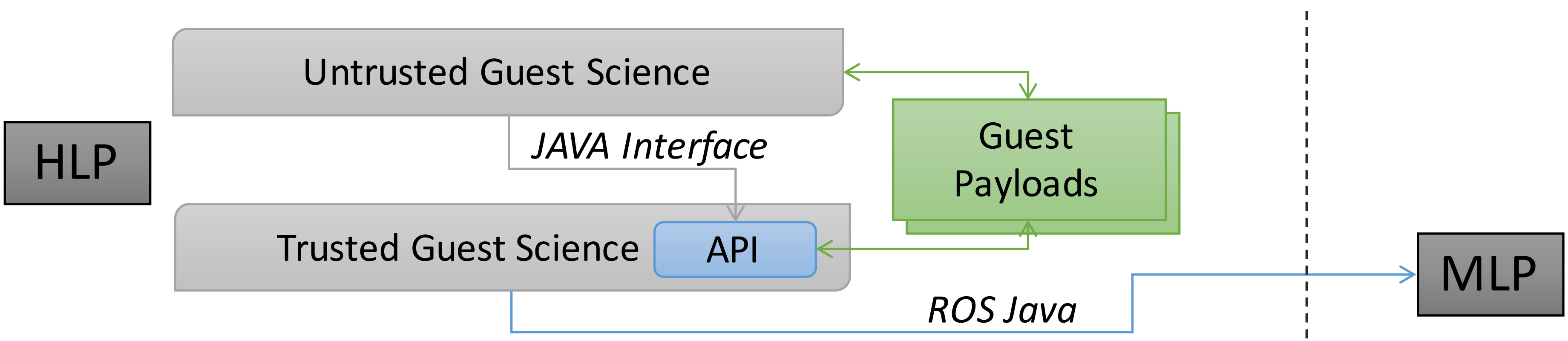


Fault Management

- Faults can enabled, triggered, or inhibited.
- All faults are sent to a central fault management module.
  - Fault management module looks up fault status and the response in a table which can be easily modified
  - Typical response is a state change, often to safe stop or safe terminate
- Specific examples:
  - **Heart beats**: A heart beat manager listens to heart beat topics, triggers a fault if process stops responding
  - **Obstacle Detection**: An obstacle detection module triggers a fault that moves to safe stop if an obstacle is in the way

Guest Science

- Guest science runs as an Android app on the high level processor.
- Android permissions provide protection for the rest of the system.
- Two guest science modes based on level of trust and review
  - "Untrusted" Guest Science has access to limited high level API (Astrobee control performance not affected)
  - "Trusted" Guest Science is granted access to the full control stack, but requires it own review



Backups

DDS Bridge and Sequencer

- DDS contains our wireless connection to GDS.
- DDS publishes a compressed version of the plan to the sequencer.
- Both DDS and Sequencer publish commands. Executives keeping track of operating state determine if they get executed.

Trade Studies

OS Selection Criteria
Modularity
Service Isolation
Messaging Performance
Usability / Familiarity
Works on Target and Host
Record/Playback raw data
Maturity
Open Source

Localization Selection Criteria
Measurement Rate
Robust Against Drift
Robust Against Occlusion
Robust Against Env. Change
Algorithm Simplicity
Implementation Available
Localization Initialization
Target Platform

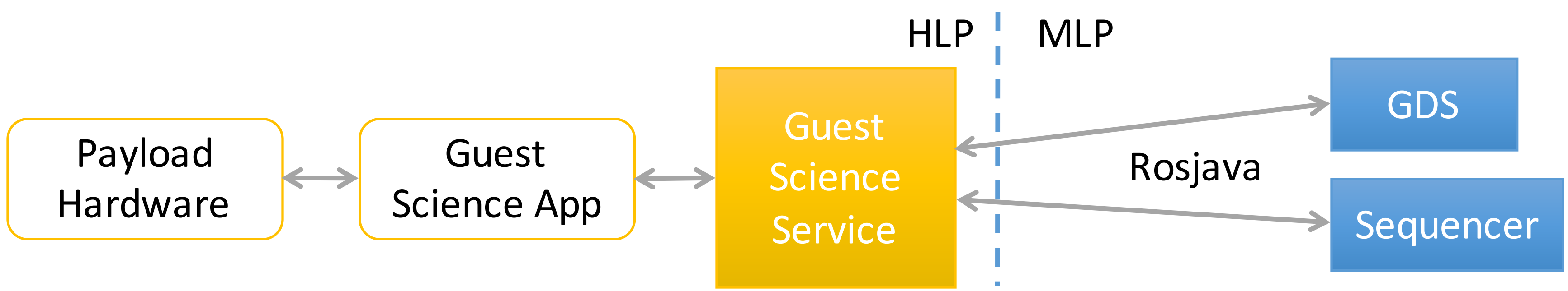
Operating Modes

- **Teleop Execution**: Obeying GDS commands.
- **Plan Execution**: Following a plan in the sequencer.
- **Guest Science**: Part of a plan, control handed to guest science code on HLP
- **Stopping:** Has a velocity, coming to a halt.
- **Stopped**: Maintaining current position.
- **Safe Terminate**: Turn off motors.
- **Hibernation**: Turn off motors and most modules.

AR tags docking

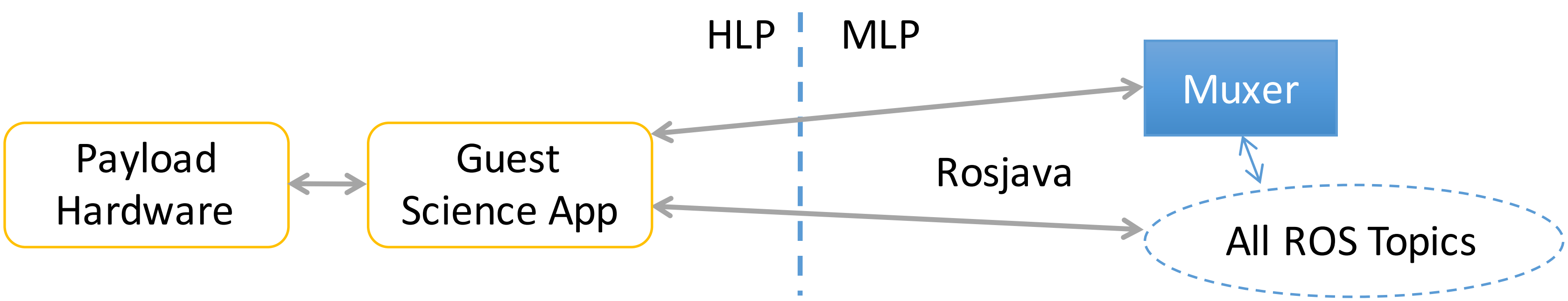
Untrusted Guest Science

- Limited functionality, Android permissions prevent general network access.
- Example: An RFID or microphone payload could survey the ISS.
- Apps are allowed to:
  - Execute plans, read robot status
  - Send messages to and from GDS
  - Communicate with payload devices
- Robustness is not compromised.



Trusted Guest Science

- Trusted apps have full network access, and can run rosjava to access all mid level processor topics and services.
- Example: An experiment to move a sloshing container of liquid could replace the EKF's outputs to control.
- A redirection node allows guest science to replace the inputs to certain nodes.
- Only limited robustness can be maintained, additional review of trusted apps needed.



Astrobee GN&C Subsystem

Design Overview

GN&C
Team Members

- Michael McIntyre (ARC-RE)
- Jesse Fusco (ARC-RE)
- Robert Nakamura (ARC-RE)

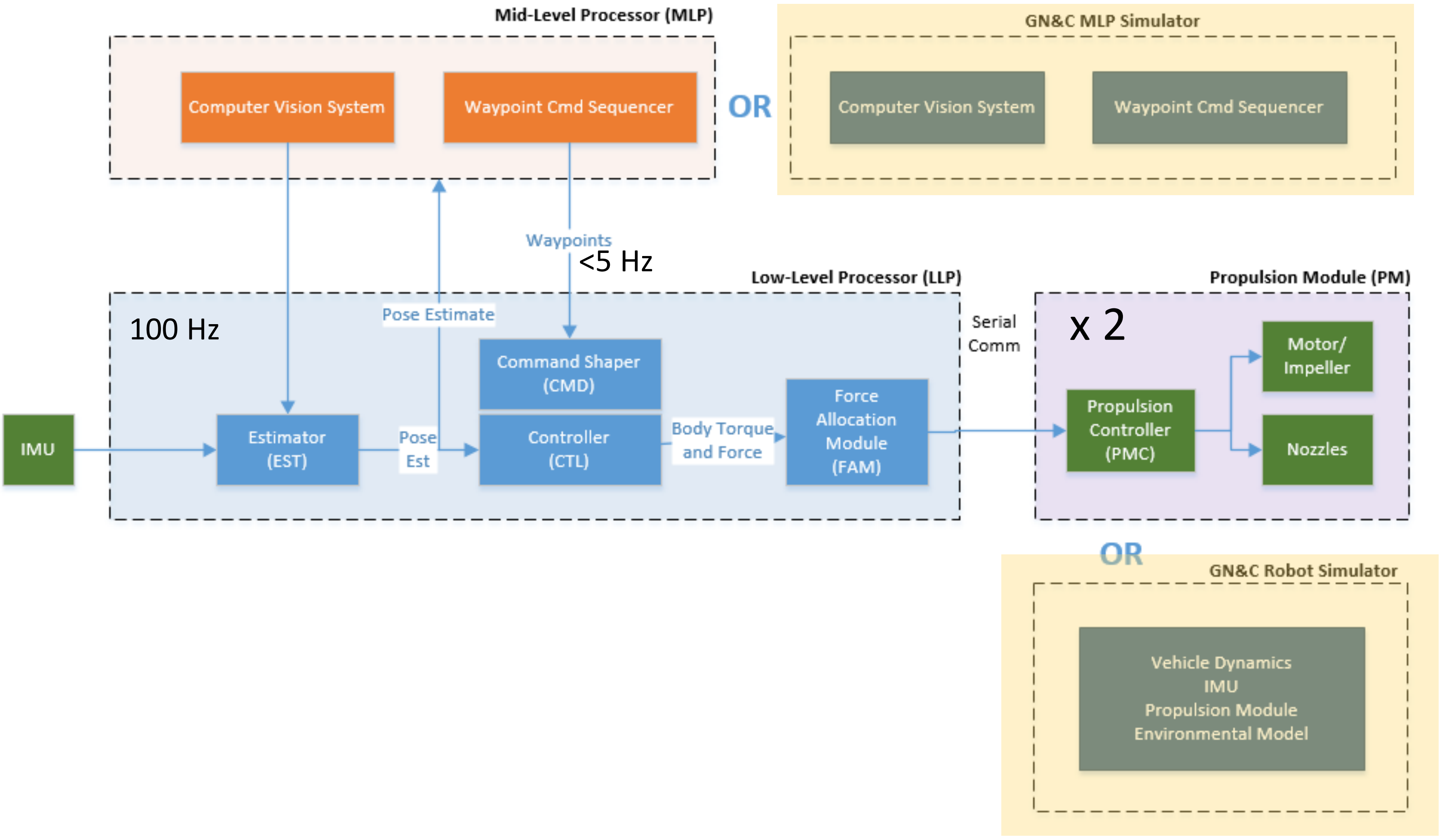
GN&C
Design Drivers

- Controllability up to 50 cm/s and 45 deg/s
- Achieve max acceleration of 10 cm/s^2 / 10 deg/s^2
- Utilize vision based navigation
- Maintain pose error less than 20 cm / 20 deg (Nominal)
- Maintain pose error less than 2 cm / 8 deg (Assisted)
  - Using artificial landmarks, AR tags, etc.

GN&C
Selected Design

- Estimator and Kalman filter
  - Sensor merging at different update rates
  - Inputs:
    - Vision system: feature recognition, optical flow
    - IMU: rate gyros, accelerometers
- Controller
  - PID
  - Outputs: PM impeller motor, nozzle servos
- Control Modes
  - Multiple propulsion impeller speeds, depending on performance need

GN&C Architecture Diagram



GN&C
HW Components- IMU

- Epson G362 Selected

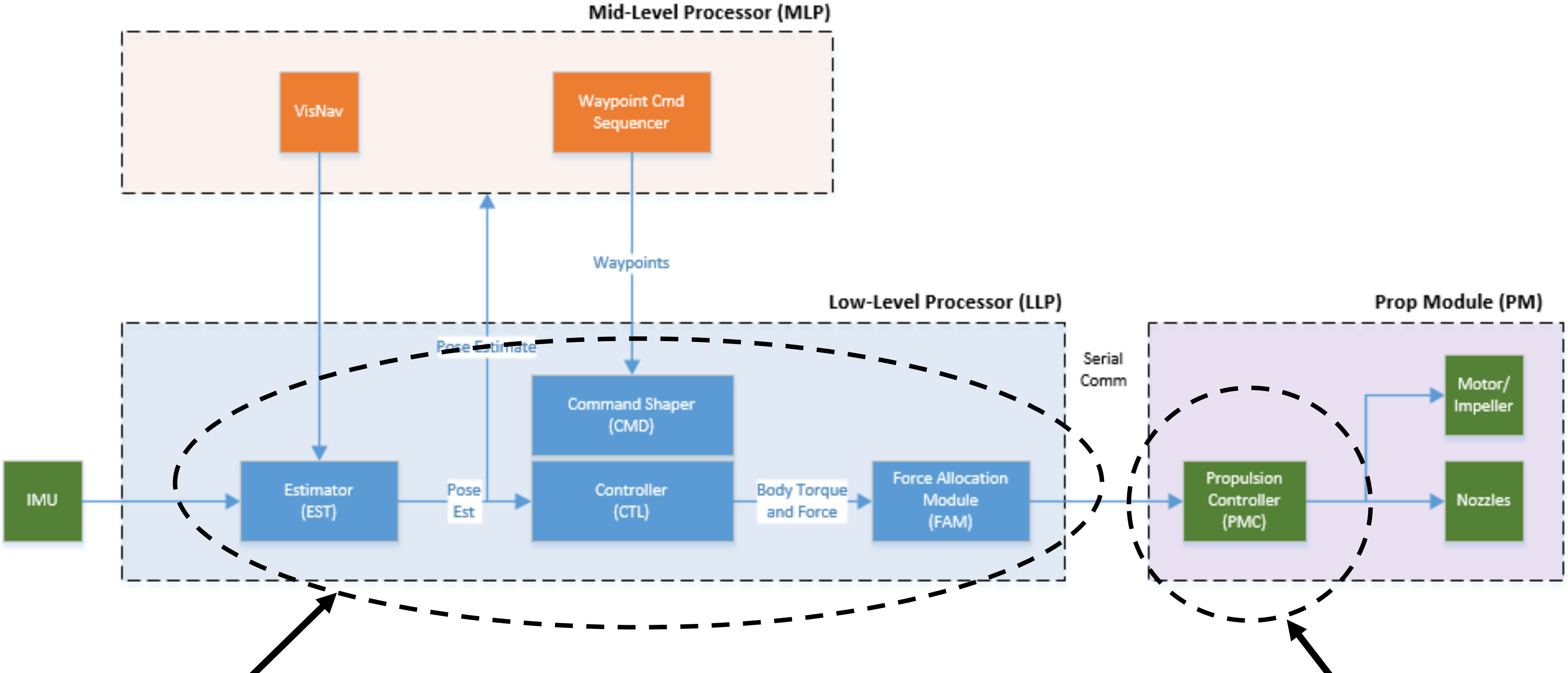
■ **FEATURES**

- Small Size, Lightweight : 24x24x10mm, 7grams
- Low-Noise, High-stability
  - Gyro Bias Instability : 3 deg/hr
  - Angular Random Walk : 0.1 deg/$\sqrt{hr}$
- Initial Bias Error : ±0.5 deg/s (1σ)
- 6 Degrees Of Freedom
  - Triple Gyroscopes : ±150 deg/s,
  - Tri-Axis Accelerometer : ±3 G
- 16/32bit data resolution
- Digital Serial Interface : SPI / UART
- Calibrated Stability (Bias, Scale Factor, Axial alignment)
- Data output rate : to 2k Sps
- External Trigger Input / External Counter Reset Input
- Calibration temperature range : −20°C to +70°C
- Operating temperature range : −40°C to +85°C
- Single Voltage Supply : 3.3 V
- Low Power Consumption : 30mA (Typ.)

Other IMUs ruled out in trade study:

- Epson G350
  - Un-needed larger range of operation
  - 2x bias and random walk
- SBG Ellipse
  - No obvious performance improvement
  - Un-needed integrated Kalman filter
  - Non-transparent documentation

GN&C
Flight Software Components



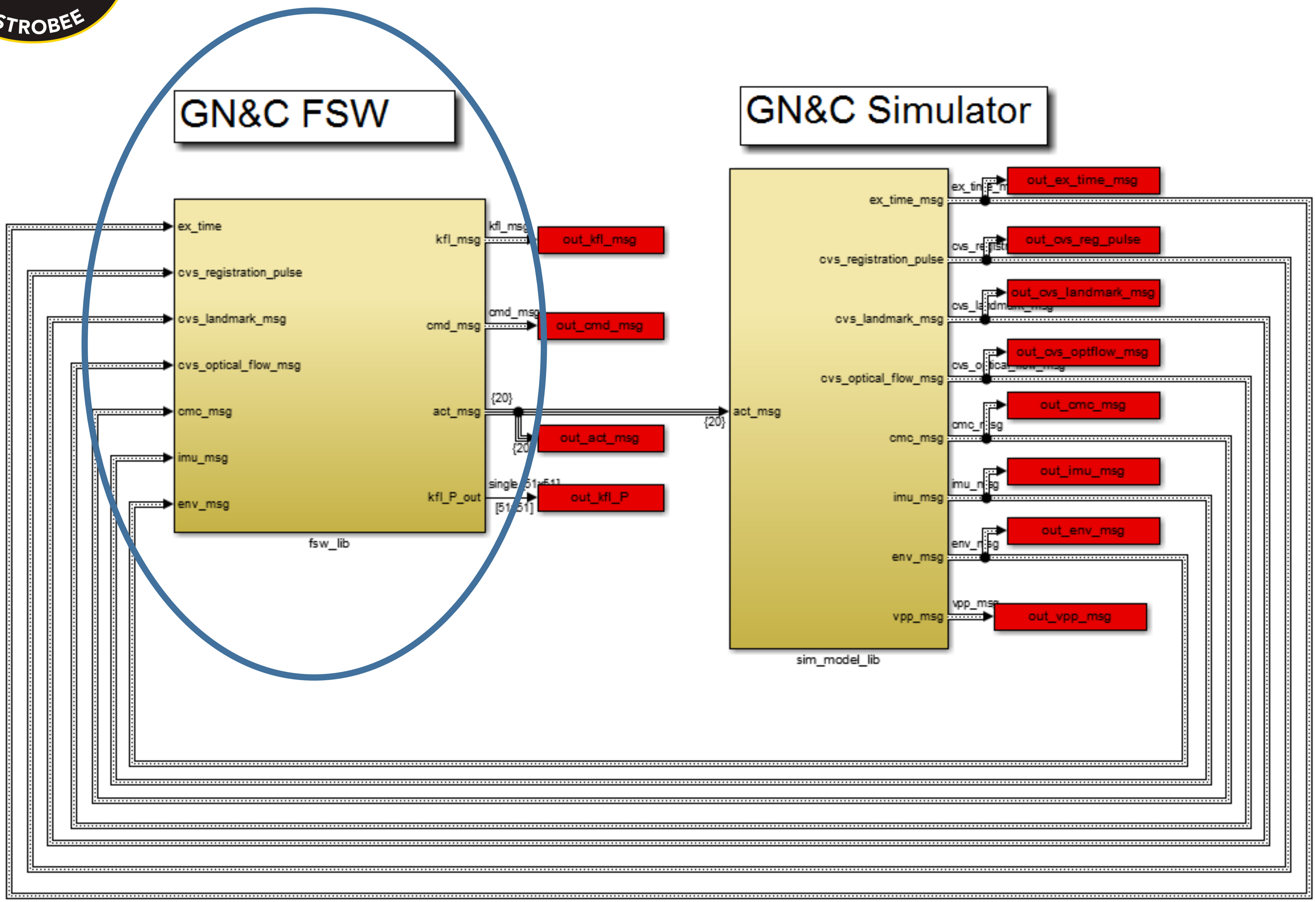
Integration with FSW

- Matlab/Simulink models ARE the source code
- GN&C SW components are auto-coded and imported into a single high priority ROS node

Microcontroller Code

- Loaded directly on to PIC32
- Under version control and CM since it is flight code

GN&C
GN&C Models



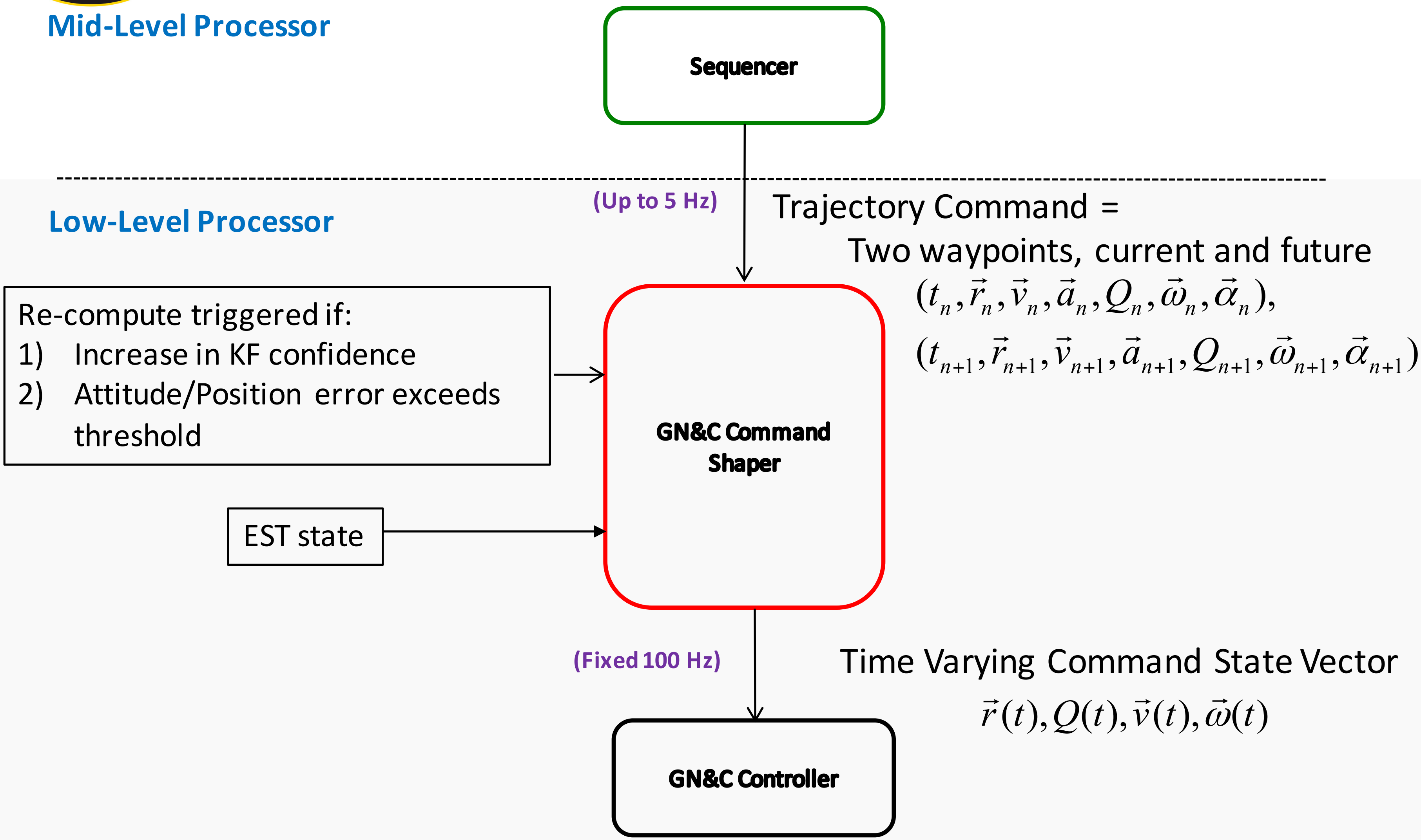
GN&C: SW Components
Estimator (EST)

- Fuses data from several disparate sources and update rates

IMU data	100 Hz with negligible delay
Optical flow data	15 Hz with small delays
Mapped landmark data	0.5 Hz with large (~2 Seconds) delays
AR Target data	5 Hz with small delays

- Extended Kalman Filter with Augmented States corrects for large time delays inherent to vision navigation systems
  - Covariance and the current state estimate are captured at the moment the camera takes an image (via a registration pulse)
  - After an image is processed, the reduced data is sent to the estimator but with significant delays (up to 2 seconds).
  - Errors in the state estimate at the time the image was taken are used to infer current state errors

GN&C: SW Components Command Shaper (CMD)



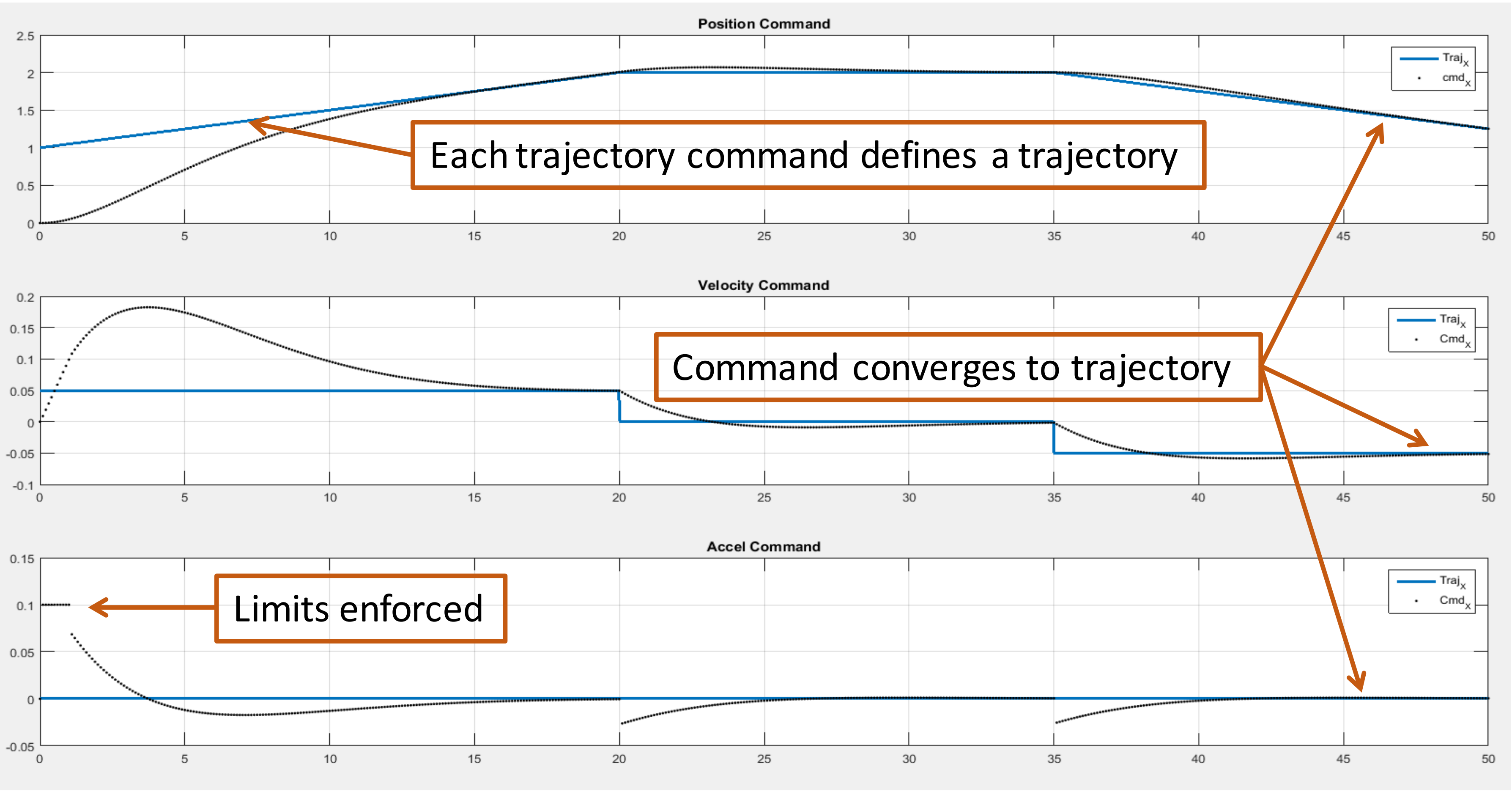
GN&C: SW Components
Command Shaper (CMD)

1D Example:

Command 1: Time =   0s, Position = 1 m, Velocity = .05 m/s, Accel = 0

Command 2: Time = 20s, Position = 2 m, Velocity = .00 m/s, Accel = 0

Command 3: Time = 35s, Position = 2 m, Velocity = -.05 m/s, Accel = 0



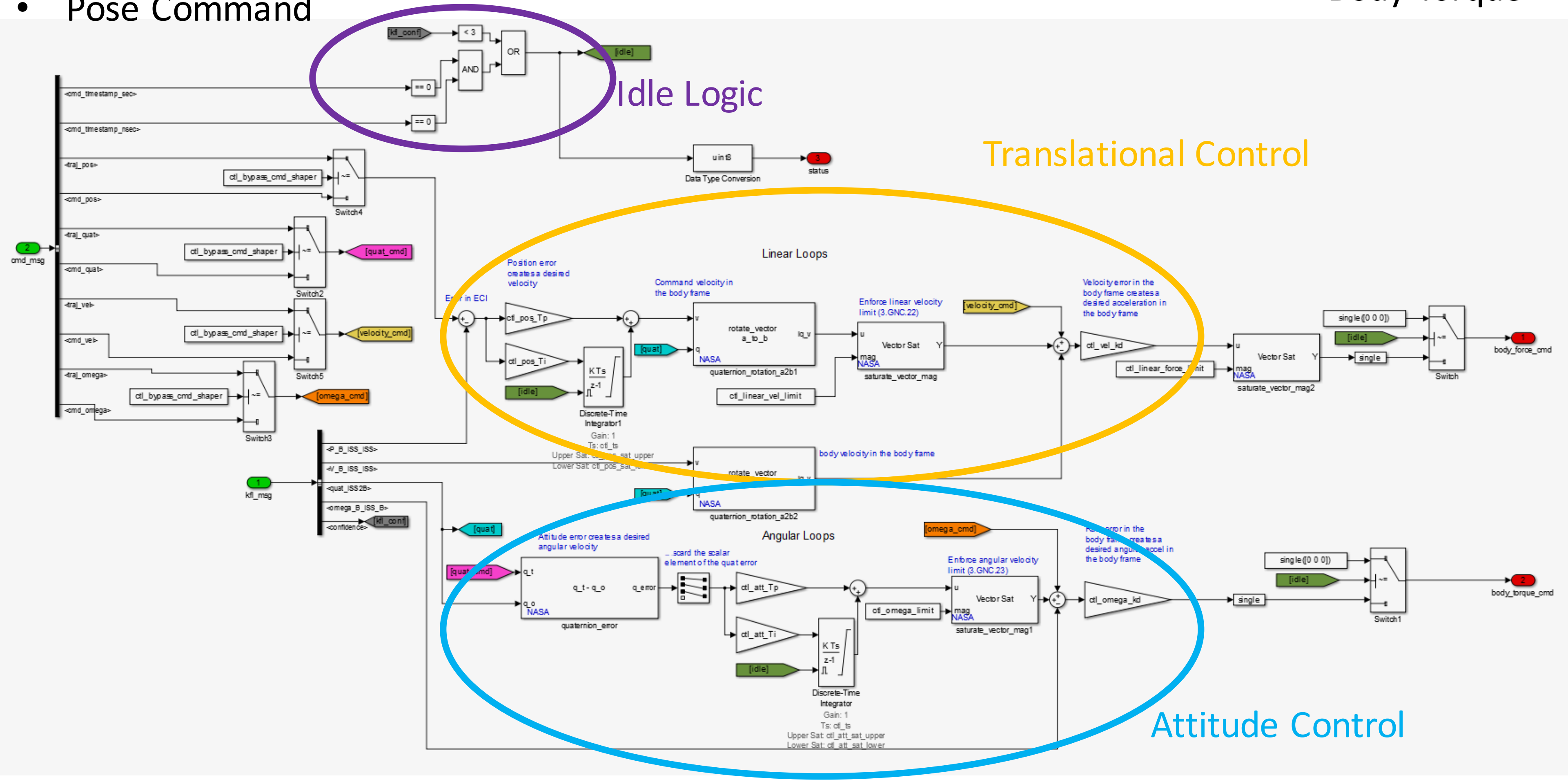
GN&C: SW Components
Control (CTL)

Inputs

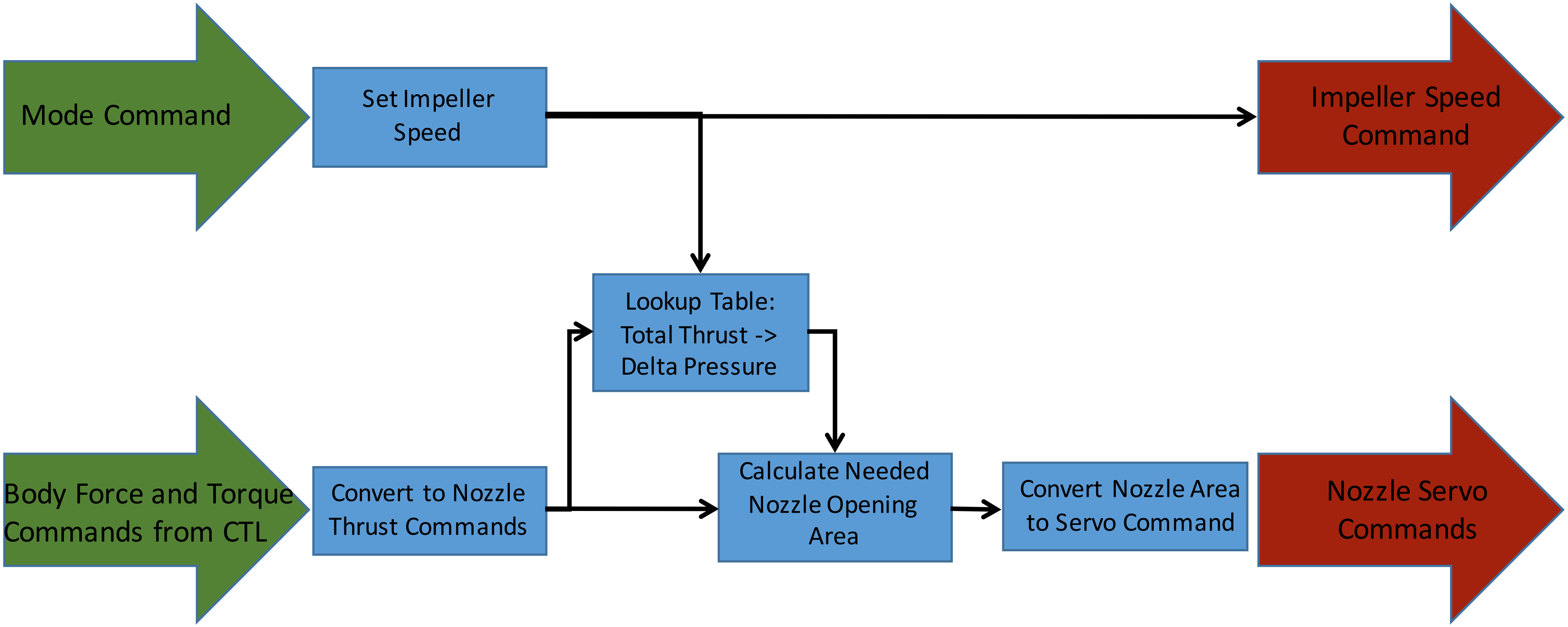
- Estimator State
- Pose Command

Outputs

- Body Force
- Body Torque

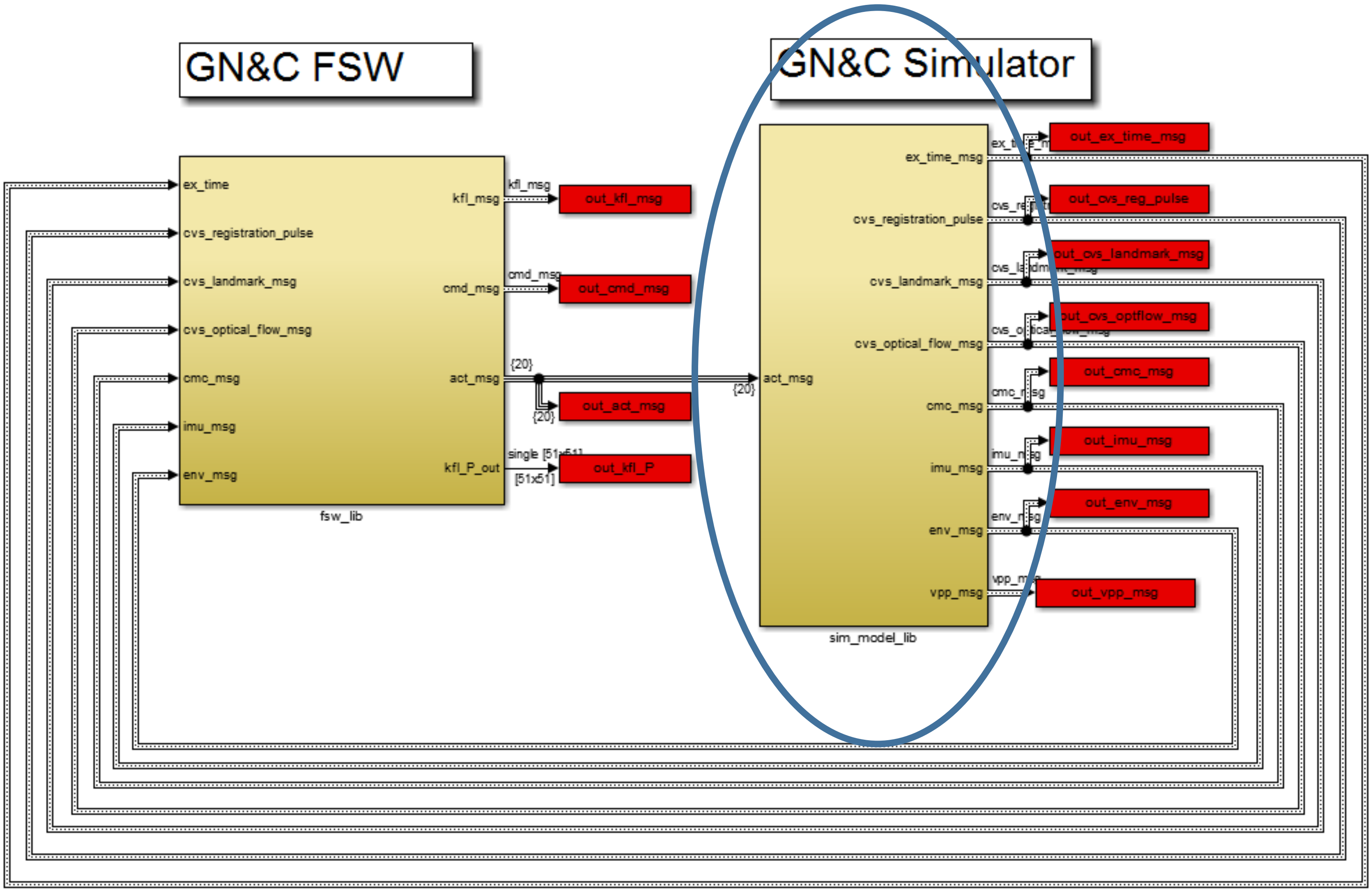


GN&C: SW Components
Force Allocation Module (FAM)



GN&C
Simulation Model

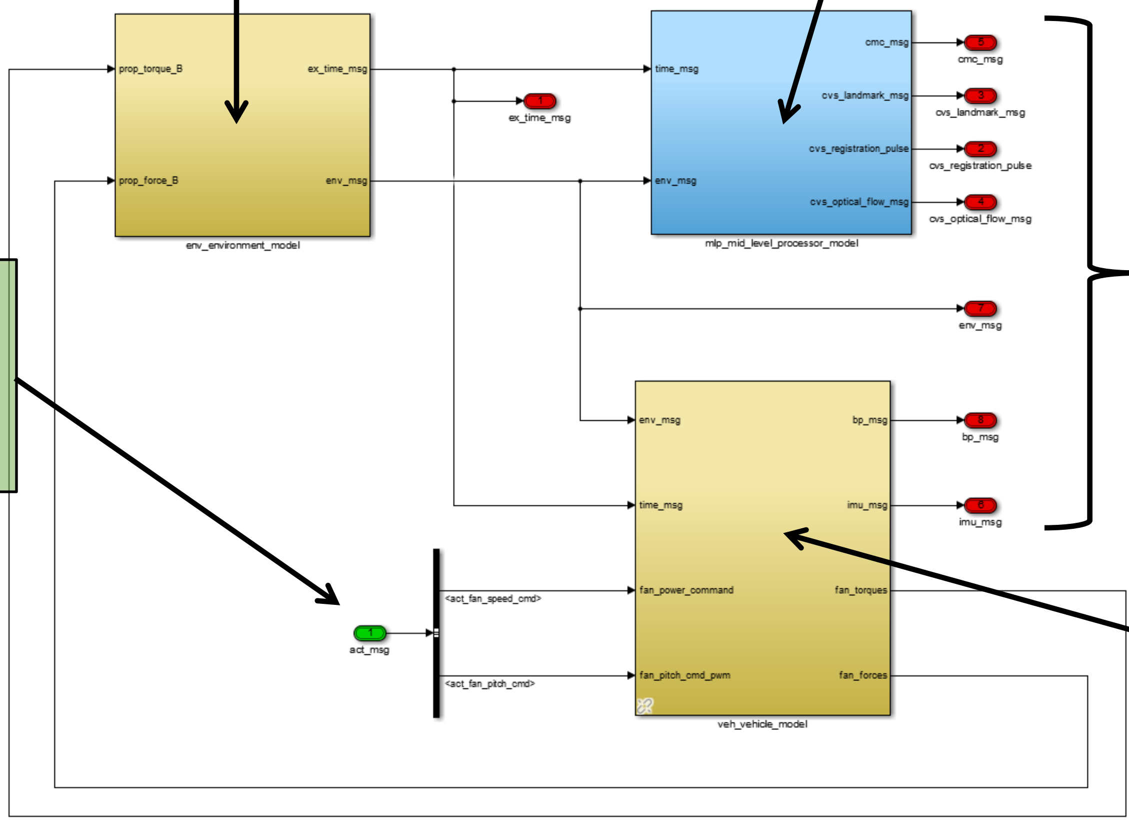
Simulation can be performed in Matlab or coded out for use in PIL testing



GN&C Simulation Model

Environment Model:
- Rigid Body Dynamics
  - Flight
  - Granite Table
- Disturbances
- Time Model

MLP Model:
- Vision System
- Cmd Sequencer



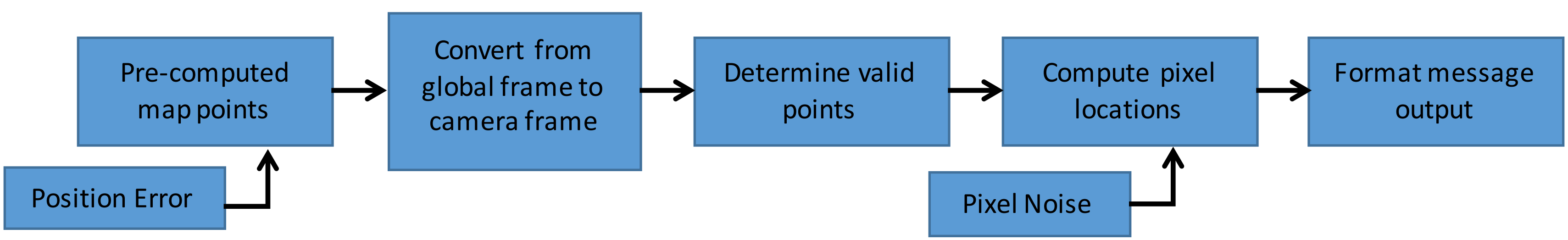
Output to GN&C FSW

Actuator Commands from FAM

Vehicle Model:
- IMU
- Propulsion Module (motor, impellor, plenum, nozzles, nozzle servos)
- EPS Model

GN&C
Vision Model Properties

- Models the landmark, AR tag and optical flow output from the MLP
- Pre-computed map points (separate for landmarks vs AR tags vs optical flow) can be randomly generated, or imported from an actual map
- Current model assumptions:
  - Resolution: 1280x960 pixels
  - Field of View: 60 degree half angle
  - Max error on mapped points: < 5cm
  - Max noise on pixel locations: < 2 pixels
  - Landmark image processing time: 0.5 sec (2 Hz)
  - Optical flow image processing time: 0.07 sec (~15Hz)
  - AR tag image processing time: 0.17 sec (~6Hz)
- Limitation: Camera model does not recreate the fish eye distortion



GN&C Simulation

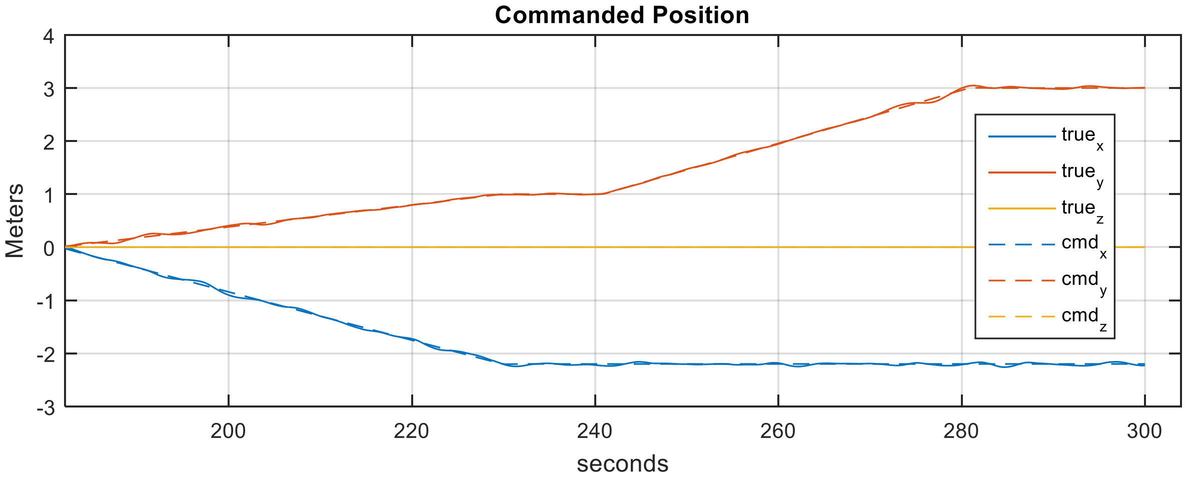
Current and Planned Uses

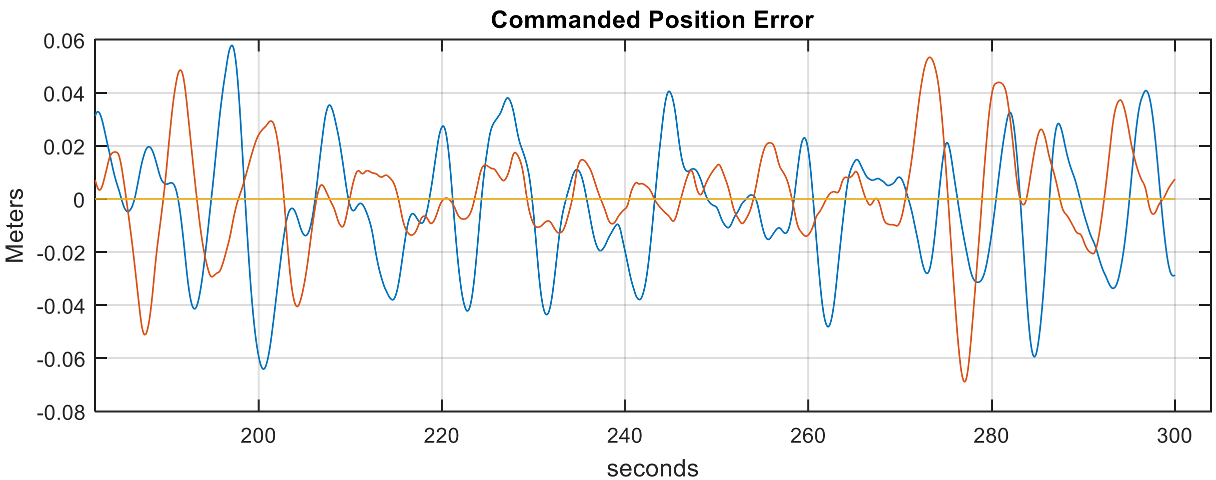
- Development of controller and estimator
- Software testing
- Control robustness analysis (linear analysis and Monte Carlo testing)
- Trade study analysis tool
- Evaluation of sortie scenarios
  - power consumption evaluation
  - Sound level histogram
  - time to execute
  - Max required rates and accelerations
- Requirements verification (where ground testing is not possible)

GN&C
Simulation Results

Plan: Translate 1m, hold, translate 2m more, hold

VNS Mode: Nominal (feature recognition). Pos Error Rqmt: 20cm





True Position Error Stats:
Max Error (m): -0.074351, -0.068885, 0.000000
Mean (m): -0.005970, 0.000987, 0.000000
Mean + 3 Sigma (m): 0.073284, 0.051370, 0.00000

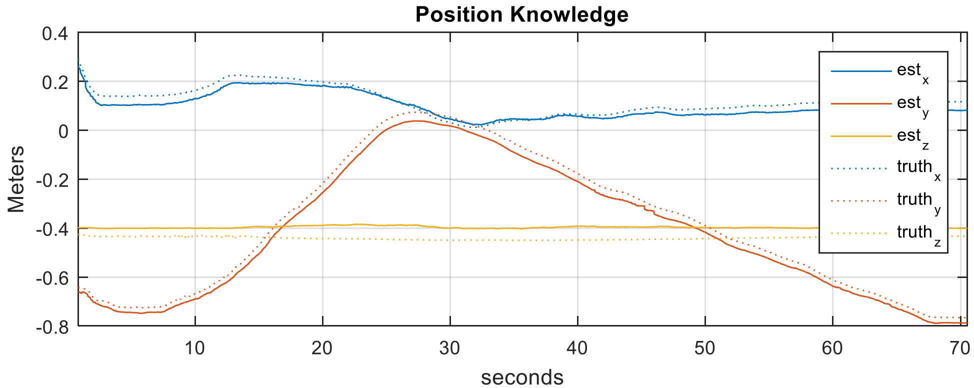
True Attitude Error Stats:
Max Error (deg): 0.634271
Mean (deg): 0.217365
Mean + 3 Sigma (deg): 0.629915

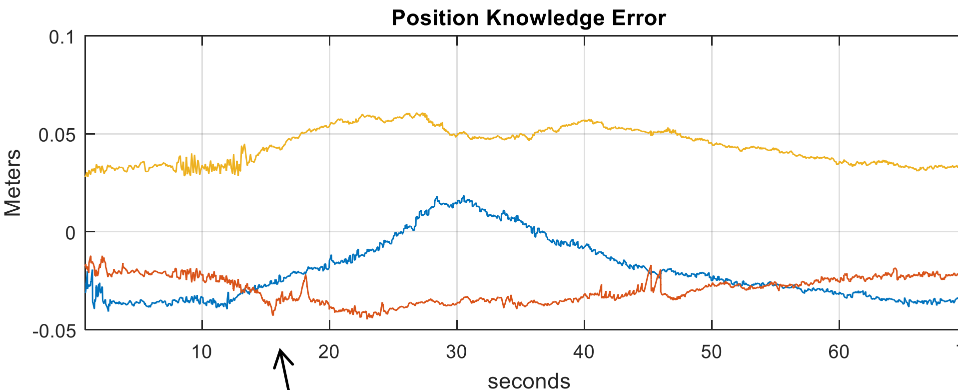
Position Knowledge Error Stats:
Max Error (m): -0.040977, -0.144290, 0.089682
Mean (m): 0.000022, 0.000594, 0.000066
Mean + 3 Sigma (m): 0.034033, 0.042330, 0.0397

Velocity Knowledge Error Stats:
Max Error (m/s): 0.045546, -0.194909, 0.095848
Mean (m/s): 0.000026, -0.000330, -0.000085
Mean + 3 Sigma (m/s): 0.043464, 0.033258, 0.025

Attitude Knowledge Error Stats:
Max Error (deg): 0.539591
Mean (deg): 0.145368
Mean + 3 Sigma (deg): 0.396710

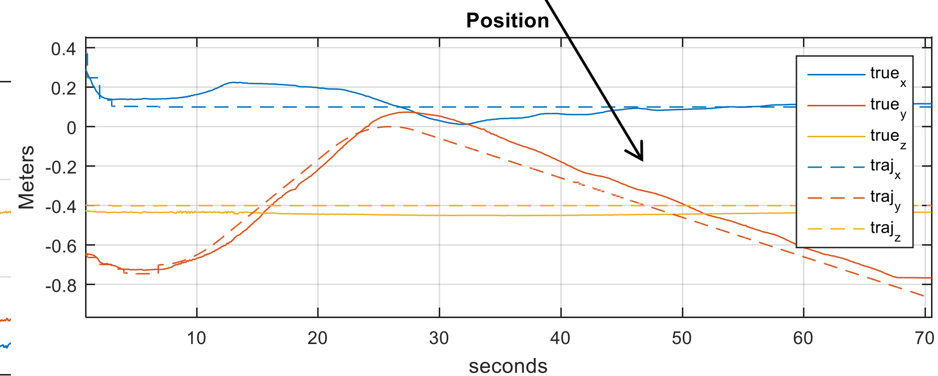
GN&C
Granite Table Test Results

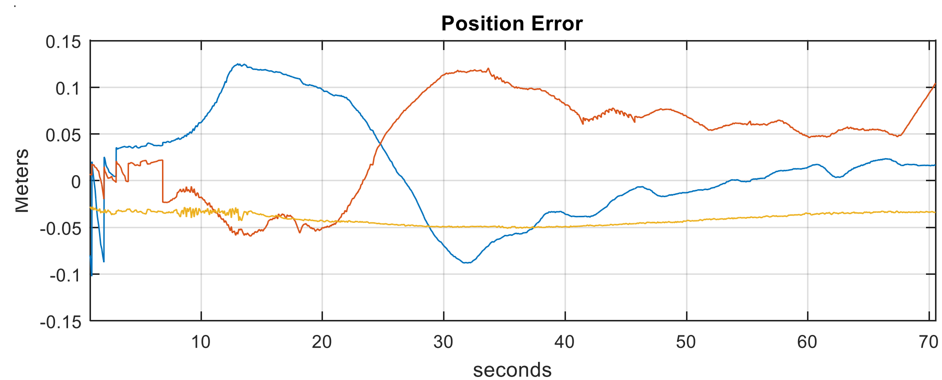




AR Target localization system performing well in granite table test (low knowledge errors)

Constant offset errors in control system are present due to difficulties in maintaining calibration of the variable pitch propeller system





Backup Slides

GN&C
Fault Management

1. Attitude/Position error exceed threshold:
   - Possible causes: External disturbance force
   - Ramification: Large errors seen by controller
   - Response: Re-compute time varying command state vector
2. Estimator Diverges:
   - Possible causes: Conflicting sensor measurements, etc.
   - Ramification: Loss of pose knowledge
   - Response: ??
3. MLP Commanded soft-stop:
   - Possible cause: Fault detected by MLP
   - Ramification: Need to come to a stop
   - Response: Mode change
4. Sensor Faults:
   - Possible cause: Fault detected in sensor
   - Ramification: Possible incorrect sensor data
   - Response: ??
5. Other

GN&C: SW Components
Propulsion Module (PM)

- **Motor**: Maxon EC45 Flat, 30W
- **Motor drive**: Maxon ESCON Module 24/2
  - 4-Q servo controller for DC/EC motors
  - 2/6 A, 10-24 VDC
- **Nozzle servo**: MKS DS92A+
- **Propulsion Controller** (PMC)
  - 32-bit microcontroller: Microchip PIC32MX795F512H
  - Development environment: MPLAB X IDE v3.10
  - Comm with LLP: I2C bus
  - Impeller motor speed control: Analog voltage
  - Nozzle position control: PWM signal, 333hz data, pulse width of 850µs~2150µs

GN&C
Test Plan – Performance Verification

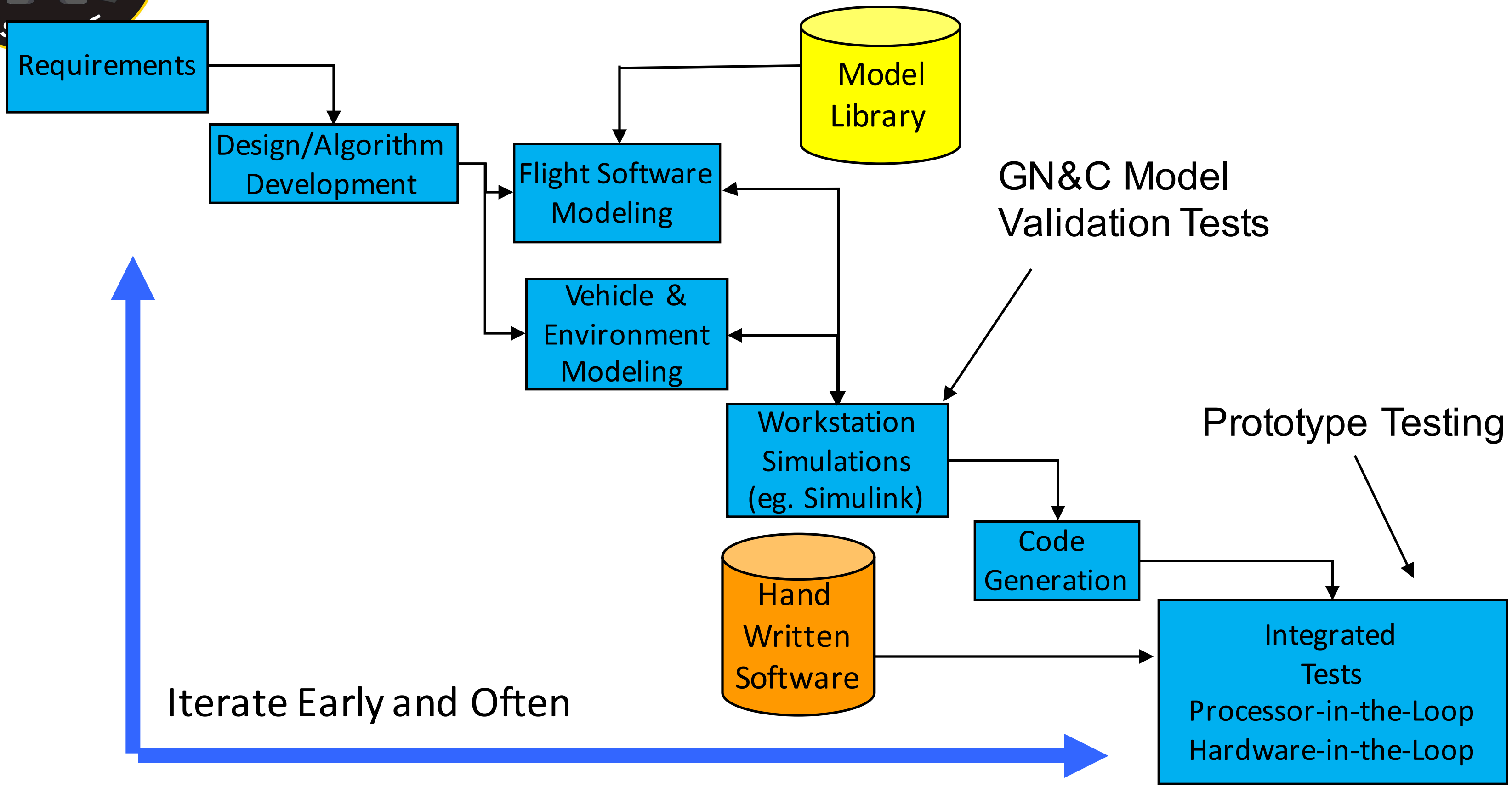
- Granite Table (open and closed loop)
  - Multiple mounting orientations on airbearing
  - Characterizes undesired coupling of axes

- Gantry + Active Gimbal System (open loop)
  - Follow predetermined trajectories and evaluate pose estimate for accuracy
  - Challenges still exist regarding pendulum motion

- (Goal) Gantry + Active Gimbal System (closed loop)
  - Attitude control loop will be closed through the Gantry + Gimbal system to achieve the desired robot motion.
  - Blower speeds and nozzle settings be forwarded to an external system that will model the robot dynamics and calculate the resultant pose of the robot in space.
  - This pose will be commanded to the Gantry + Gimbal system.

- High Speed Test on Smooth Floor or Cart (closed loop)

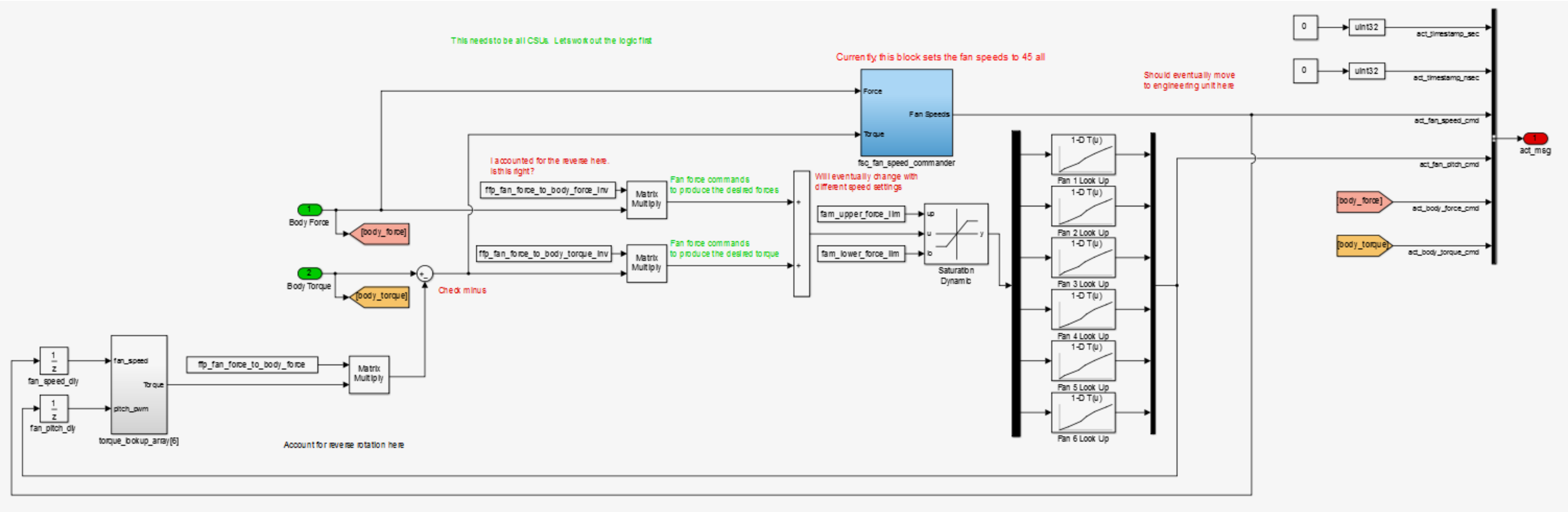
GN&C
Model based design approach



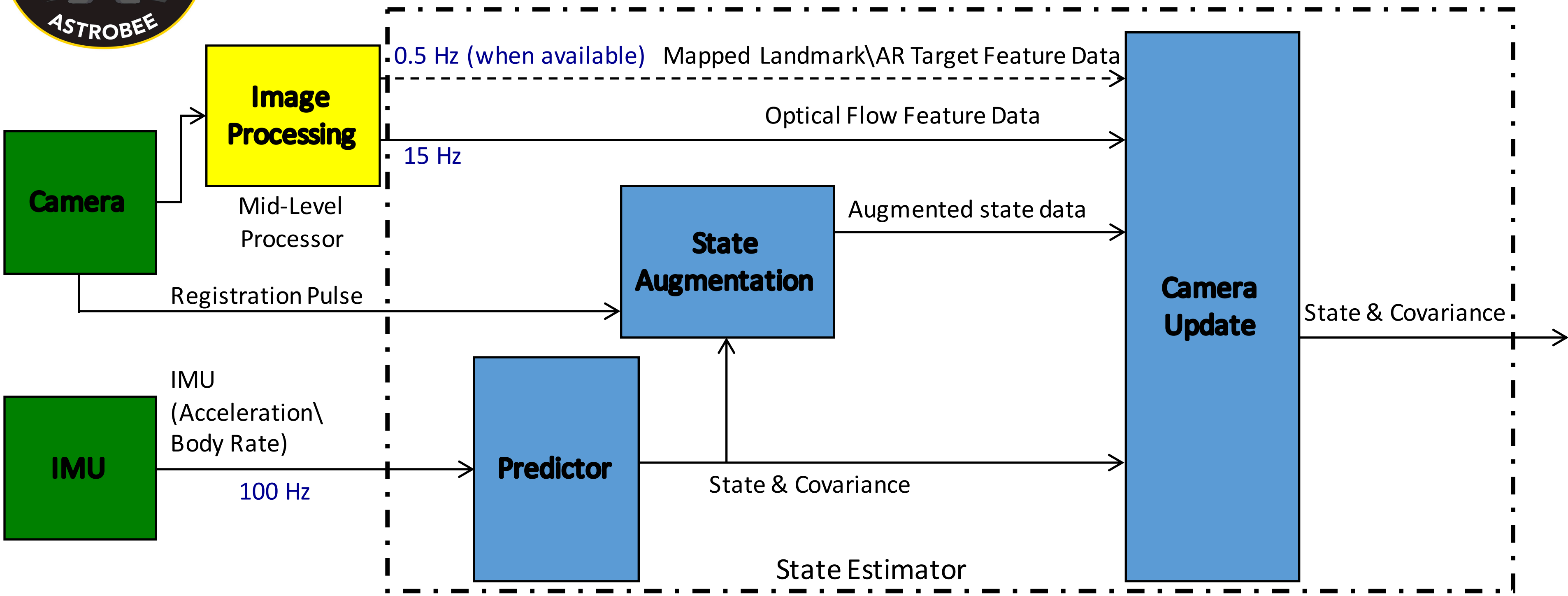
1. Modification of the LADEE GN&C software development approach
2. Develop models of FSW, robot, and environment in Simulink
3. Auto-generation of source code using RTW/EC
4. Integrate with hand-written software
5. Iterate while increasing fidelity of tests – workstation simulation and prototype testing

GN&C: SW Components
Force Allocation Module (FAM)

Proto3 Design (VPP)

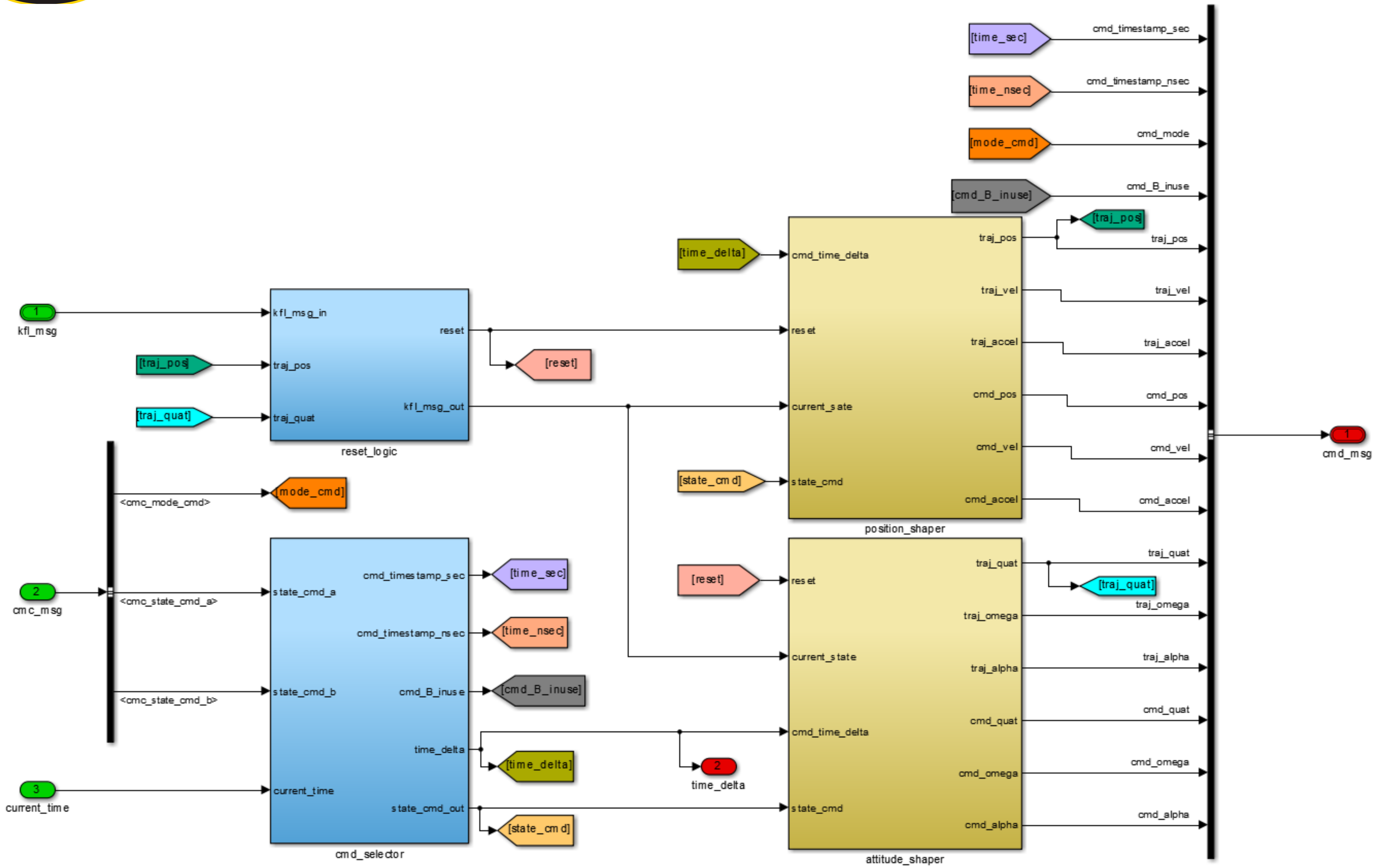


GN&C: SW Components Estimator (EST) – Cont.



- IMU data is used to replace a dynamics model in the predictor, which allows for:
    - Changes to the physical properties of Astrobee
    - Non-actuated pose determination
- Vision data uses the augmented state to calculate errors at the time the image was taken
    - Accommodates large sensor delays
- In nominal operations the mapped landmark features are compared against a map of ISS, optical flow allows the system to move through areas where no features are recognized
- When docking, the AR Target features replace the mapped landmark features inside the estimator

GN&C: SW Components
Command Shaper (CMD)



Astrobee Perching Arm

Design Overview

Team

- In Won Park (ARC-TI)
- Matei Ciocarlie (Columbia Univ.)
- Nghia Mai (ARC-RE)
- Steve Wu (ARC-RE)
- Jongwoon Yoo (ARC-TI)
- Ted Morse (ARC-TI)
- Dong-Hyun Lee (ARC-TI)

Design Drivers

1. Lightweight
   - Mass budget = 200 g
2. Compact
   - Volume = 150 mm x 254 mm x 100 mm
     - Able to stow inside the robot so that it is not exposed to collision hazard while stowed
3. Compliant
   - Arm joints should be fully back-drivable and gripper tendons should relax when it detects large astronaut-induced torques
   - Astronaut should be able to manually open gripper
4. Pan-Tilt Module
   - For a camera attached on the opposite side of the robot to support remote monitoring operations

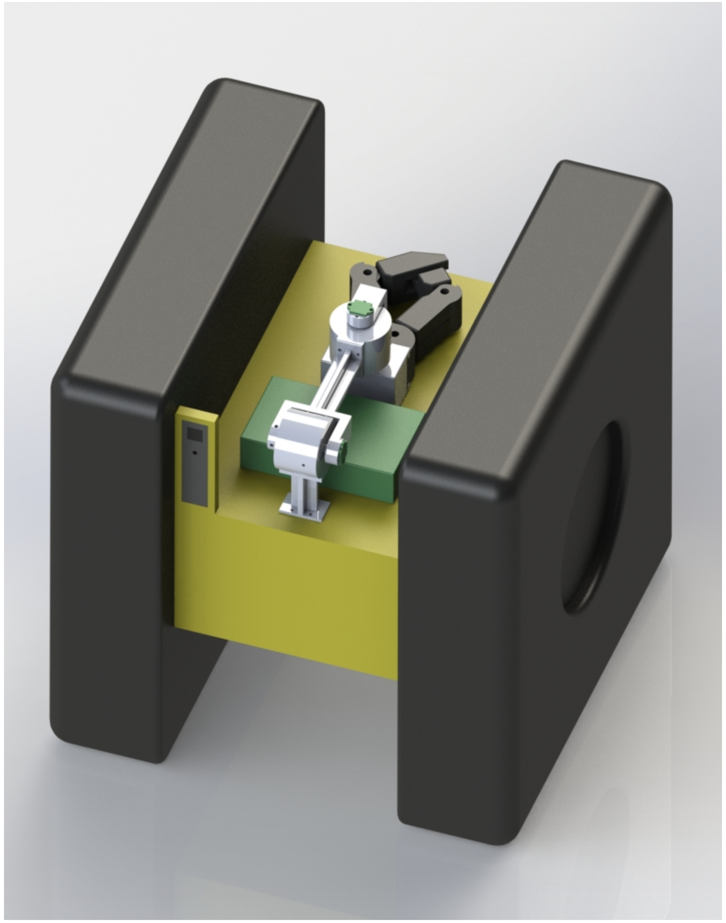
Gripper Trade Study

Options	
Gripper	• Suction (jamming) • Electro-adhesive • Microspine • Gecko-adhesive • Under-actuated tendon-driven

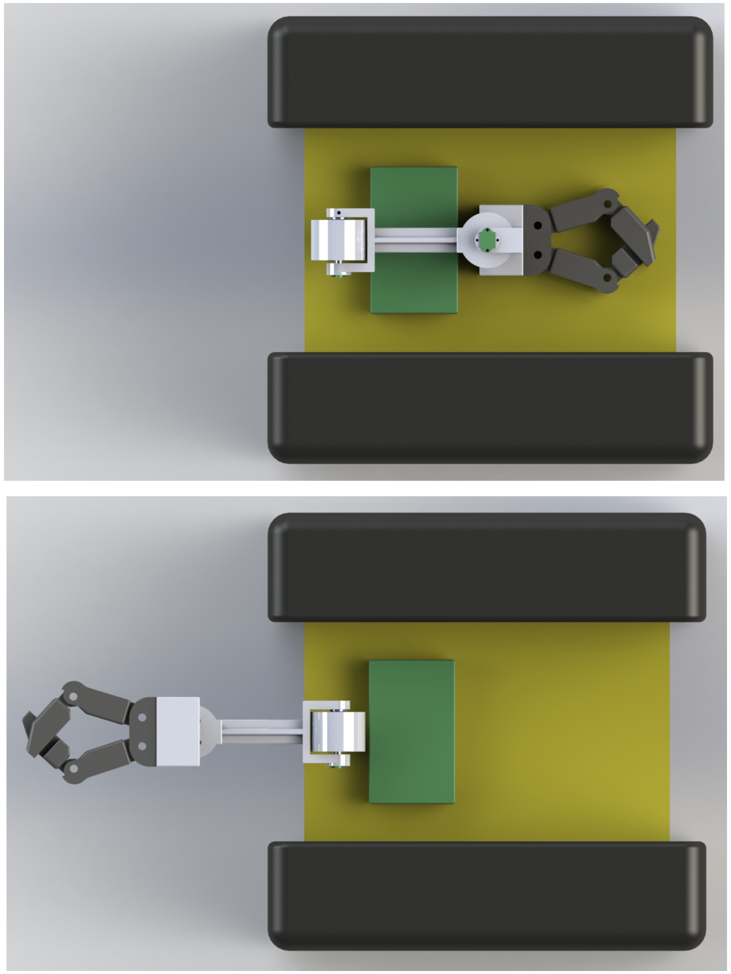
Selected Design

- Gripper :: under-actuated tendon-driven
  - Tendons are biased so gripper passively stays closed; motor is used to open gripper
  - Pros : high technical maturity, small form factor (single actuator), compliant contact with the surface, potentially high adhesion through mechanical clinging
  - Cons : depends on friction of the substrate

Mechanical Design

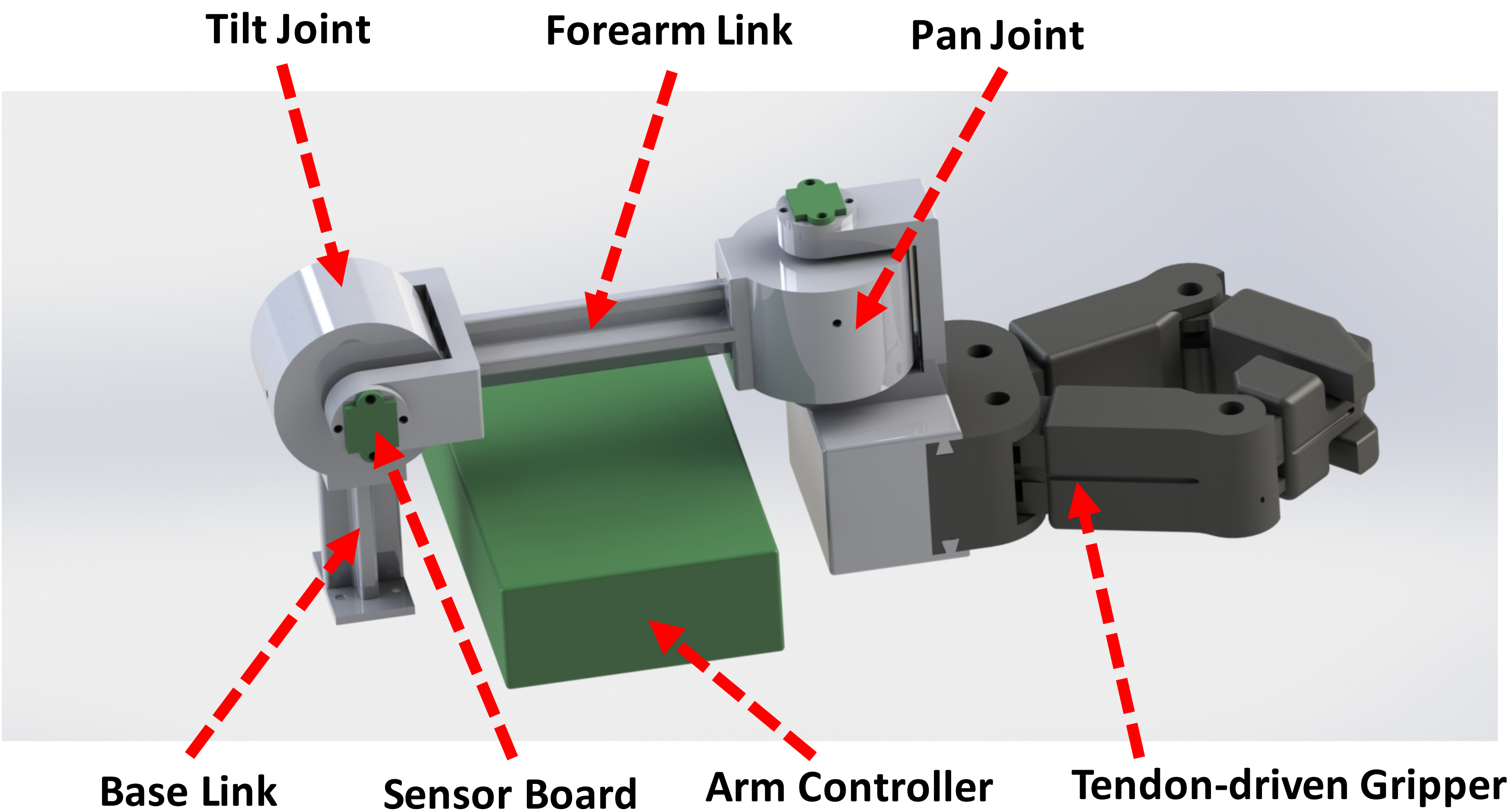


Stowed Configuration
(diagonal view)

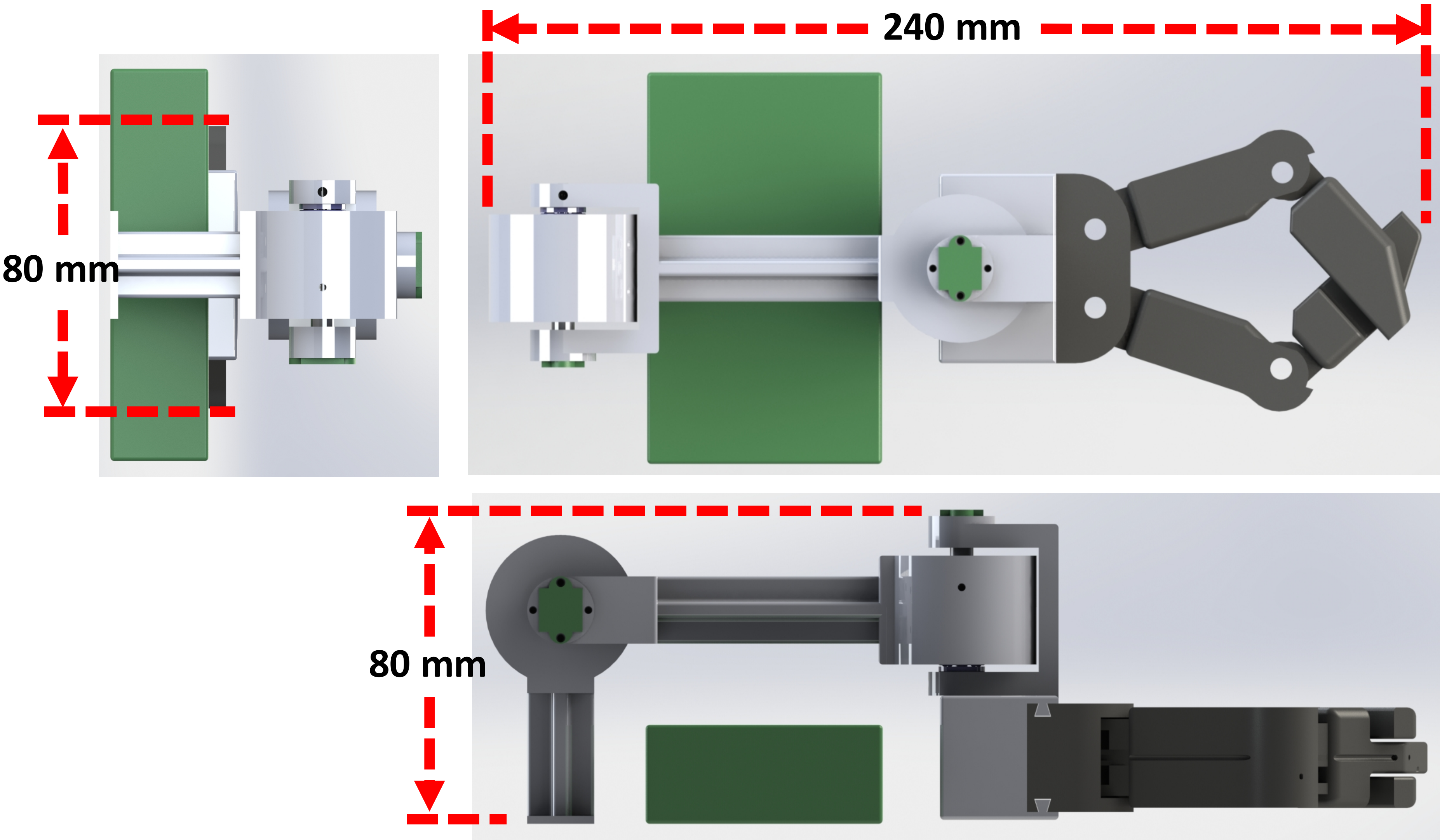


Stowed/Deployed Configuration
(top view)

Component List



Dimension



Estimated Mass

- Three different material options:

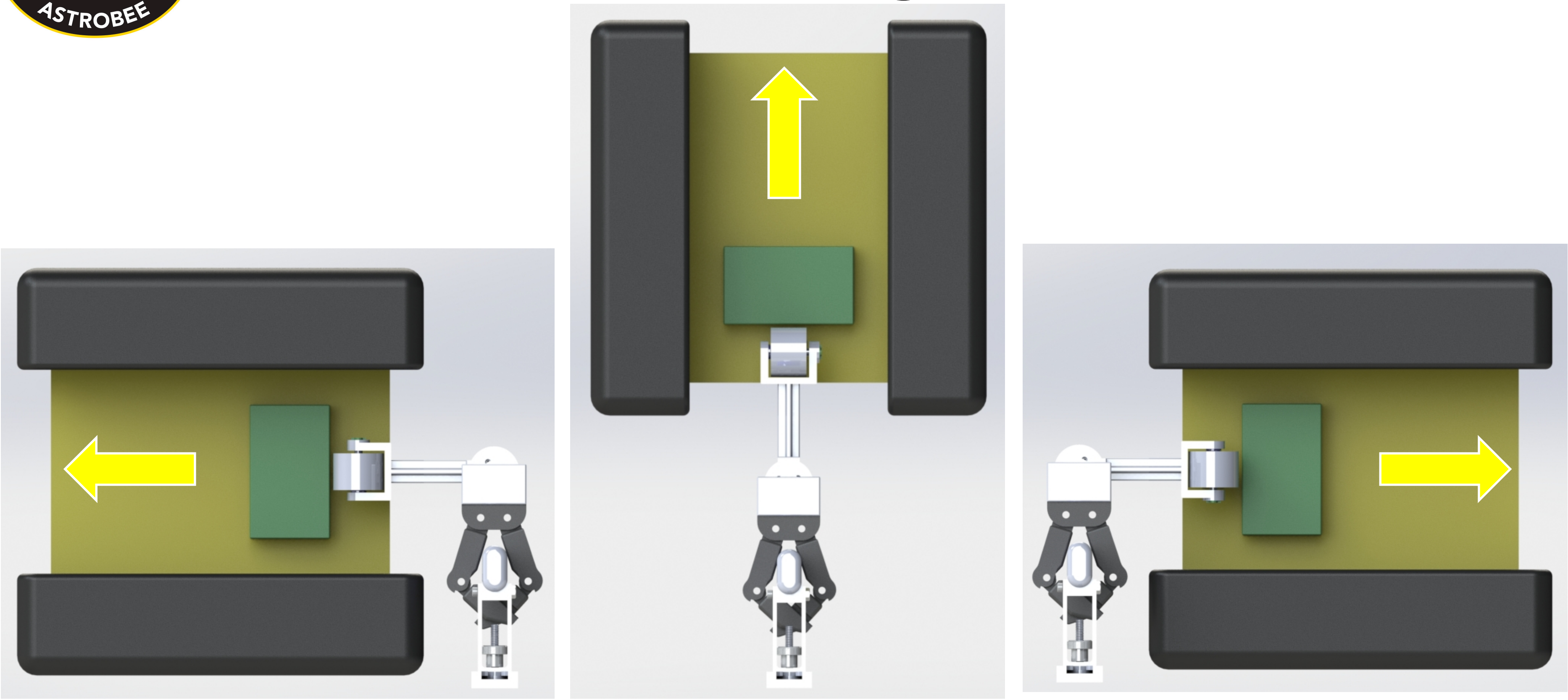
	Base Link	Tilt Joint	Forearm Link	Pan Joint	Gripper	Total [g]	Note
Aluminum	14.89	102.18	21.95	103.84	110.0	352.86	0.002712 g/mm^3
Ultem 9085	7.36	64.15	10.85	64.97	110.0	257.33	0.00134 g/mm^3
Windform XT	6.05	57.52	8.91	58.20	110.0	240.68	0.001101 g/mm^3

- The mass of gripper is equivalent to P3 gripper
- The mass of bearing, bolt, connector board, sensor boards, and electrical wire has not been added

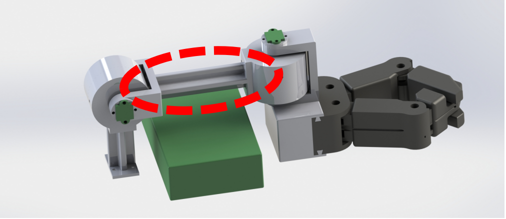
Con-ops of Perching Approach

1. Navigate to perching approach point
2. Confirm handrail is in view and switch to perching localization
3. Deploy arm and open gripper
4. Reconfigure Astrobee's center of gravity and inertia tensor parameters to account for arm deployment
5. Fly along perching approach path (use platform motion to stay on track, no arm motion)
6. In case of a motion anomaly during approach, abort, return to approach point, and retry
7. Upon contact with handrail, allow gripper to close
8. Switch to perched mode (turn off prop system and visual pose estimator to reduce power consumption)
9. Use arm as pan/tilt platform for SciCam on opposite side of Astrobee

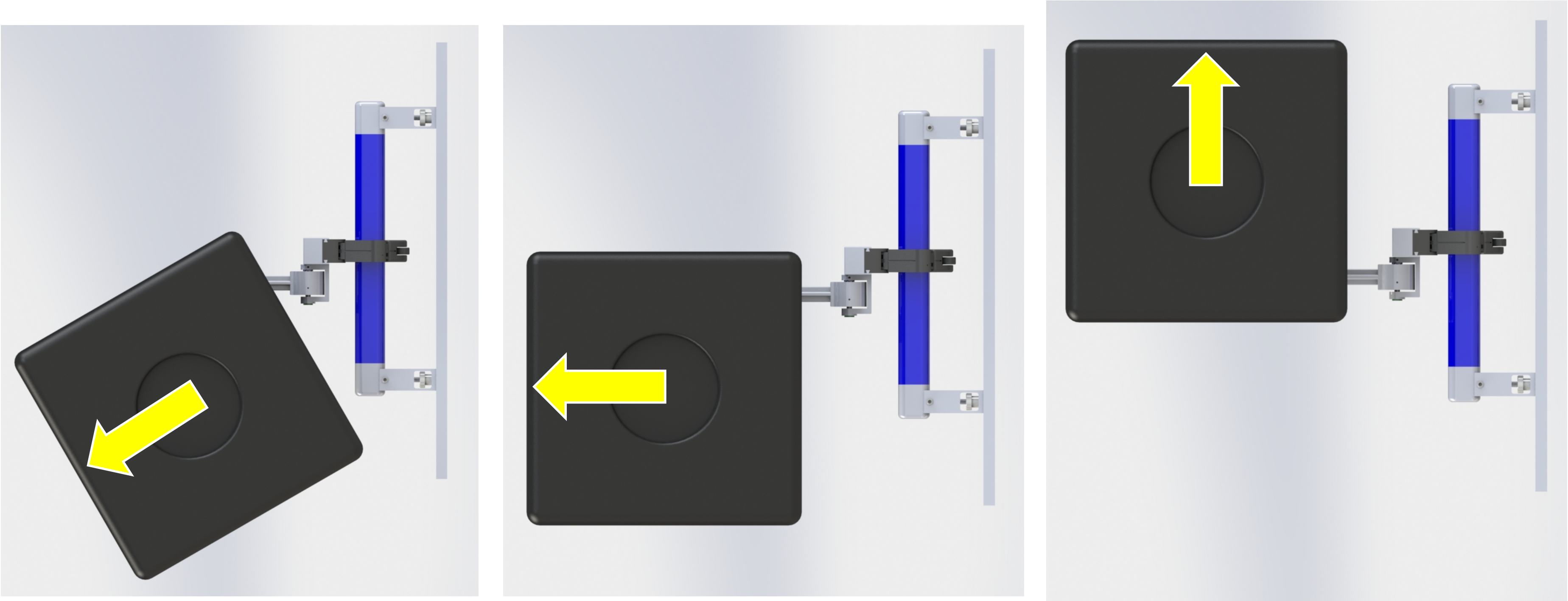
Pan Range



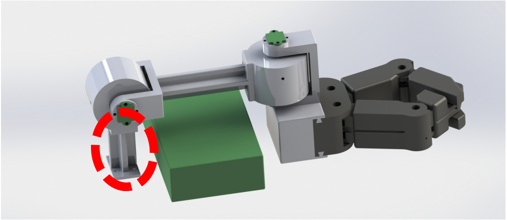
✔ [FFREQ-175] *The perching arm shall pan at least -90° to 90° out from center while perched.*



Tilt Range



✔ [FFREQ-175] *The perching arm shall tilt at least -30° to 90° out from center while perched.*



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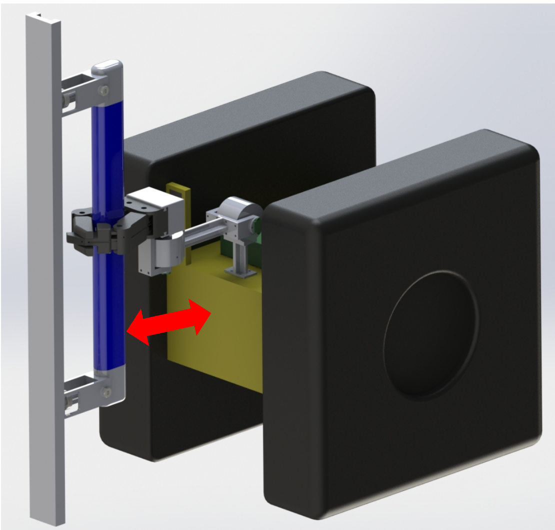
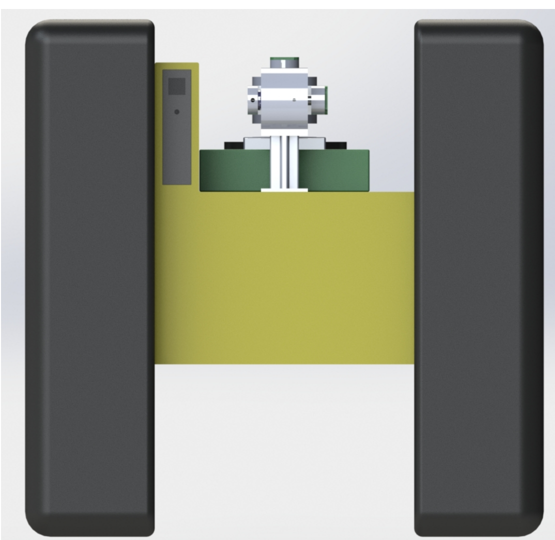
Perch Cam Location





✔ [FFREQ-185] *The perching arm shall be within the view range of perching camera when the arm is deployed.*

- CamBoard Pico Flexx
  - Measurement range = 0.1 ~ 4.0 m
  - Viewing angle (H x V) = 62° x 45°
- The minimum distance between perch cam and handrail is 12.5 cm
- The perch camera is placed in ‘Aft Top Bay’

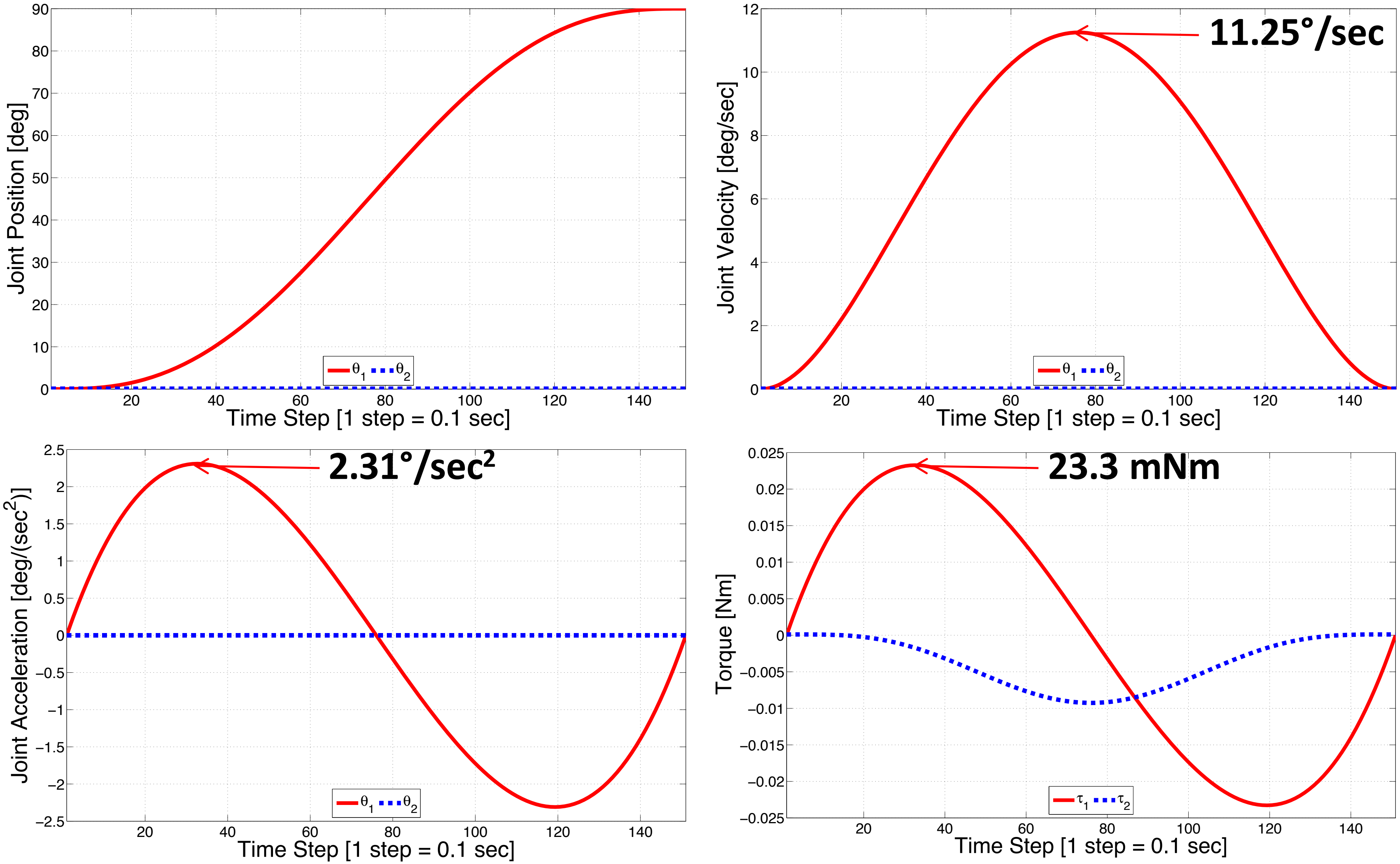
CamBoard Pico Flexx

Motor Selection

- MATLAB Robotics Toolbox is used to obtain kinematics and dynamics
  - Assumed point mass with 6 kg of Astrobee structural mass
  - Assumed micro-gravity environment (9.8E-6 m/s^2)
- Minimum-jerk trajectory is used to obtain position/velocity/acceleration trajectory

✔ [FFREQ-175] *The perching arm shall pan/tilt 90 degrees in 15 seconds.*

Motor Selection



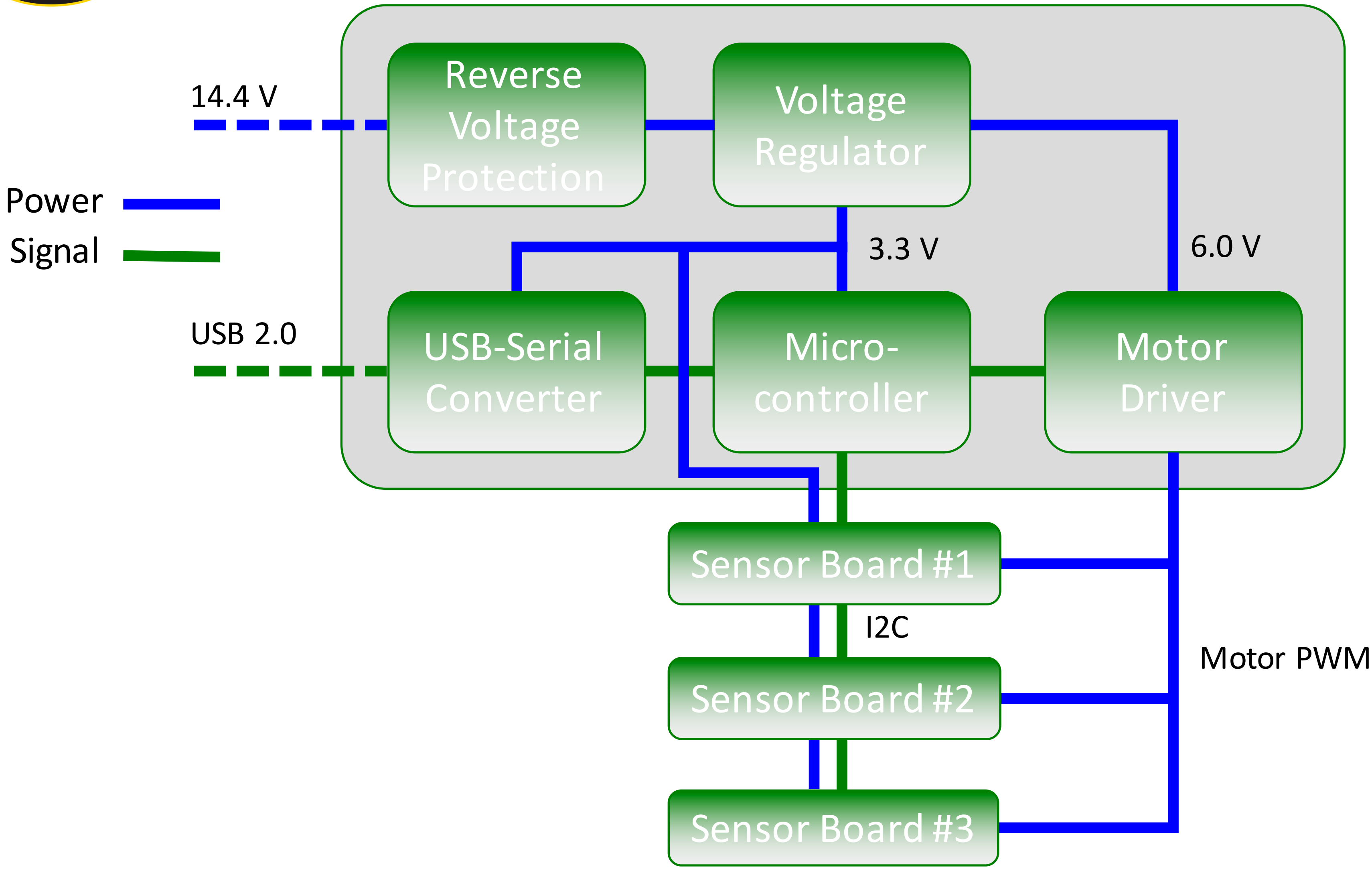
Motor Selection

- Faulhaber 2619
  - DC-geared motor (gear ratio of 112:1)
  - Diameter 26 mm, length 21.5 mm
  - Input voltage = 6V
  - Encoder resolution = 0.05 °/Tick

Specifications

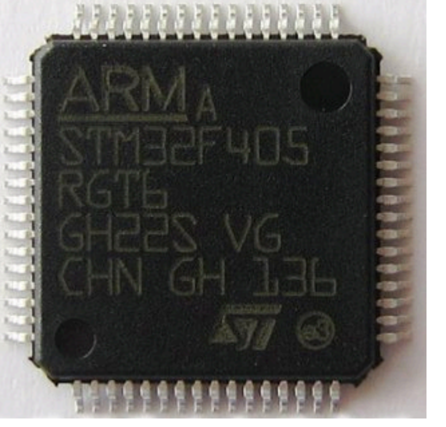
reduction ratio (rounded)	output speed up to n_{max} rpm	weight with motor g	output torque continuous operation M_{max} mNm	output torque intermittent operation M_{max} mNm	direction of rotation (reversible)	efficiency %
8 : 1	635	25	9	30	=	81
22 : 1	223	26	23	75	≠	73
33 : 1	151	26	30	100	=	66
112 : 1	44	27	93	180	≠	59
207 : 1	24	27	100	180	=	53
361 : 1	14	27	100	180	=	53
814 : 1	6	28	100	180	=	43
1 257 : 1	4	29	100	180	=	43

Controller Board Block Diagram



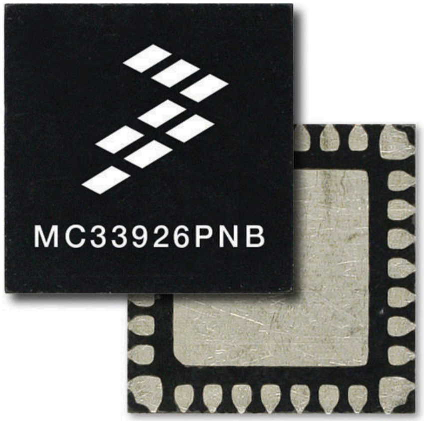
Microcontroller

- STM32F405
  - ARM Cortex-M4 32b MCU+FPU
  - Frequency up to 168 MHz
  - Up to 17 timers
    - 12 x 16-bit timer, 2 x 32-bit timer
  - 6 x QEP module
    - Calculating motor encoder pulse from 3 DC motors
  - 3 x 12-bit A/D converters
    - Calculating input current to 3 motor drivers

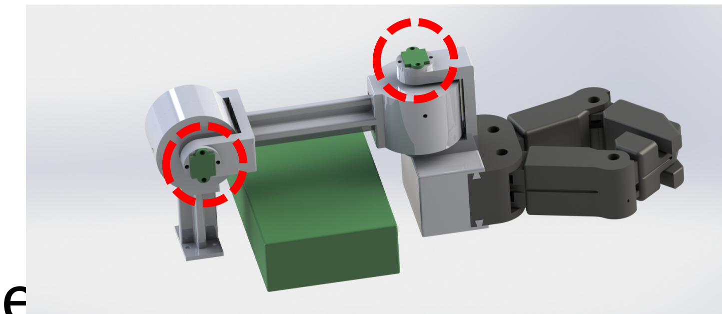


Motor Driver

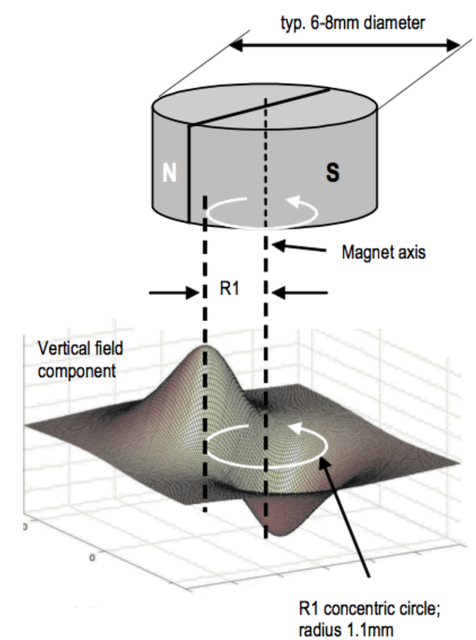
- MC33926
  - 5 V to 28 V continuous operation
  - 3 V/5V TTL/CMOS logic compatible inputs
  - Overcurrent limiting
  - Output short-circuit protection
  - Load current feedback



Magnetic Rotary Encoder



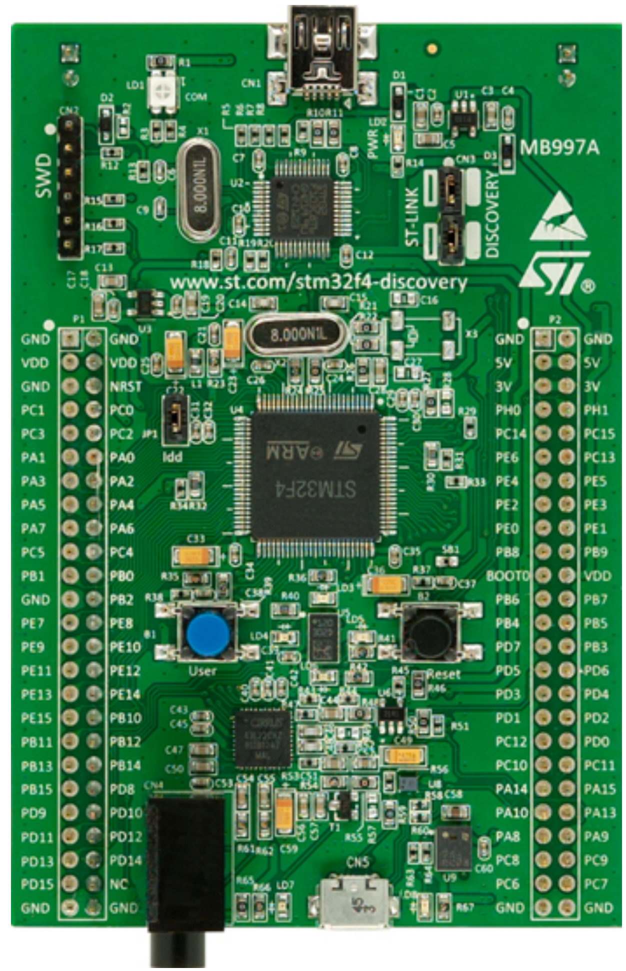
- AS5048
  - Absolute position sensor
  - Contactless rotary position sensor over 360°
  - Measure the absolute position of the magnet's rotation angle with a 14-bit high resolution output (0.05° accuracy)
  - The zero position can be programmed via I^2C command



Remote Software Upgrade

✔ [FFREQ-441] *The Perching Arm shall be capable of updating software.*

- STM32 has the built-in ST serial bootloader over UART or I2C
- Able to compile and upgrade firmware remotely from Linux to STM32F4 Discovery Board using open source cross platform flash program



Astrobee Thermal Subsystem

Design Overview

Subsystem Team

- Jeffrey Feller (ARC-RE, alum)

Design Drivers

- Reject 30 W (max) heat produced by avionics + 5 to 10 W from other components (LEDs, batteries, motors, etc.).
- No gravity-driven convection: forced convection + thermal radiation.
- Temperature limits: Surface touch temperature limit from ISS human factors, max. operating temperatures of components.
- Minimize mass.
- Minimize thermal subsystem power draw and impact on GN&C.
- Avoid complexity.
- Design for reliability, testability in lab (1g), and easy maintenance.
- Thermal safing mechanisms.

Thermal Trade Study

- Passive solution—thermal radiation (primarily) from heat rejection panels: not enough surface area given touch temperature limit.

- Active thermal control concepts considered and ranked:

1. **Direct cooling of avionics boards using dedicated fans.**
   Simple, low mass, low impact on schedule and other sub-systems.
2. **Same as 1, but use air flow bled off from propulsion modules.**
   Low mass, but potentially high impact on propulsion, schedule.
3. **Heat sink components and strap to compact HX; use dedicated fans.**
   Higher mass, higher complexity.
4. S**ame as 3, but use air flow bled off from propulsion modules.**
   Higher mass, potentially high impact on propulsion, schedule.
5. **Heat sink components and strap to HX plates in propulsion modules.**
   High mass (heat sinks, straps), heat rejection capacity and impact on propulsion uncertain.

Thermal Trade Study: Down-Select

	Overall	Impact	Reliability	Effort	Mass	Schedule	Volume	Power	Serviceability	Verifiability	Cost
Priority		1	1	1	1	2	2	2	2	2	3
Option 1	**3.68**	4	4	4	4	4	3	2	4	5	4
Option 2	**3.06**	2	4	3	5	2	4	2	4	4	3
Option 3	**2.94**	4	4	2	3	2	2	4	3	5	2
Option 4	**2.73**	2	4	2	3	2	4	3	3	4	2
Option 5	**2.87**	4	4	2	2	2	4	3	3	4	3

Option 1: Direct forced air cooling of electronics using dedicated fan(s).
Option 2: Direct forced air cooling of electronics using plenum bleed.
Option 3: Heat sink boards to compact HX, cooled using dedicated fan(s).
Option 4: Heat sink boards to compact HX, cooled using plenum bleed.
Option 5: Heat sink boards to thermal bus, link bus to HX plates in plena.

Scores	
5	Very good
4	Good
3	Average
2	Poor
1	Very poor

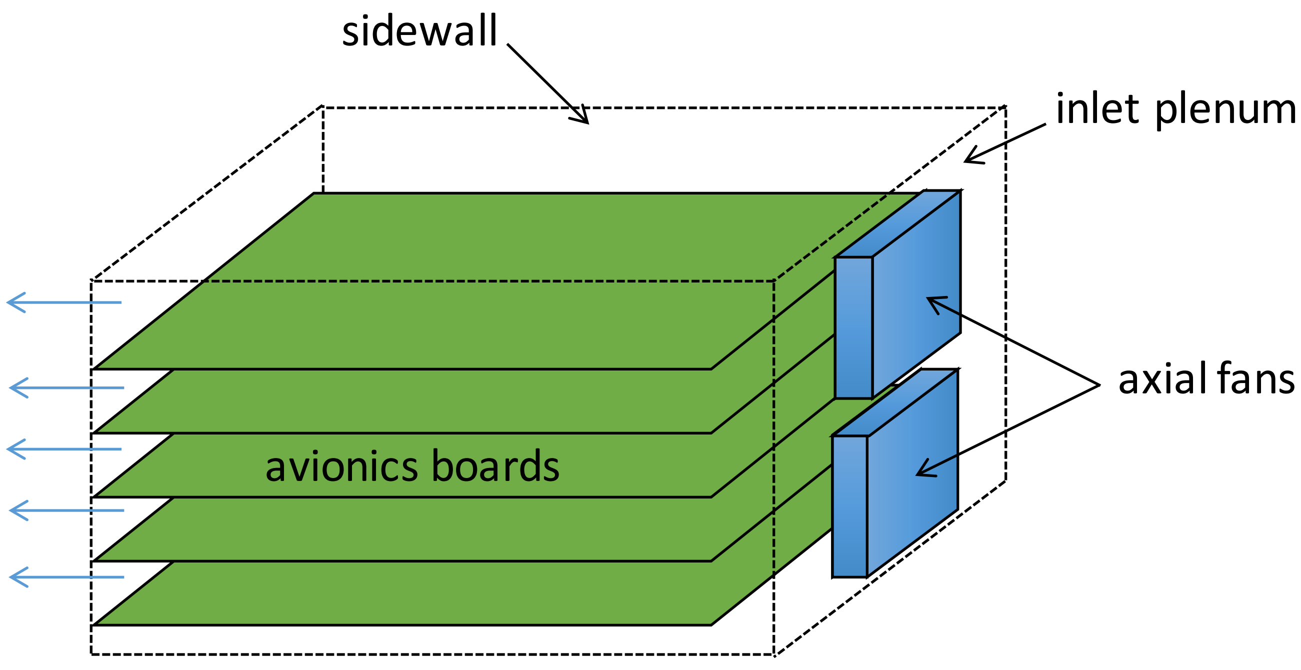
Priorities	
1	High
2	Medium
3	Low

- **Down-select to Option 1: Direct forced-air cooling of avionics boards and other components using dedicated fans.**
- Reject heat from propulsion motor housing to heat rejection plate at plenum wall (partial Option 5).

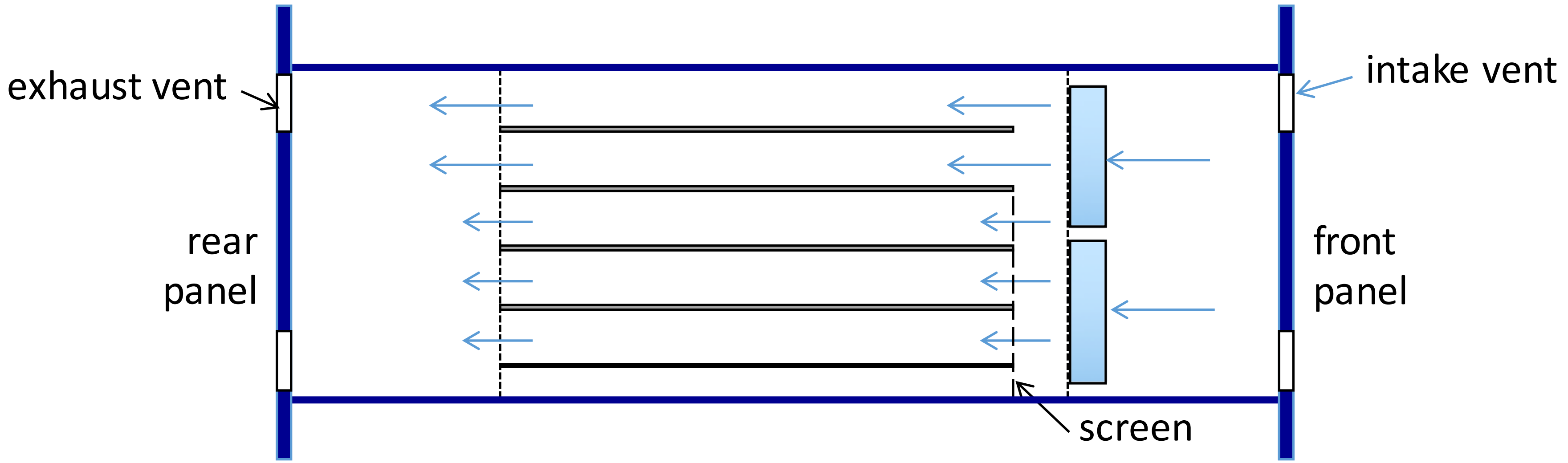
Forced-Air Design Concept

- 5 boards, dimensions 5.6” long X 3.6” wide X 1/16” thick.
- Board spacing: ~ 0.6”.
- “Avionics box”: 5-board stack enclosed by Kapton (?) shell.
- All boards cooled by forced convection. No heat-sinking to external (external to avionics box) heat exchangers. Air flow along the long dimension.
- Aluminum HX plates bonded to processors for increased surface area.
- Two counter-rotating (if necessary) axial fans.
- Redundancy; e.g., if one fan fails, remaining fan can cool all boards, perhaps at reduced capacity.
- Lower flow impedance across high-power processor boards → higher flow: $\Delta P = R_{flow} U$.
- No external (to avionics box) ducts. Intake and exhaust through perforated walls. Bulkhead isolates intake from exhaust.

Baseline Design Concept



Baseline Design Concept

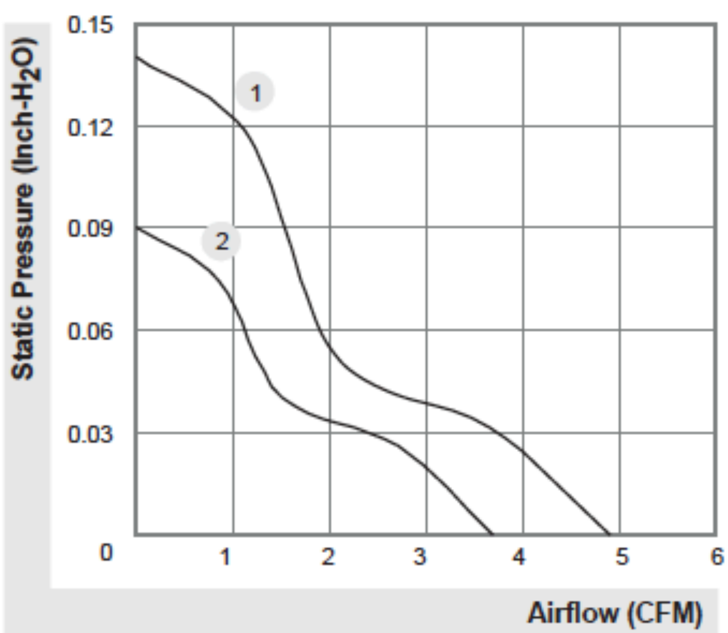


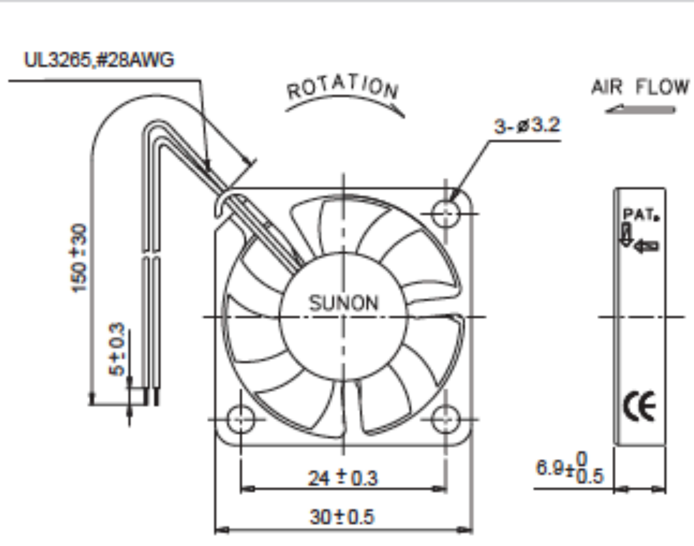
- Top boards: High power density processors:
  LLP (3.5 W max), MLP and HLP (10 W max each).
- Flow rate disproportionately higher across top boards—flow impedance (screen or perforated plate) limits flow to low-power boards.
- Total flow required ~ 7 CFM.
- Exhaust temperature ~ 34 C at max power (< max. touch temperature: 40 C).
- Counter-rotating fans have not been identified—may require custom build.
- Filters or 0.04” screens mounted behind intake vents.

DC Axial Fans

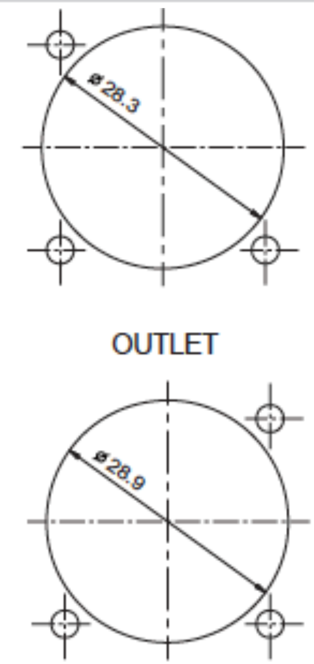
Dimensions: 1.2” x 1.2” x 0.24”

	P/N	Bearing ● VAPO	Rating Voltage (VDC)	Power Current (AMP)	Power Consumption (WATTS)	Speed (RPM)	Air Flow (CFM)	Static Pressure (Inch-H_2O)	Noise (dBA)	Weight (g)	Curve
GM0503PEV1-8	N.GN	●	5	0.13	0.7	9500	4.9	0.14	28	6	1
GM0503PEV2-8	N.GN	●	5	0.08	0.4	7500	3.7	0.09	24	6	2





(Units : mm)



External Heat Sources

- Other heat sources: External to avionics box (LED lamps, display, batteries, etc.).

- LED lamps on front and back panels. Up to ~ 5 W each. Heat sink to fins mounted at intake/exhaust vents.

- Low-power components (batteries, display): Thermal radiation and “natural” convection (cabin air flow); sink to heat exchanges in flow path if necessary.

- Propulsion motor housing: sink to HX plate on inside wall of plenum.

Safing Modes

- Electrical fuses.

- On-board software monitors component temperatures—ramps down power until safe steady-state temperature reached.

- Thermal fuse cuts power if max temperature exceeded.

Astrobee Dock Mechanical Subsystem

ISS ROBOTIC FREE FLYER

ASTROBEE

Design Overview

Subsystem Team

- Rafael "Omar" Talavera (ARC-RE, Lead)
- Hugo Sanchez (ARC-RE)

- Travis Mendoza (ARC-RE, Intern)

Design Drivers

- Two Free Flyer berths
- Battery charging
- Autonomous docking
  - 5deg angular error
  - 1cm position error
- Human Factors
  - Kick loads while docked
  - Connector pin protection
- Location within ISS
  - Determined by Topology Group
  - Will constrain volume and keep-out zones

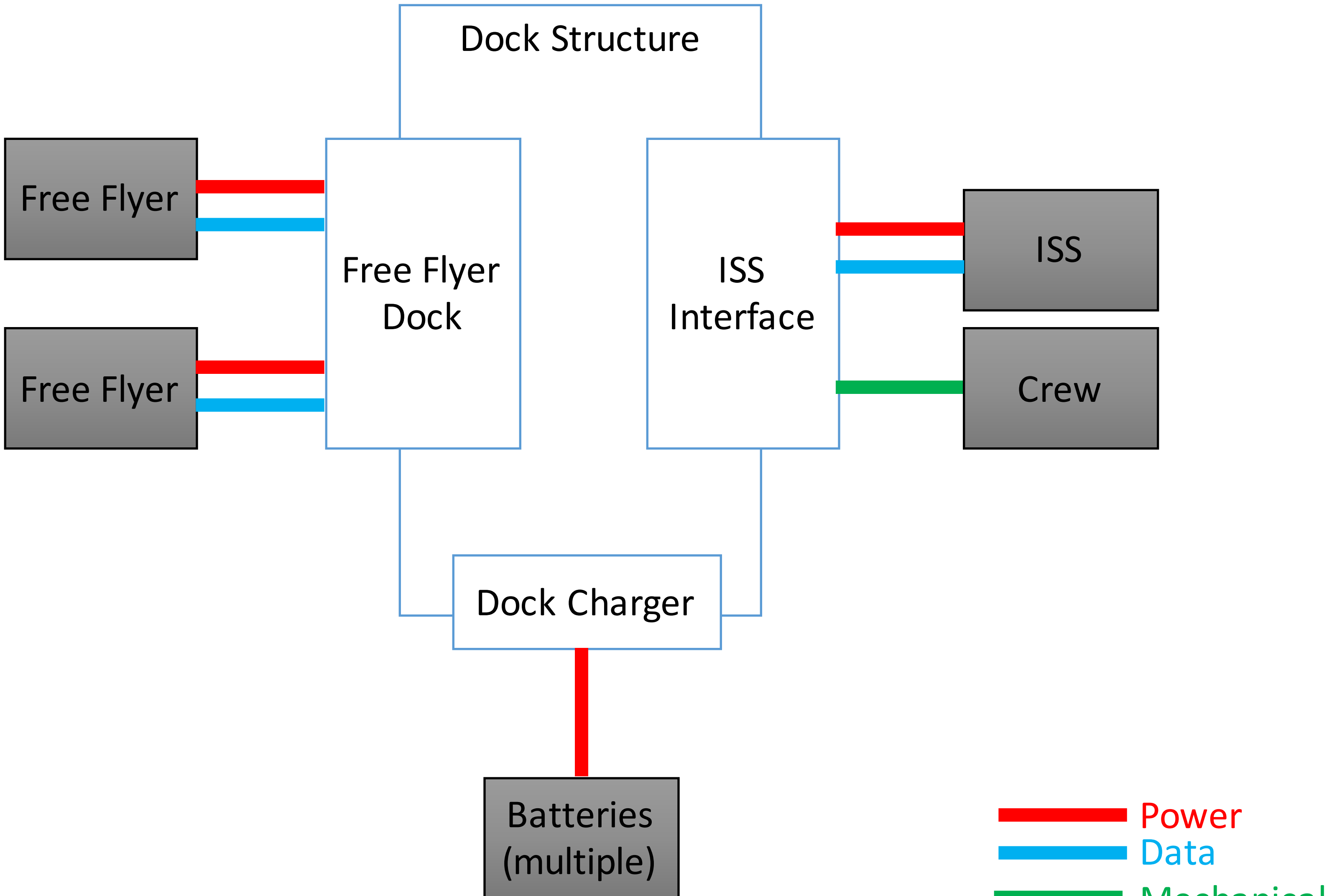
Trade Study

Attributes	Options
Lance	• Cone • Cone and cylinder • Cone, cylinder, and head
Retention System	• Magnet and linear actuator • Electromagnet
ISS Mounting	• Single Seat track • Double Seat Track • Velcro

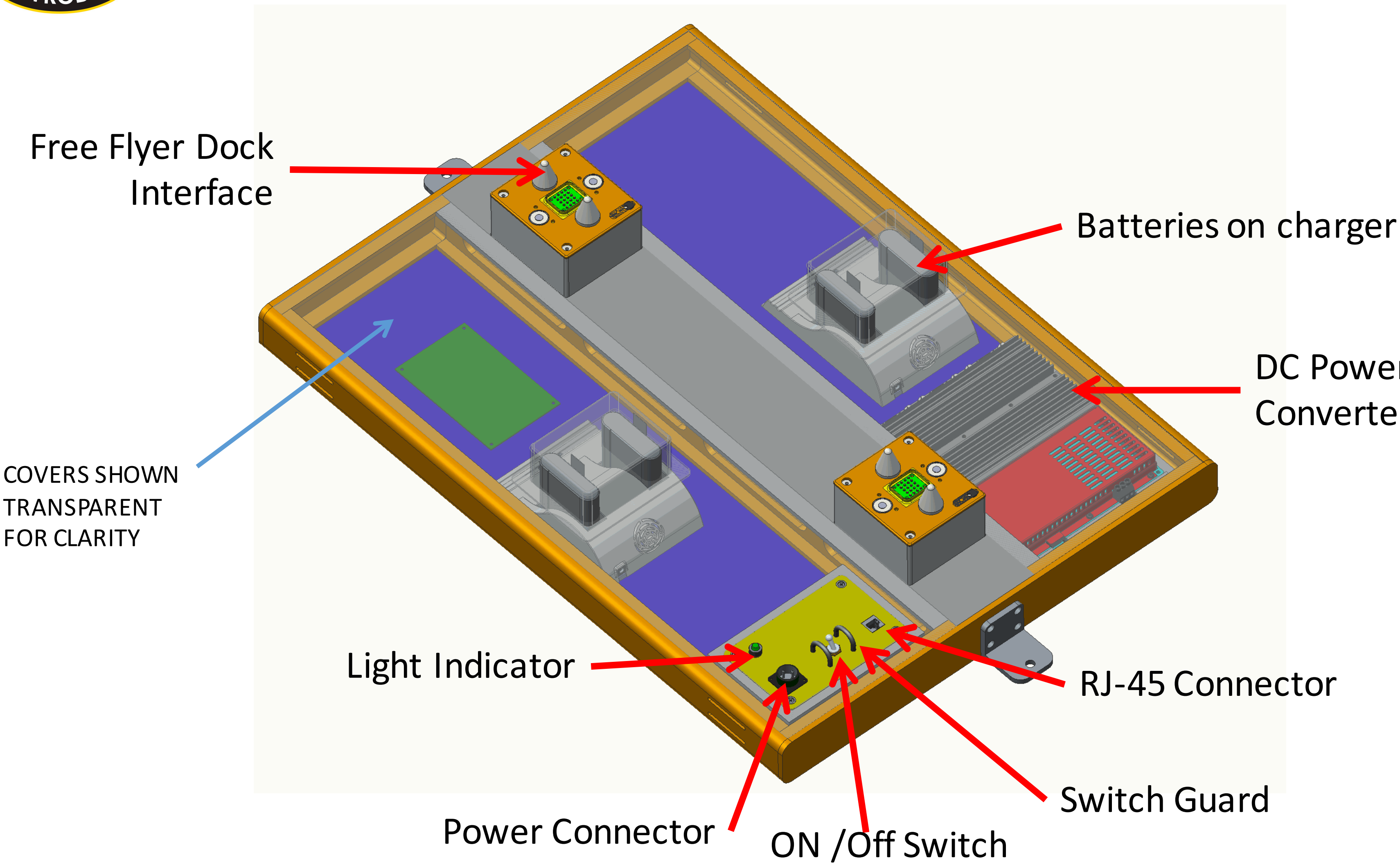
Selected Design

- **Cone shaped lance**
  - Pros
    - Easy detachment in case of lateral kick load
  - Cons
    - Less precise position near final engagement
- **Double seat track mounting**
  - Pros
    - Preliminary approval from ISS topology group
    - Secure mounting
  - Cons
    - Limited mounting options on ISS

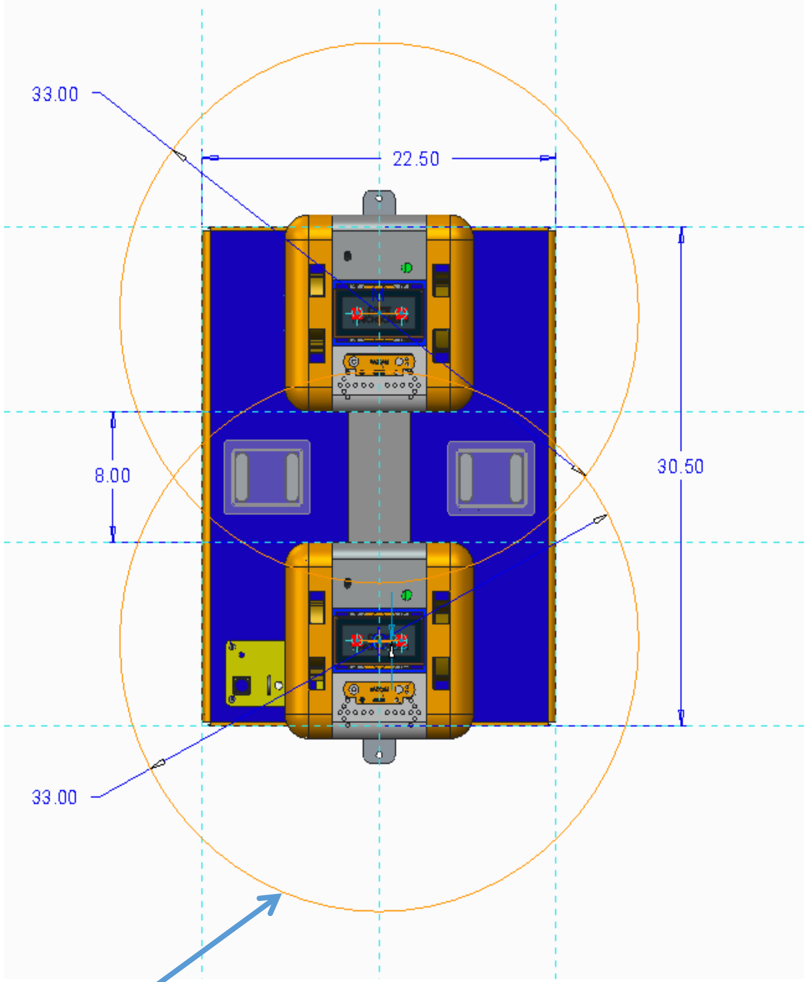
Architecture Diagram



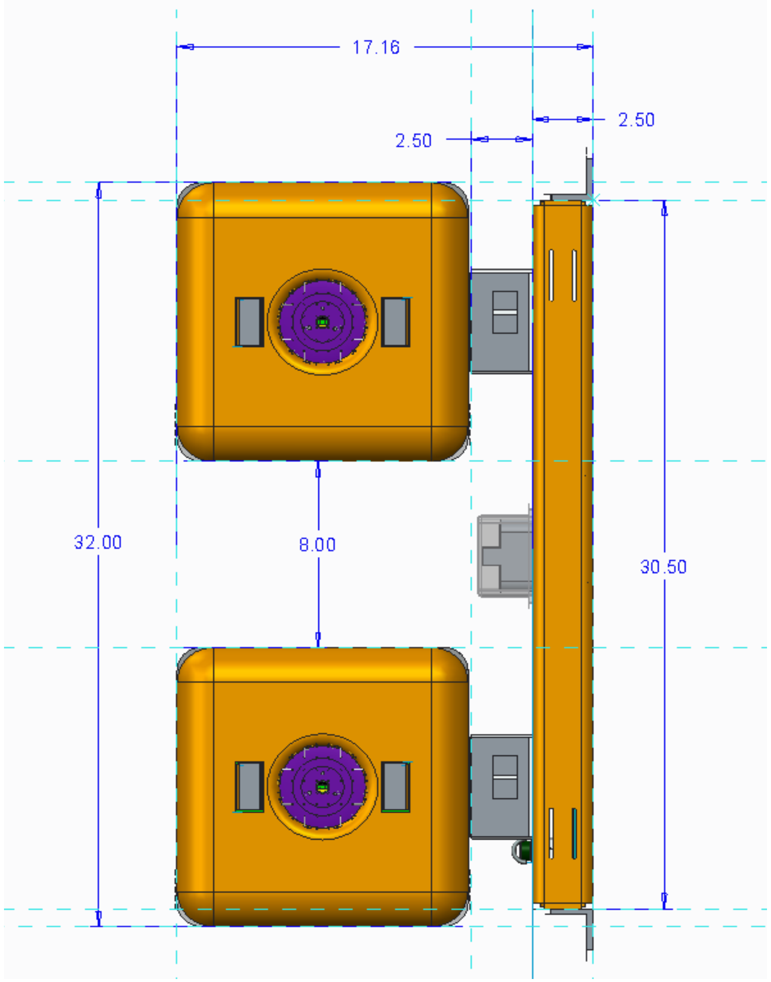
ISO View - Dock



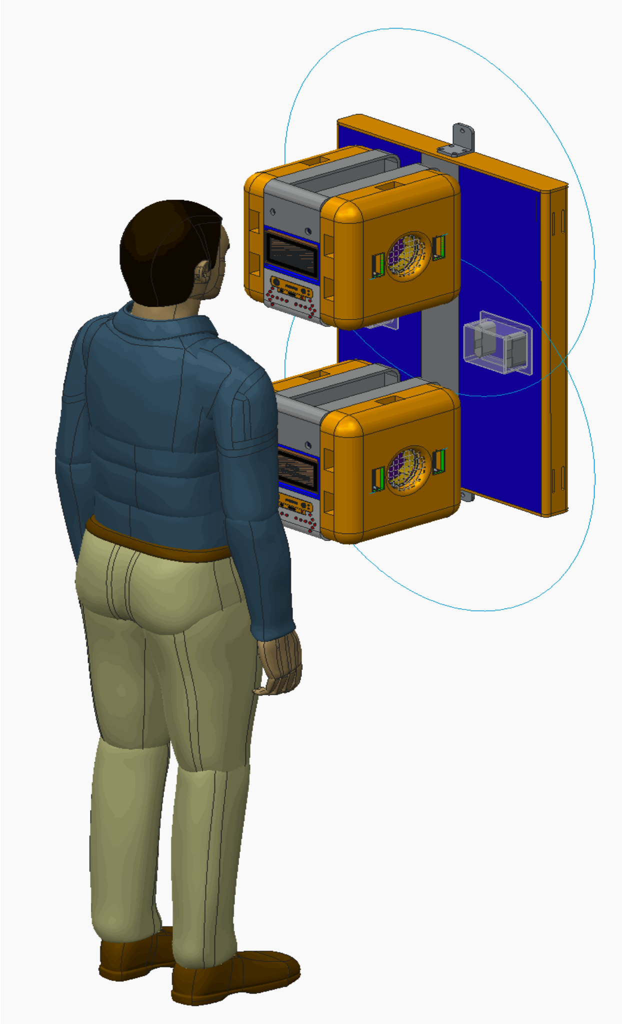
Flyer and Dock
Front and Side View

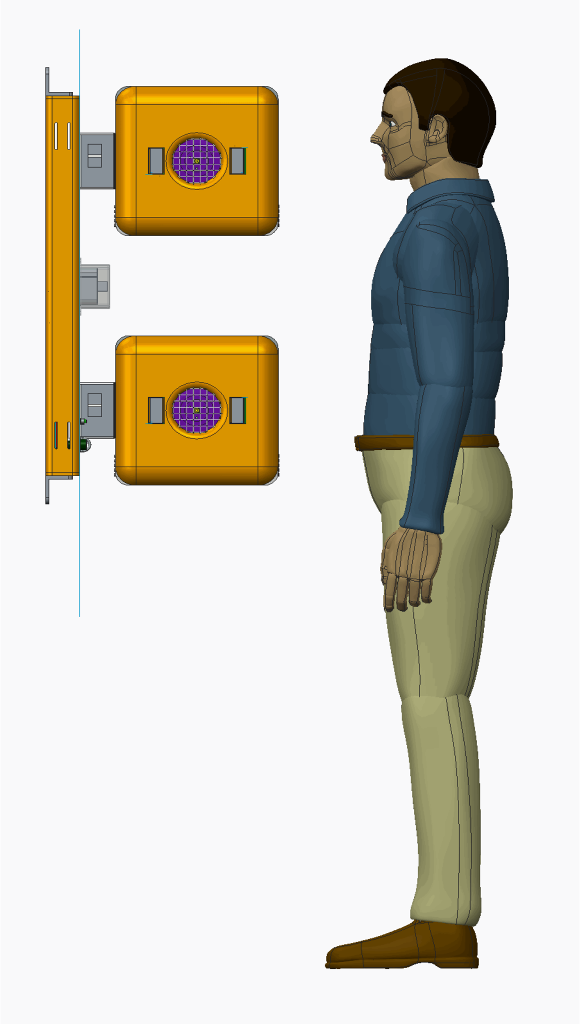


KEEP OUT ZONE

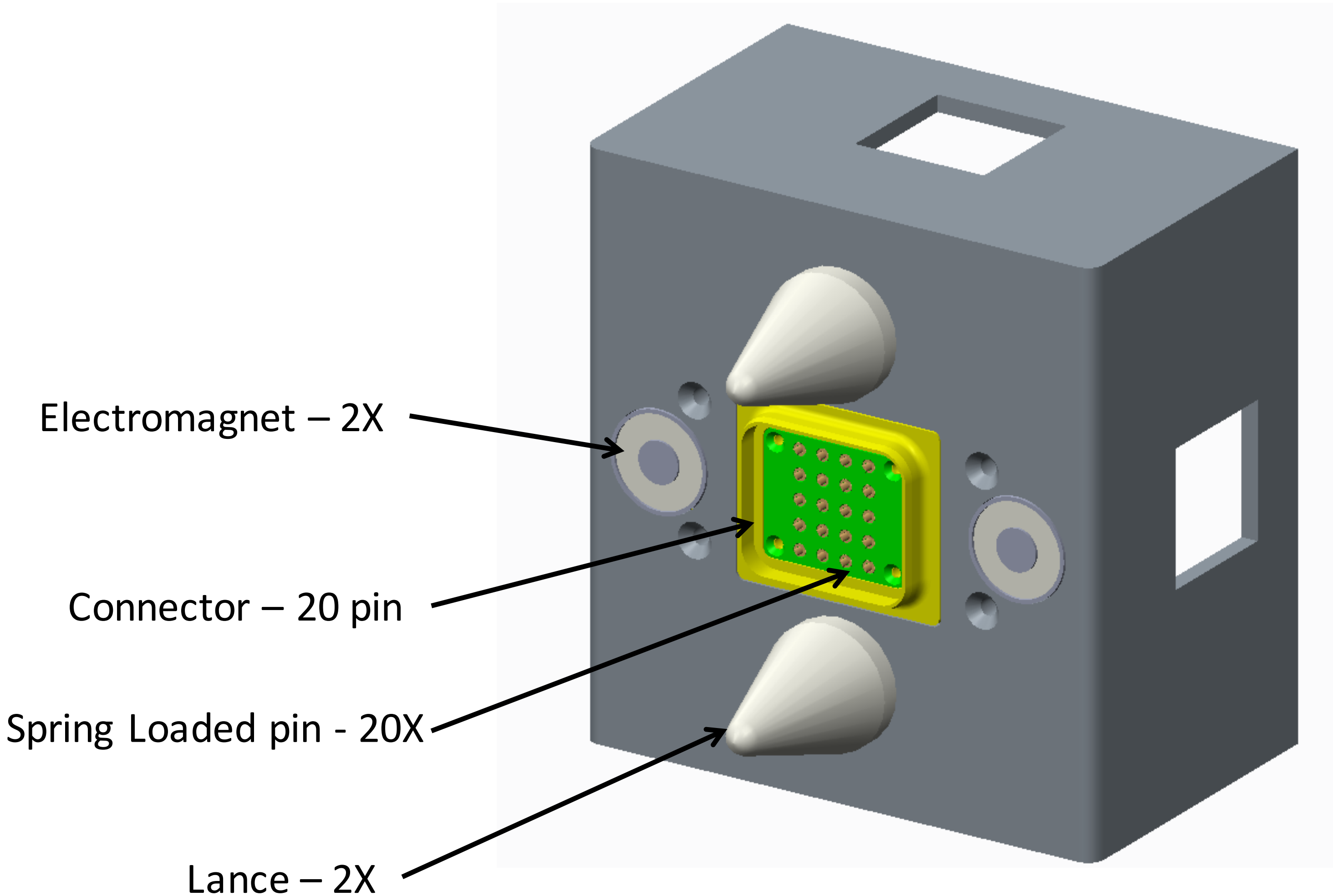


Flyer and Dock

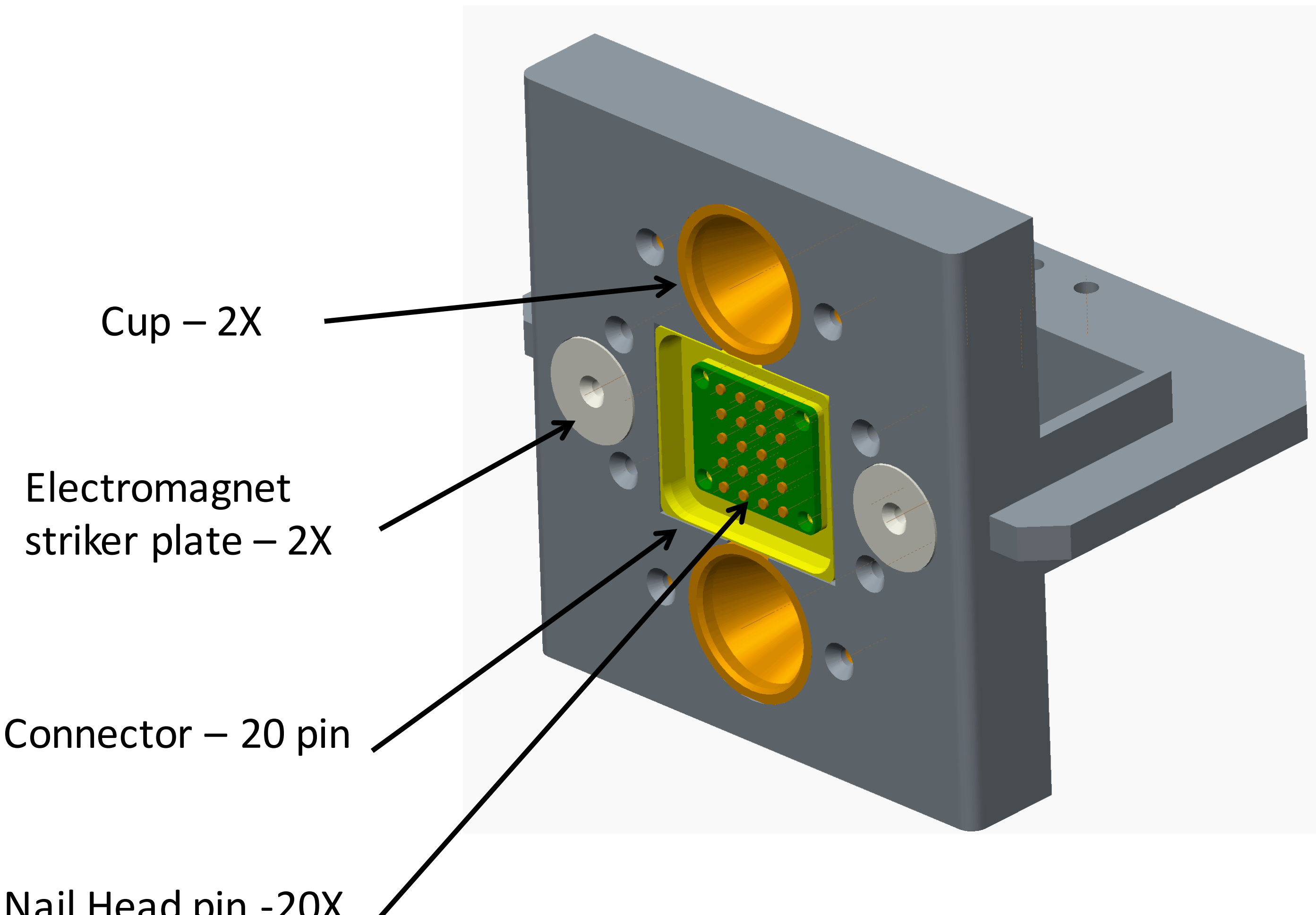




Free Flyer Dock Interface

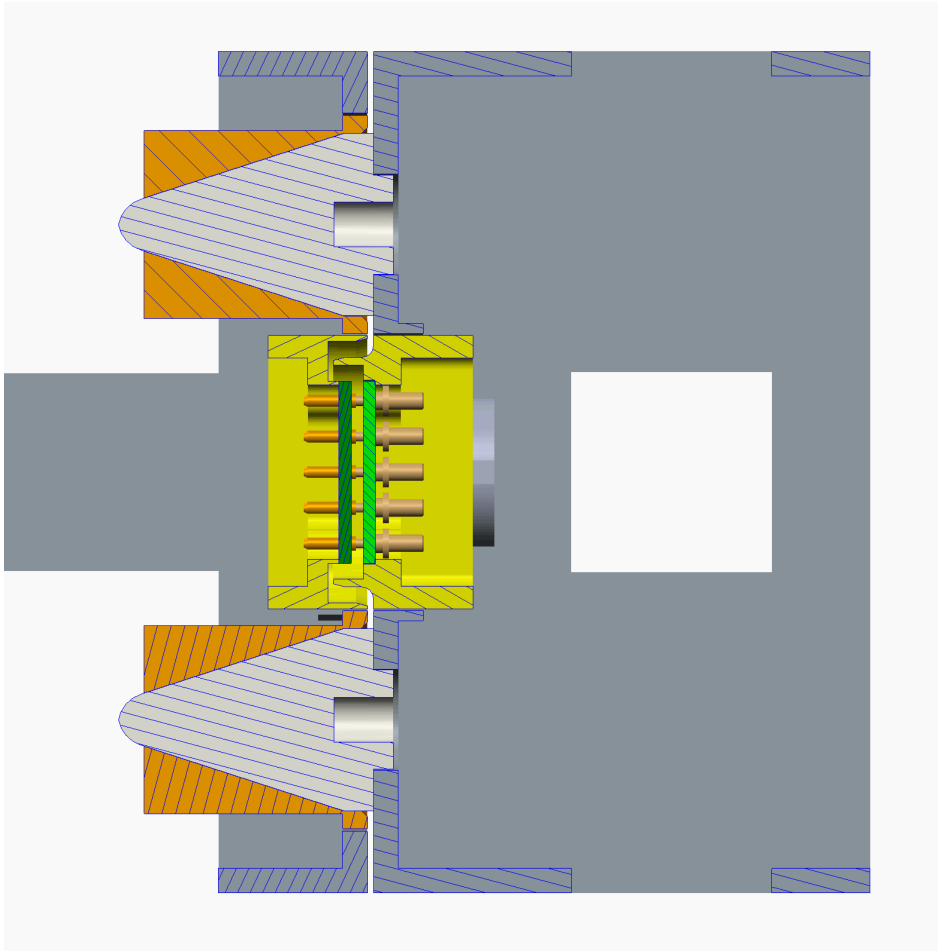


Dock Adaptor (on Free Flyer)



Cross-section
Full Dock

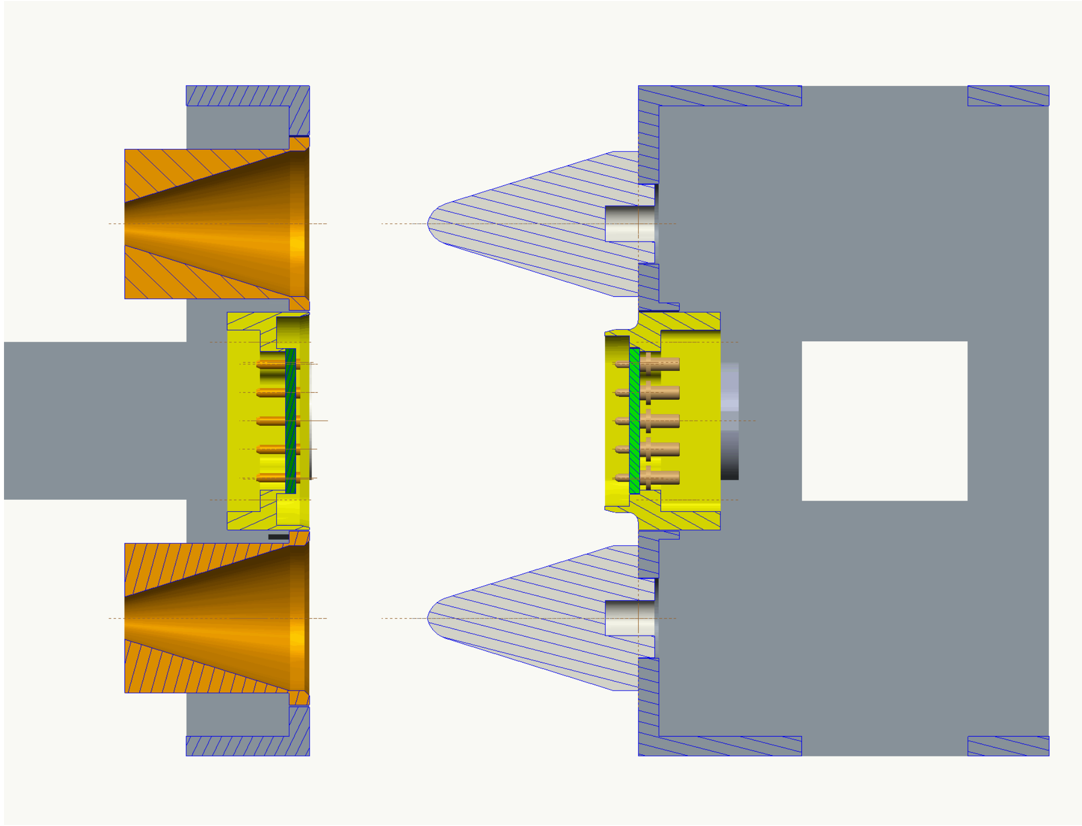
Flyer Side



Dock Side

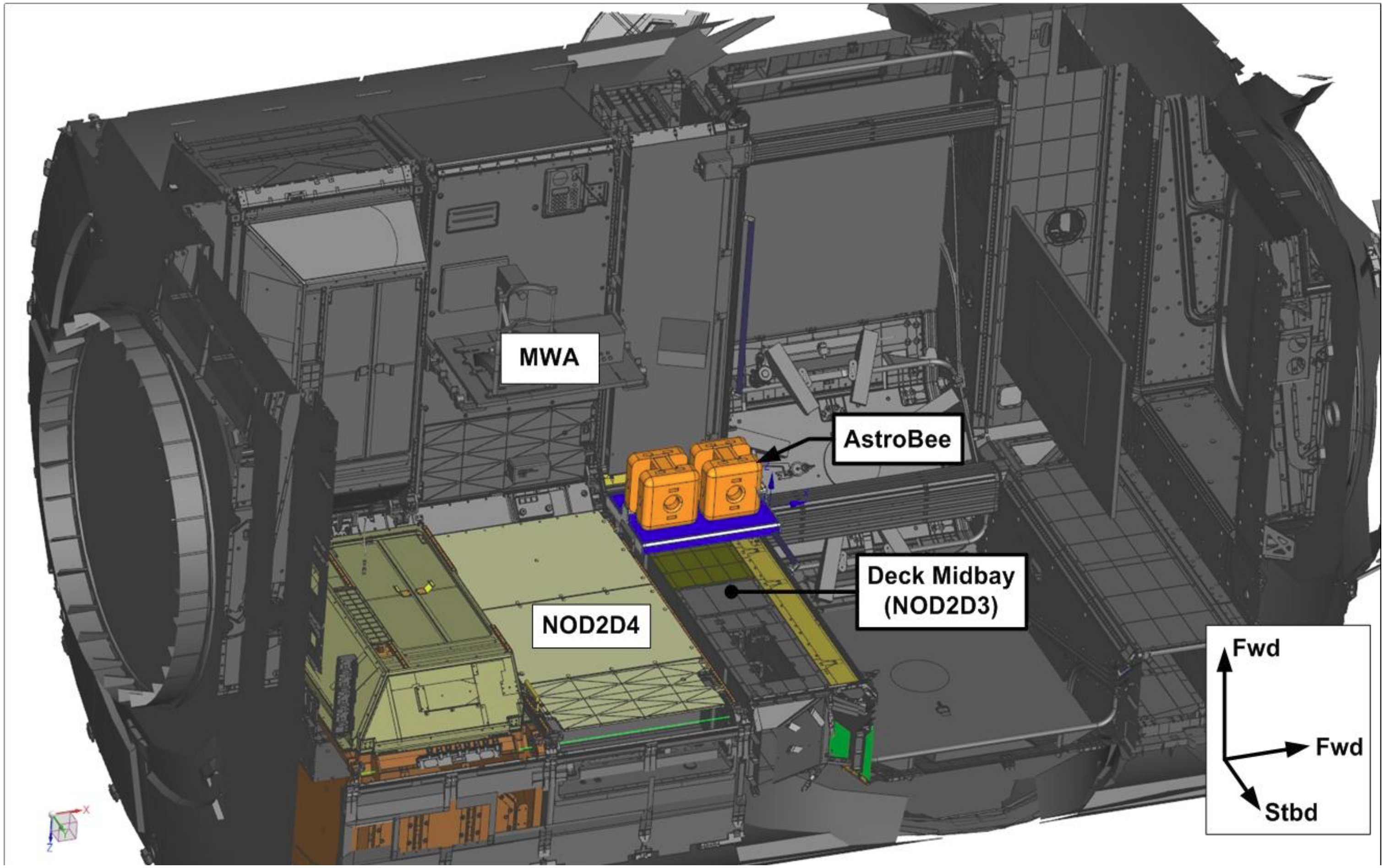
Cross-section Cont.

Astrobee Side



Dock Side

Dock Placement Study



Astrobee Dock Avionics Subsystem

Design Overview

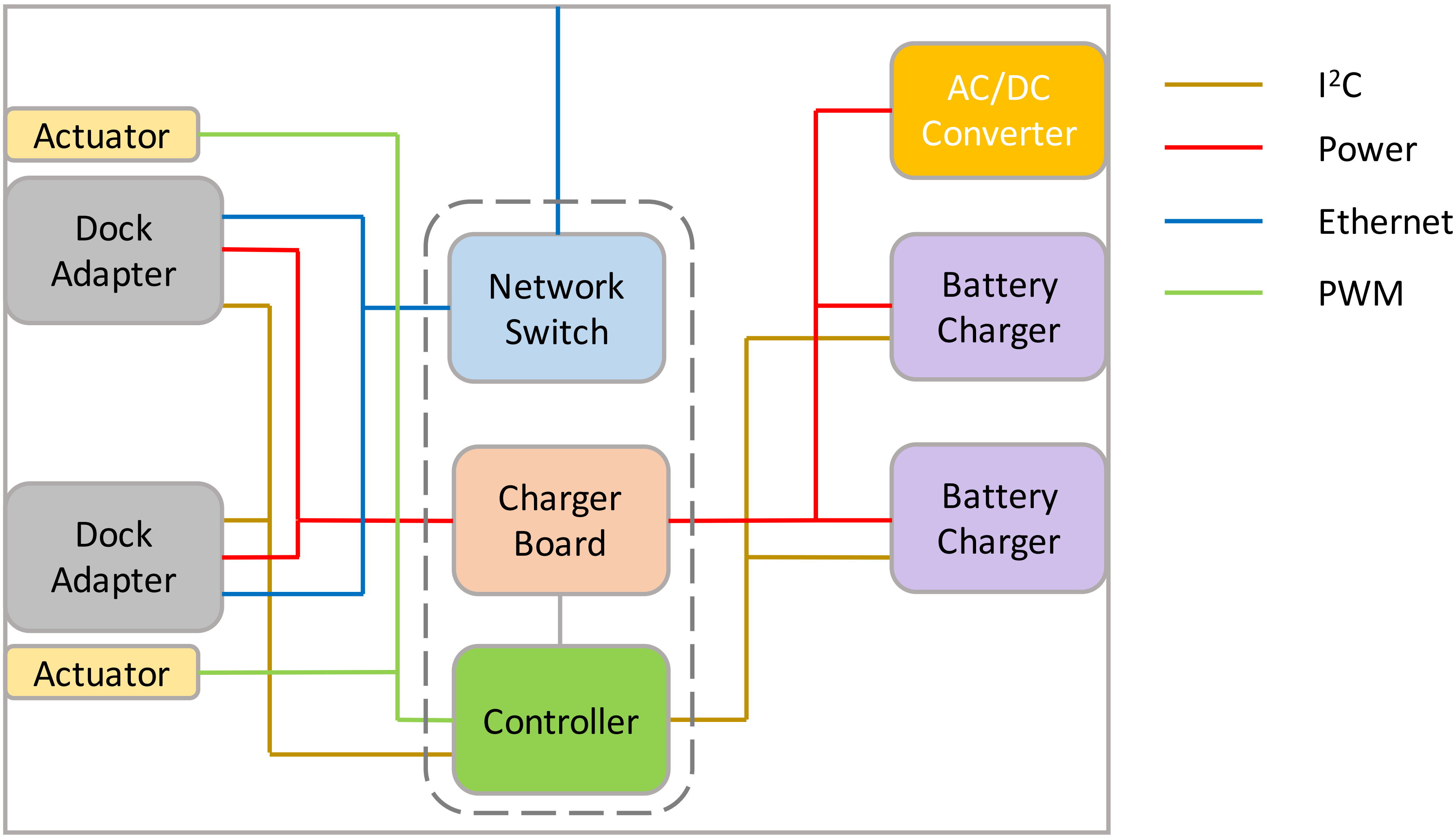
Subsystem Team

- Dmitriy Arbitman (ARC-RE)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE)
- Brandon Gigous (ARC-TI, Intern)
- Jason Lum (ARC-TI)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)
- Vinh To (ARC-TI)

Design Drivers

- Provide power to Astrobee
- Provide wired network
- Power and network without crew interaction
- Charge additional batteries
- Modular

Architecture Diagram



Component List

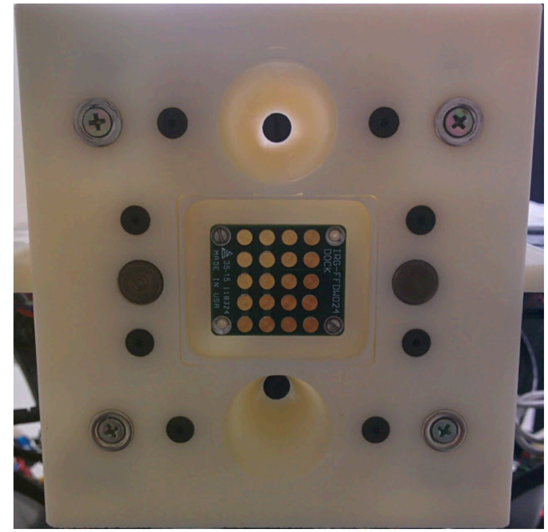
- Vicor AC/DC converters (3 output channels)
  - 235mm x 188mm x 35mm
  - Power battery charger
  - Charge 2 Astrobees at 24V @ 3A each
- Network switch to connect Astrobee to wired LAN
- Mating Dock connector to Astrobee would have contacts for Ethernet and power
- Charger board
- COTS battery chargers

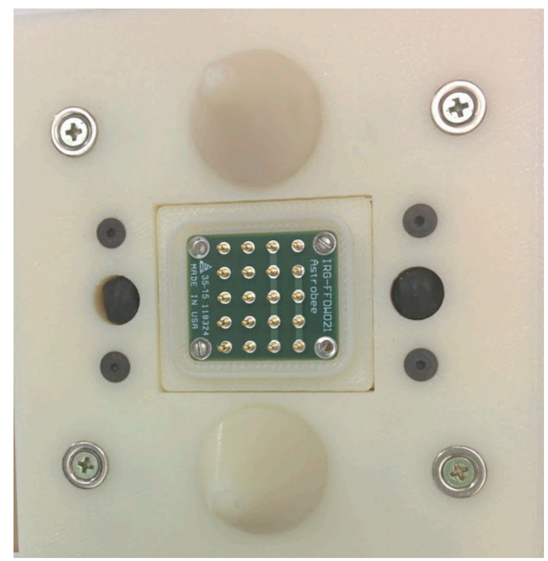
Components – Battery Charger

- Using COTS charger from Inspired Energy
  - Provides battery calibration and error resetting
- 2.25”x7”x5”, 360 g
- 24V, 2.5A input
- 3.5 hour recharge time for 49 Wh battery

Connectors

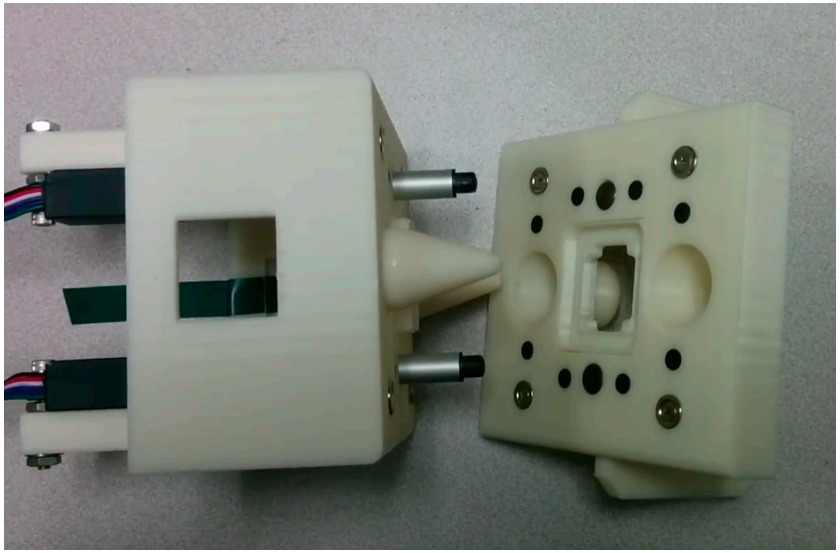
- Pogo pins for network signal & power
- 1,000,000 cycles
- Pin rated for 100V @ 2 A
- 20 pin configuration
- Mounted to PCB





Undocking

- Permanent Electro Magnets
  - Normally in hold condition
  - Apply voltage to release magnet
  - Remove voltage to go back to hold condition
- Linear actuator
  - 0 to 5 V input
  - 0 mm to 50 mm stroke



Astrobee GDS Subsystems

Design Overview

Subsystem Team

- DW Wheeler (ARC-TI, Lead)
- Jay Torres (JPL-397G)
- Ryan Goetz (JPL-397J)
- Maria Bualat (ARC-TI)
- Connor Hitt (ARC-TI, Intern)
- Jessica Marquez (ARC-TH) - collaborator
- Youngwoo Park - alumnus
- Hyunjung Kim – alumna
- Andy Martinez - alumnus

Design Drivers

- Leverage previous GDS “Workbenches” used to control Smart SPHERES and Surface Telerobotics
  - Eclipse RCP
  - RAPID comm protocol
- UI must be simple to learn and use
- UI must comply with IDAGS
- Try not to restrict future functionality

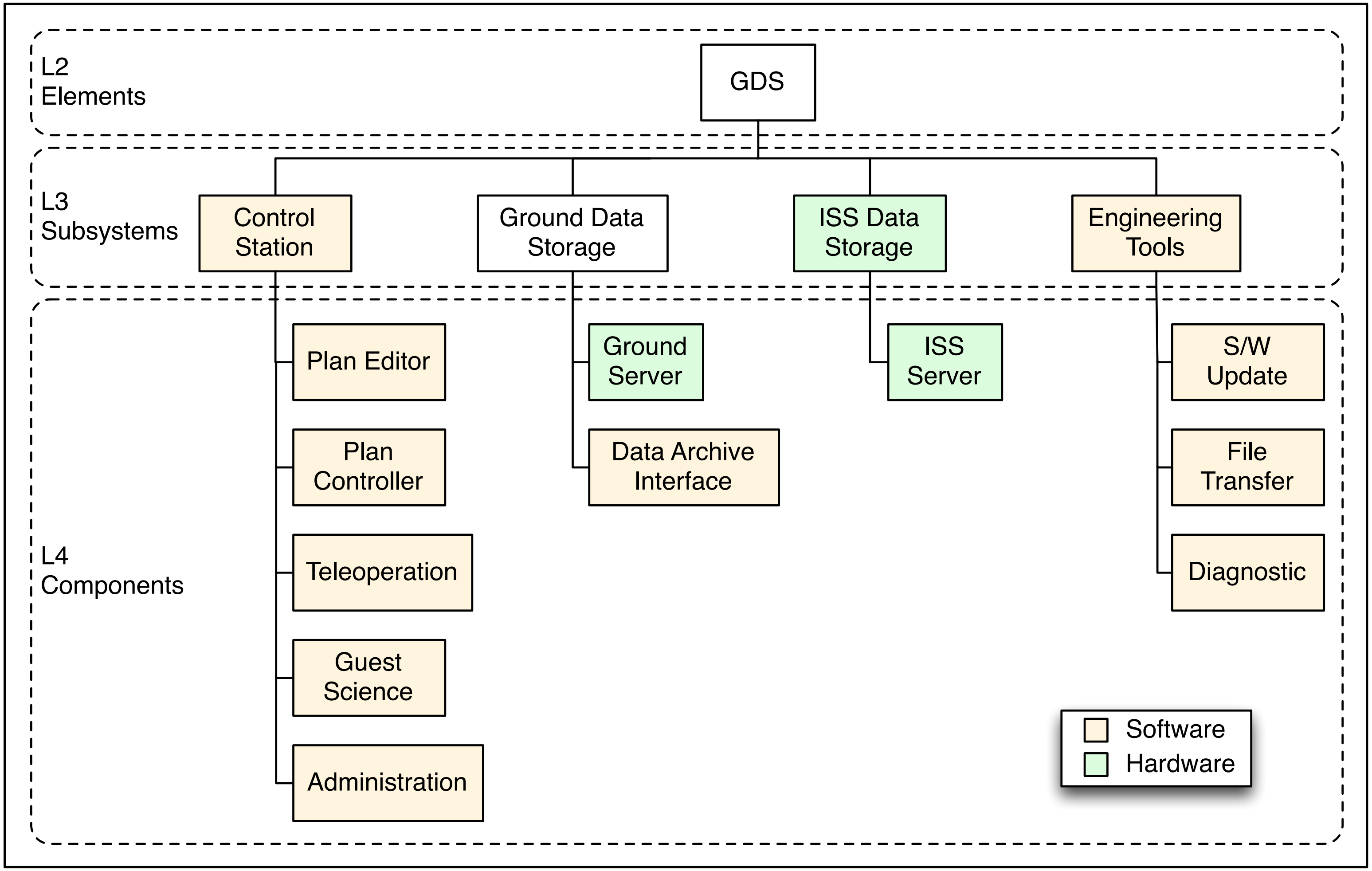
Selected Design

- Eclipse RCP application
- Communicate with Astrobee using RAPID
- Data from Astrobee will be downloaded to an ISS server when Astrobee is in dock, then downlinked
- Streaming video displayed through VLC

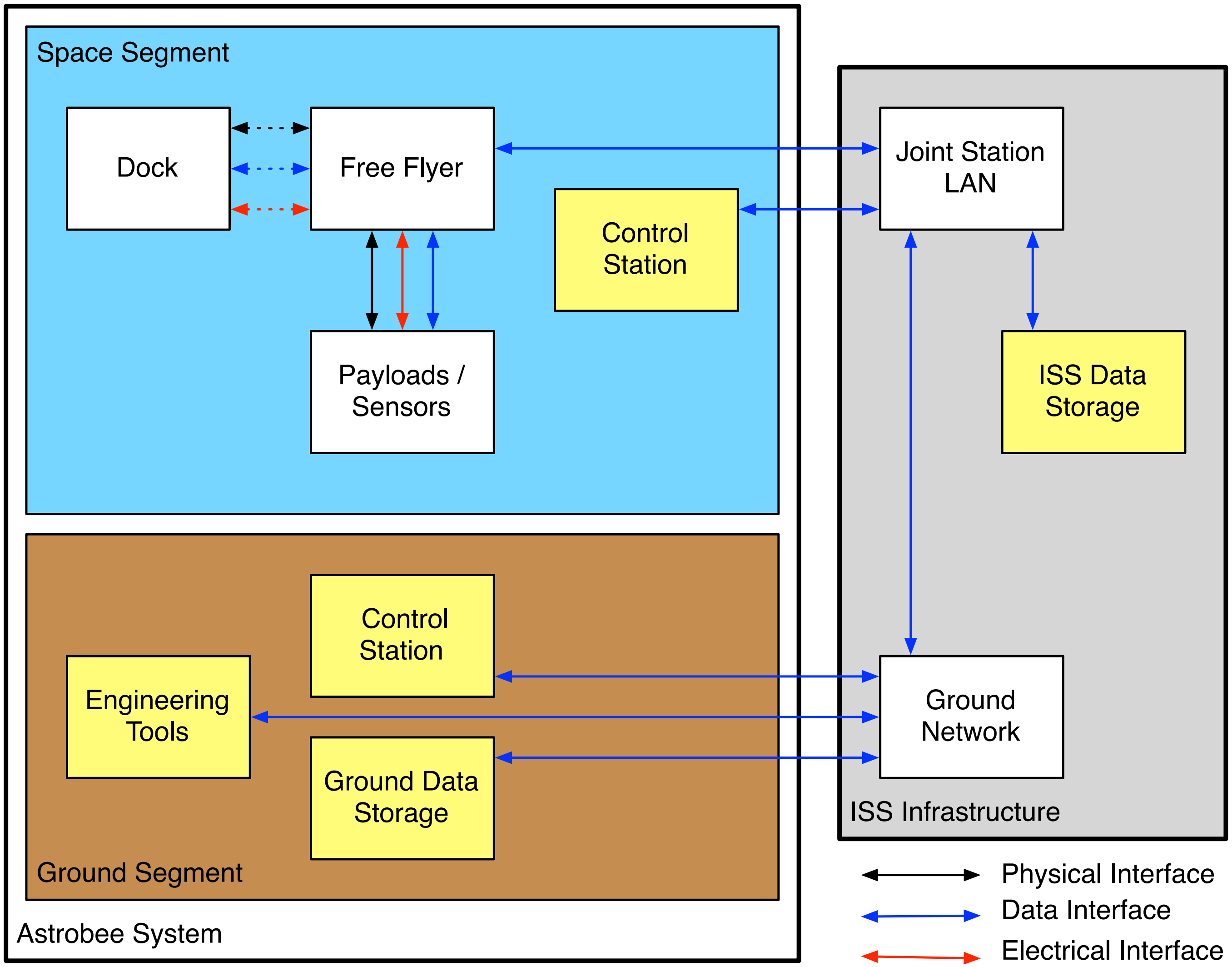
Selected Design

- Pros
  - Allows reuse of much code with "flight heritage"
  - Familiar coding platform
- Cons
  - Messages must be translated from ROS to RAPID on Astrobee
  - Harder to customize look and feel of widgets in Eclipse

GDS Subsystems



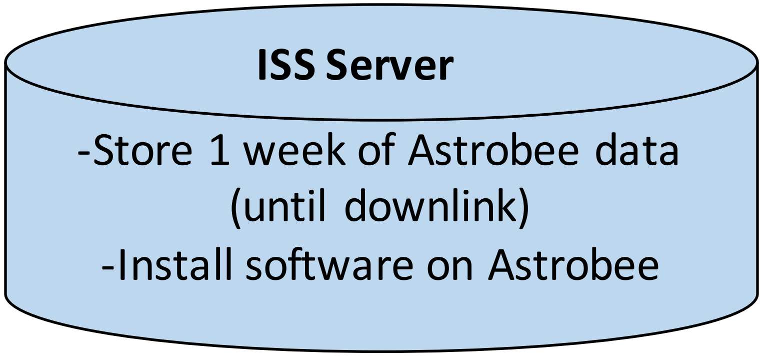
Architecture Diagram



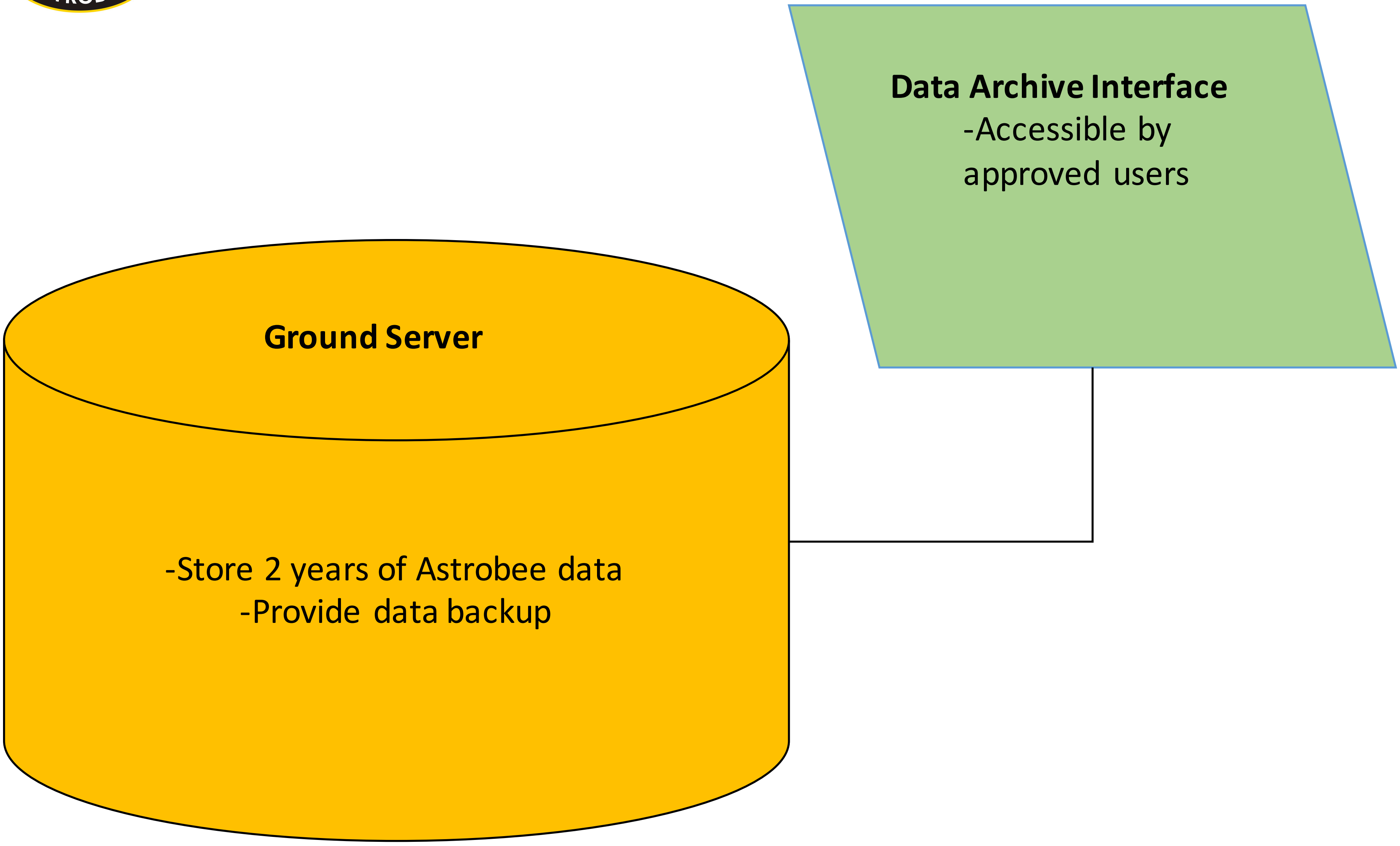
Control Station

Element	Description	Crew	GC	PI
Plan Editor	Create and edit plans		X	X
Plan Controller	Run plans and monitor execution	X	X	
Teleoperation	Send individual commands		X	
Guest Science	Run science on up to 3 Astrobees	X	X	X
Administration	Modify and monitor admin settings	X	X	X

ISS Data Storage



Ground Data Storage

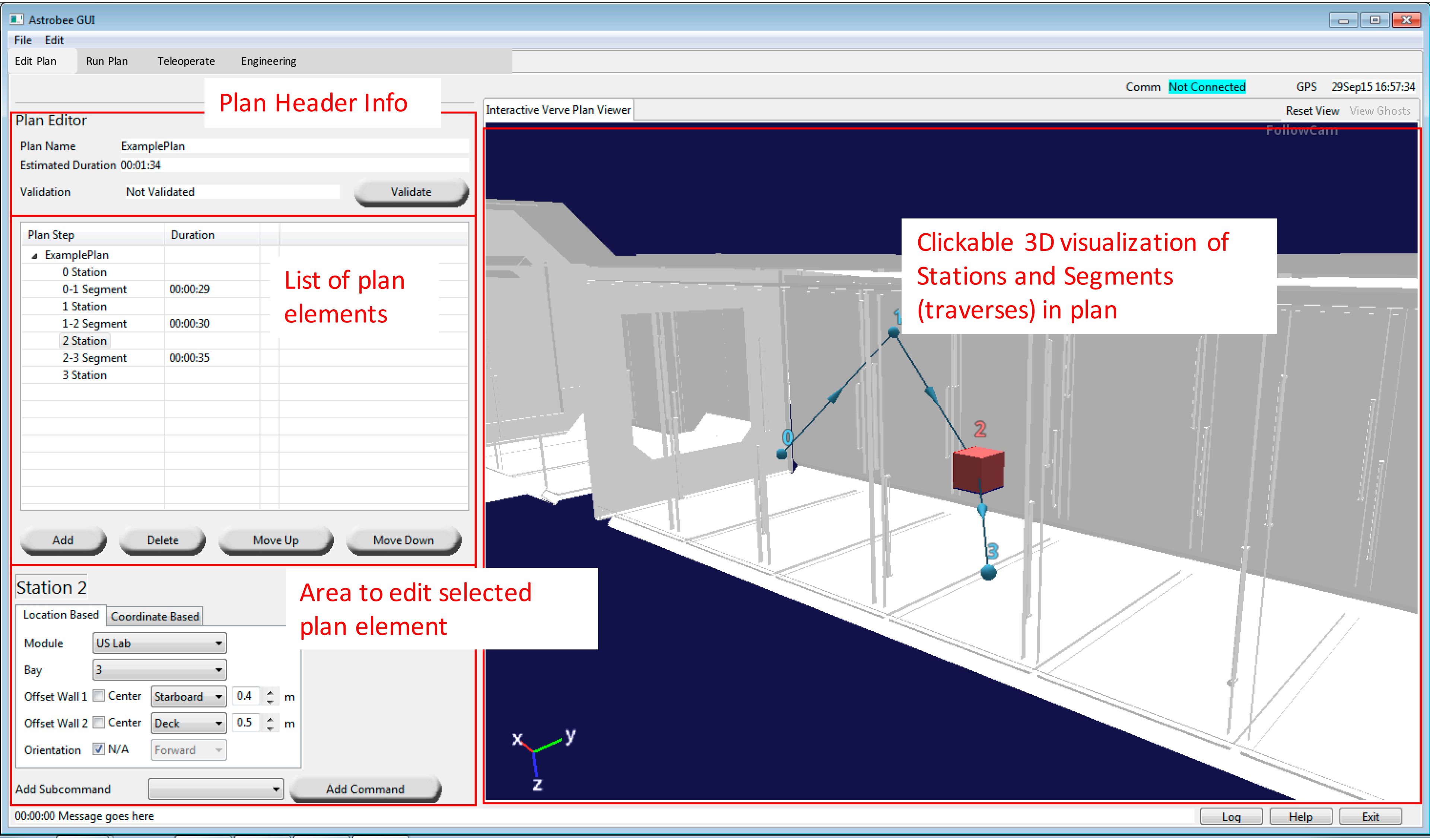


Engineering Tools*

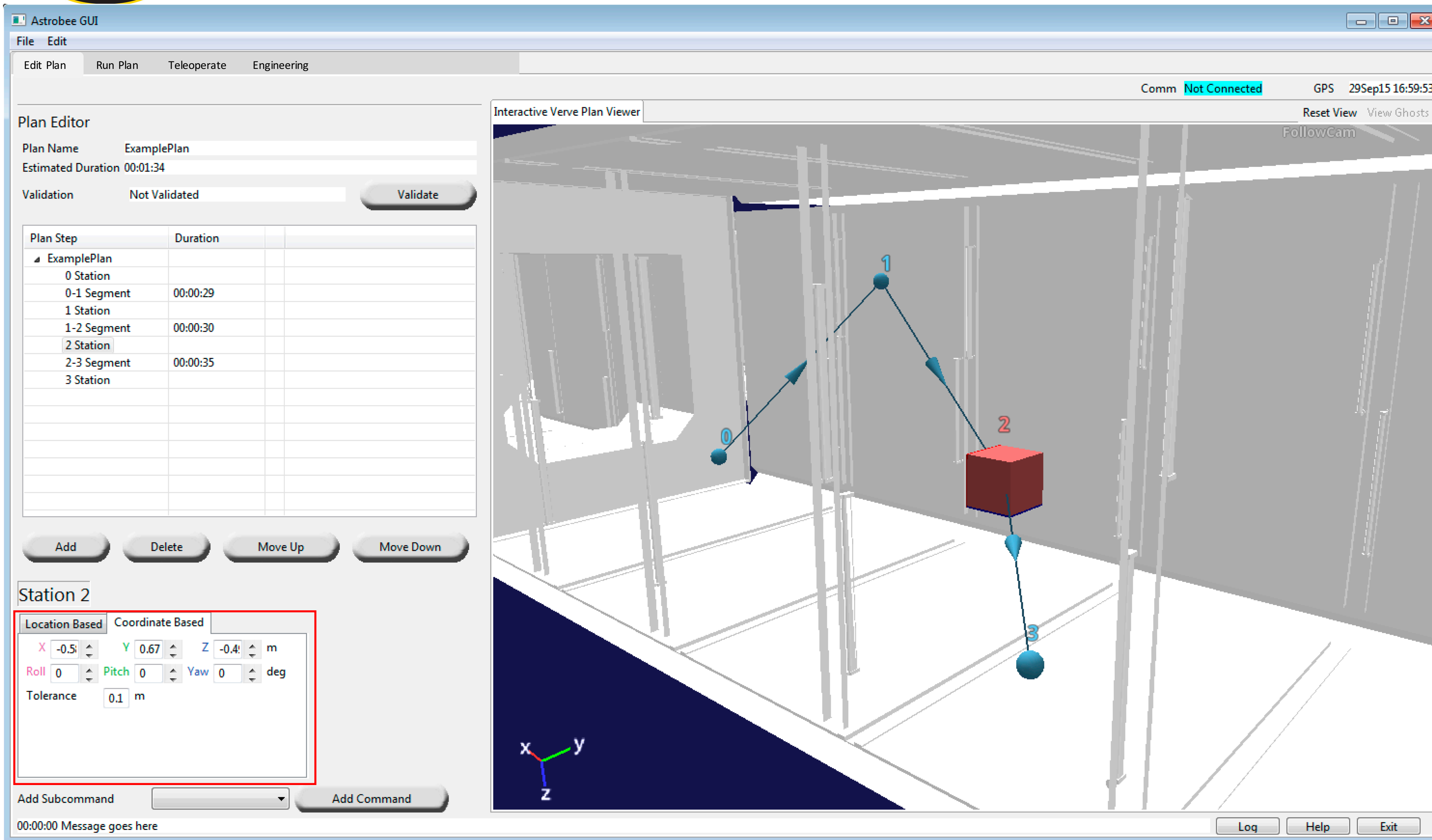
Element	Description
File Transfer	Command line interface to Astrobee
Software Update	Install software on Astrobee
Diagnostic	Display debug telemetry from Astrobee Simulate command execution Display confidence value of Astrobee state estimate

* These are defined as what the FSW team uses as they do development

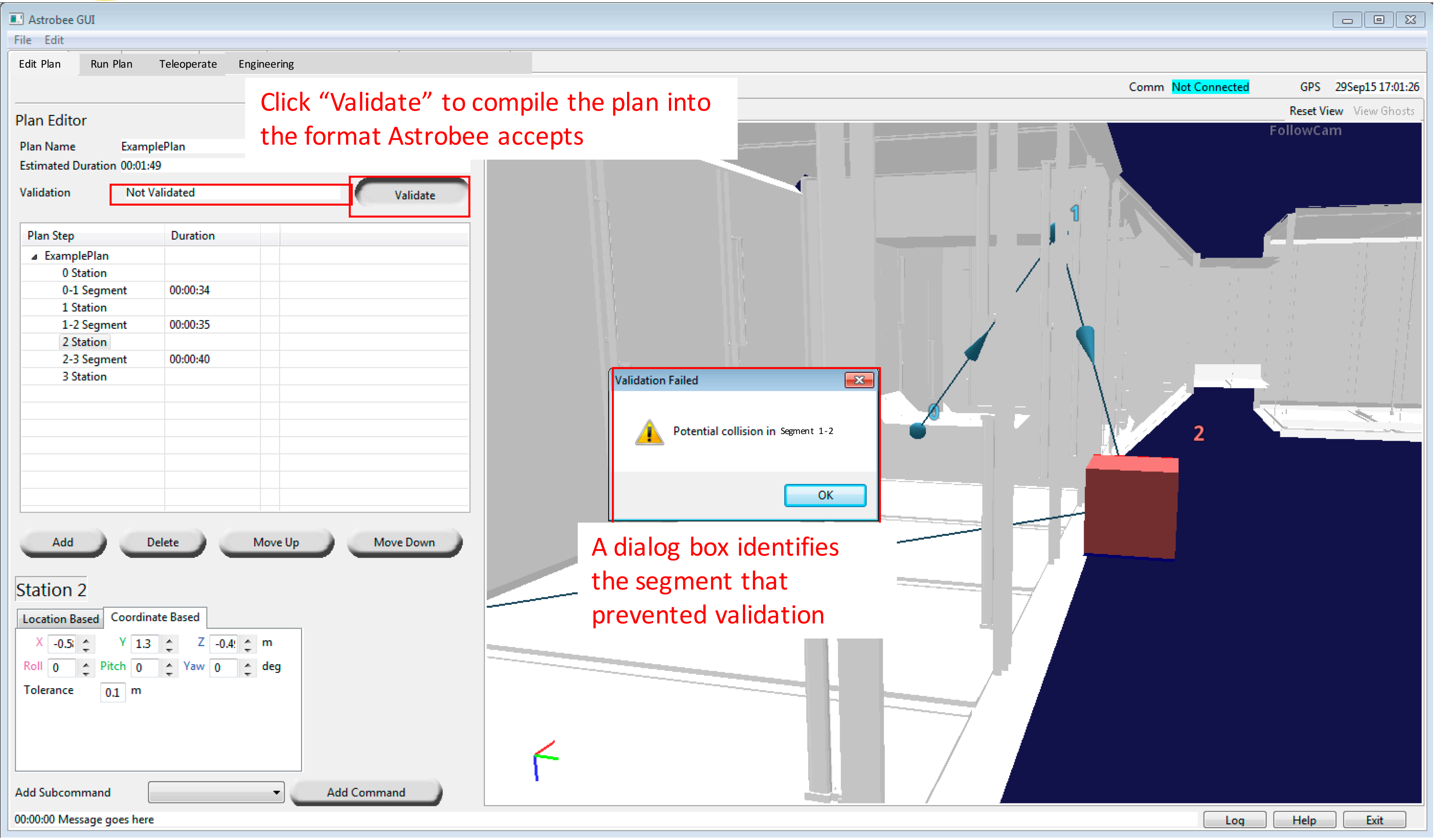
Plan Editor


Astrobee GUI
File Edit
Edit Plan
Run Plan
Teleoperate
Engineering
Comm Not Connected
GPS 29Sep15 16:57:34
Plan Header Info
Plan Editor
Plan Name ExamplePlan
Estimated Duration 00:01:34
Validation Not Validated
Validate
Interactive Verve Plan Viewer
Reset View
View Ghosts
FollowCam
Plan Step
Duration
ExamplePlan
0 Station
0-1 Segment 00:00:29
1 Station
1-2 Segment 00:00:30
2 Station
2-3 Segment 00:00:35
3 Station
List of plan elements
Add
Delete
Move Up
Move Down
Clickable 3D visualization of Stations and Segments (traverses) in plan
Station 2
Location Based
Coordinate Based
Area to edit selected plan element
Module US Lab
Bay 3
Offset Wall 1 Center Starboard 0.4 m
Offset Wall 2 Center Deck 0.5 m
Orientation N/A Forward
Add Subcommand
Add Command
00:00:00 Message goes here
Log
Help
Exit

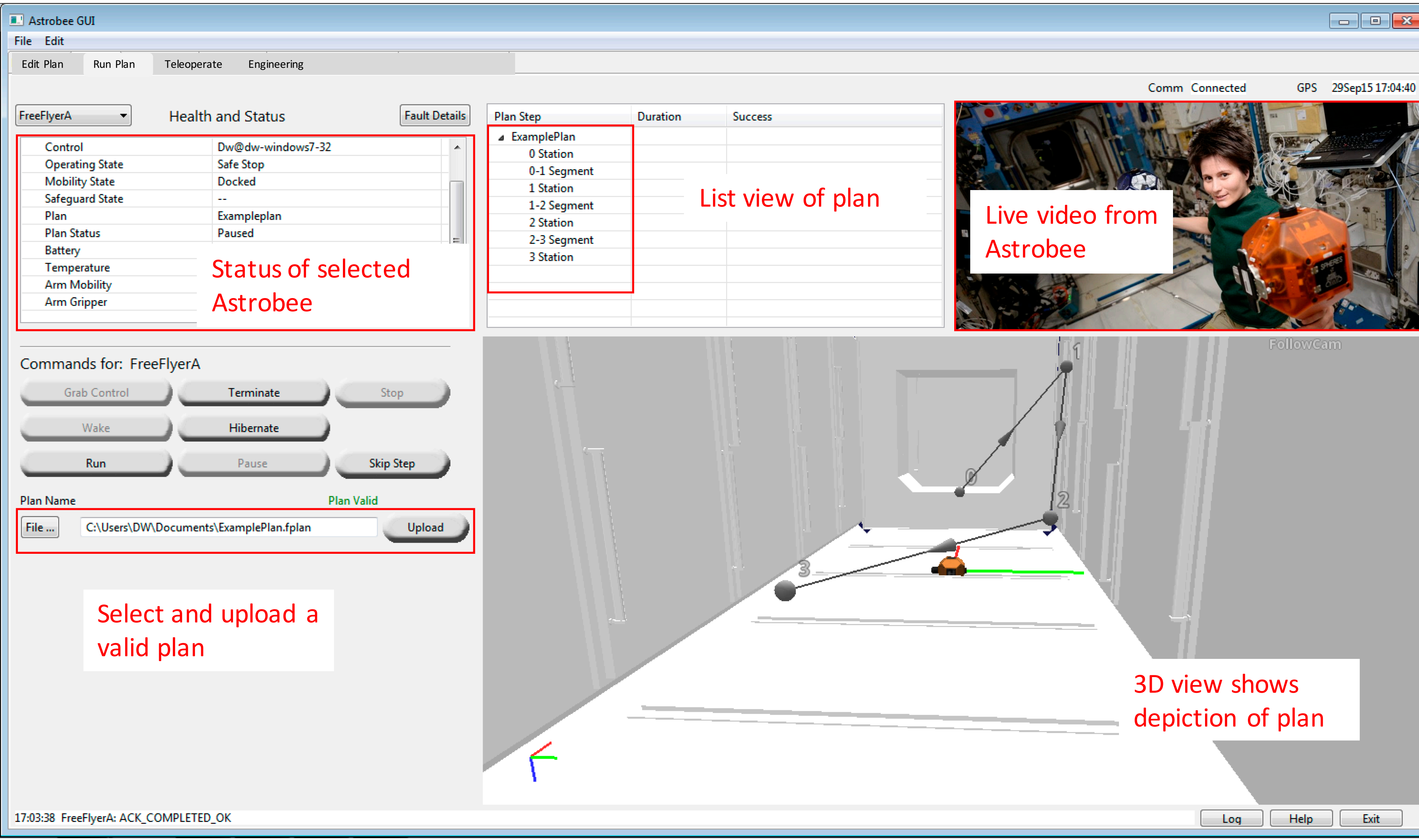
Plan Editor


Astrobee GUI
File Edit
Edit Plan
Run Plan
Teleoperate
Engineering
Comm Not Connected
GPS 29Sep15 16:59:53
Plan Editor
Plan Name ExamplePlan
Estimated Duration 00:01:34
Validation Not Validated
Validate
Plan Step
Duration
ExamplePlan
0 Station
0-1 Segment 00:00:29
1 Station
1-2 Segment 00:00:30
2 Station
2-3 Segment 00:00:35
3 Station
Add
Delete
Move Up
Move Down
Station 2
Location Based
Coordinate Based
X -0.5
Y 0.67
Z -0.4
m
Roll 0
Pitch 0
Yaw 0
deg
Tolerance 0.1 m
Add Subcommand
Add Command
00:00:00 Message goes here
Interactive Verve Plan Viewer
Reset View
View Ghosts
FollowCam
0
1
2
3
x
y
z
Log
Help
Exit

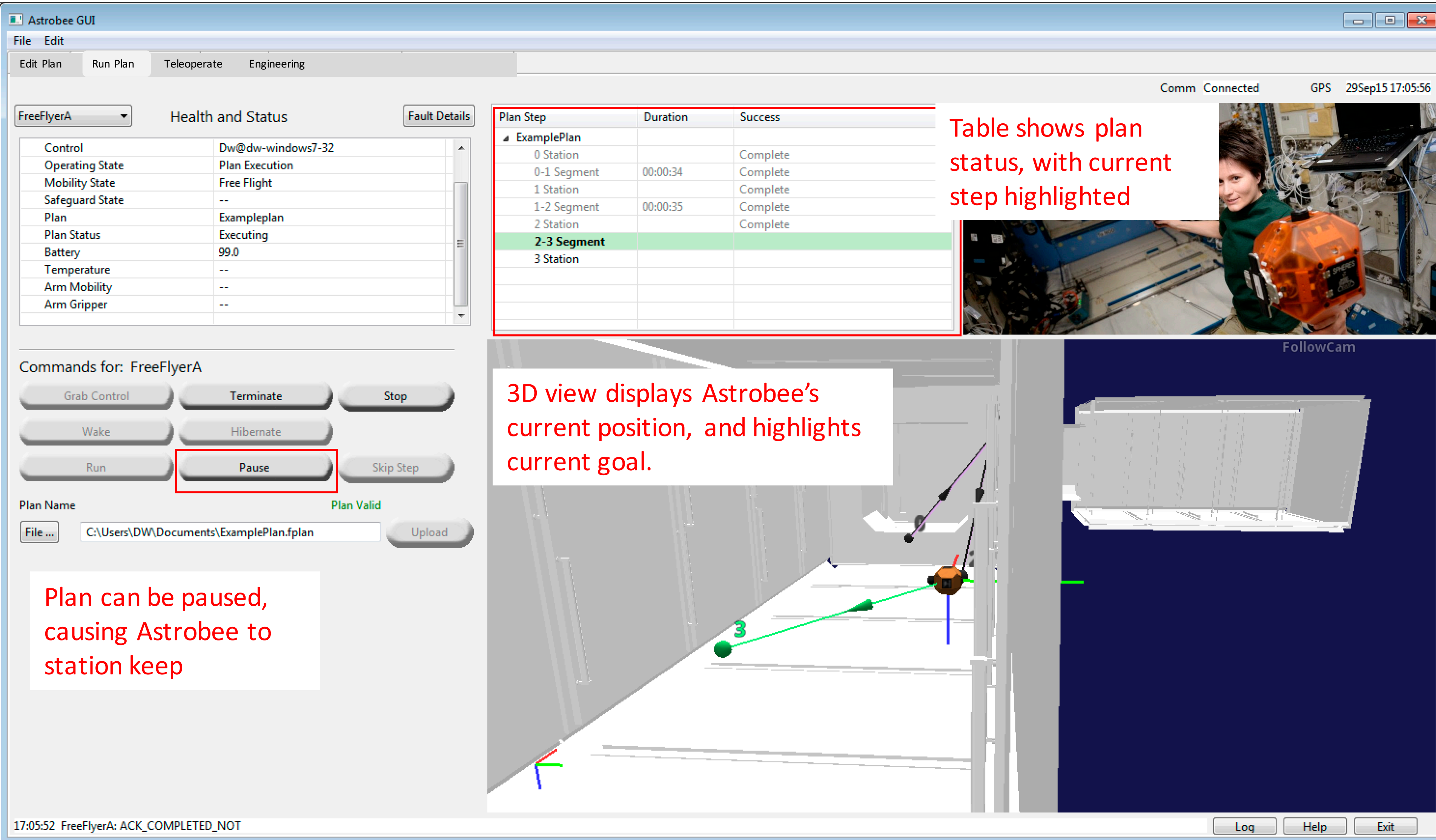
Plan Editor


Astrobee GUI
File Edit
Edit Plan
Run Plan
Teleoperate
Engineering
Click "Validate" to compile the plan into the format Astrobee accepts
Comm Not Connected
GPS 29Sep15 17:01:26
Reset View
View Ghosts
FollowCam
Plan Editor
Plan Name ExamplePlan
Estimated Duration 00:01:49
Validation
Not Validated
Validate
Plan Step
Duration
ExamplePlan
0 Station
0-1 Segment 00:00:34
1 Station
1-2 Segment 00:00:35
2 Station
2-3 Segment 00:00:40
3 Station
Validation Failed
Potential collision in Segment 1-2
OK
A dialog box identifies the segment that prevented validation
Add
Delete
Move Up
Move Down
Station 2
Location Based
Coordinate Based
X
Y 1.3
Z
m
Roll 0
Pitch 0
Yaw 0
deg
Tolerance 0.1 m
Add Subcommand
Add Command
00:00:00 Message goes here
Log
Help
Exit

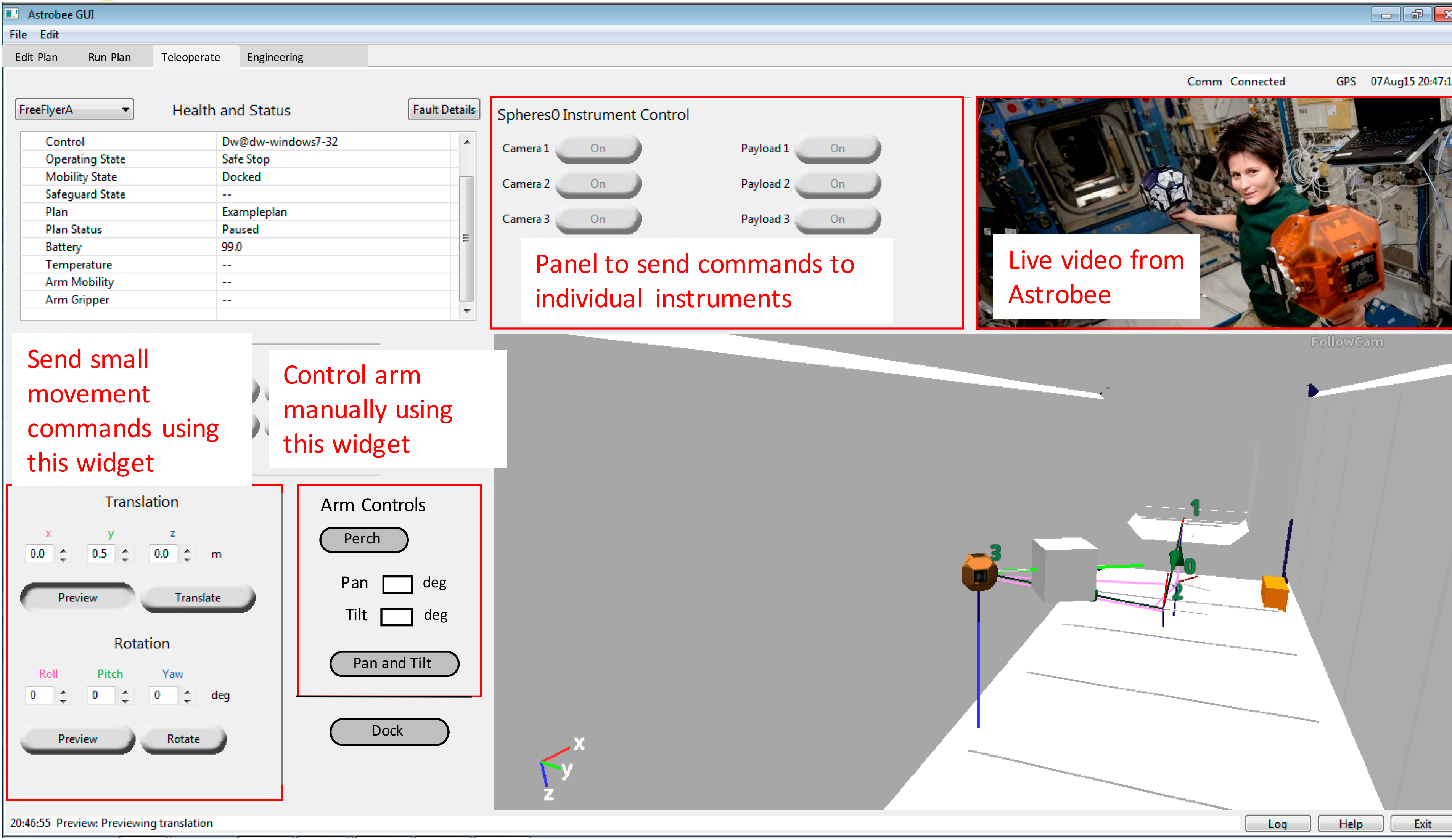
Plan Running



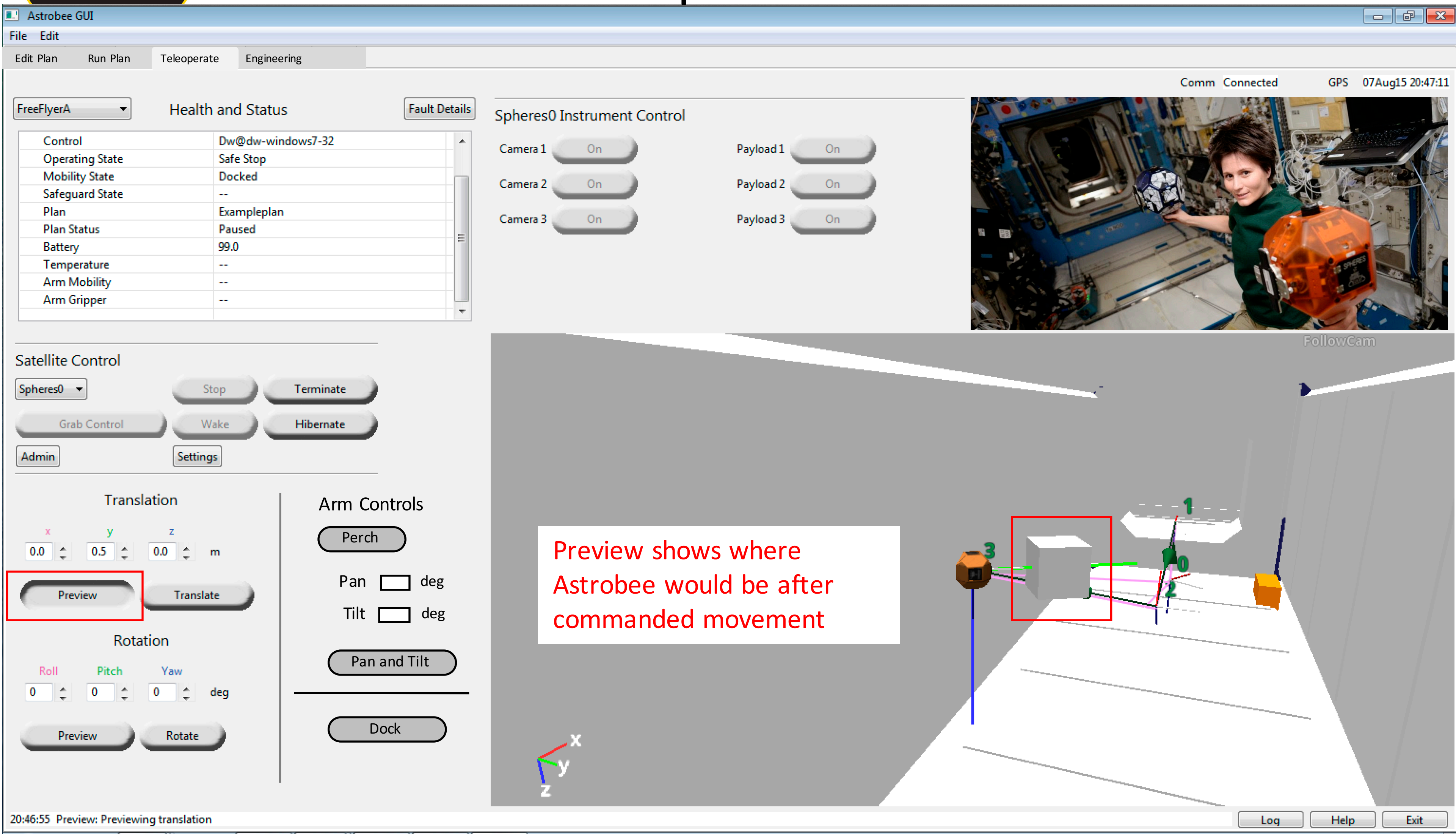
Plan Running



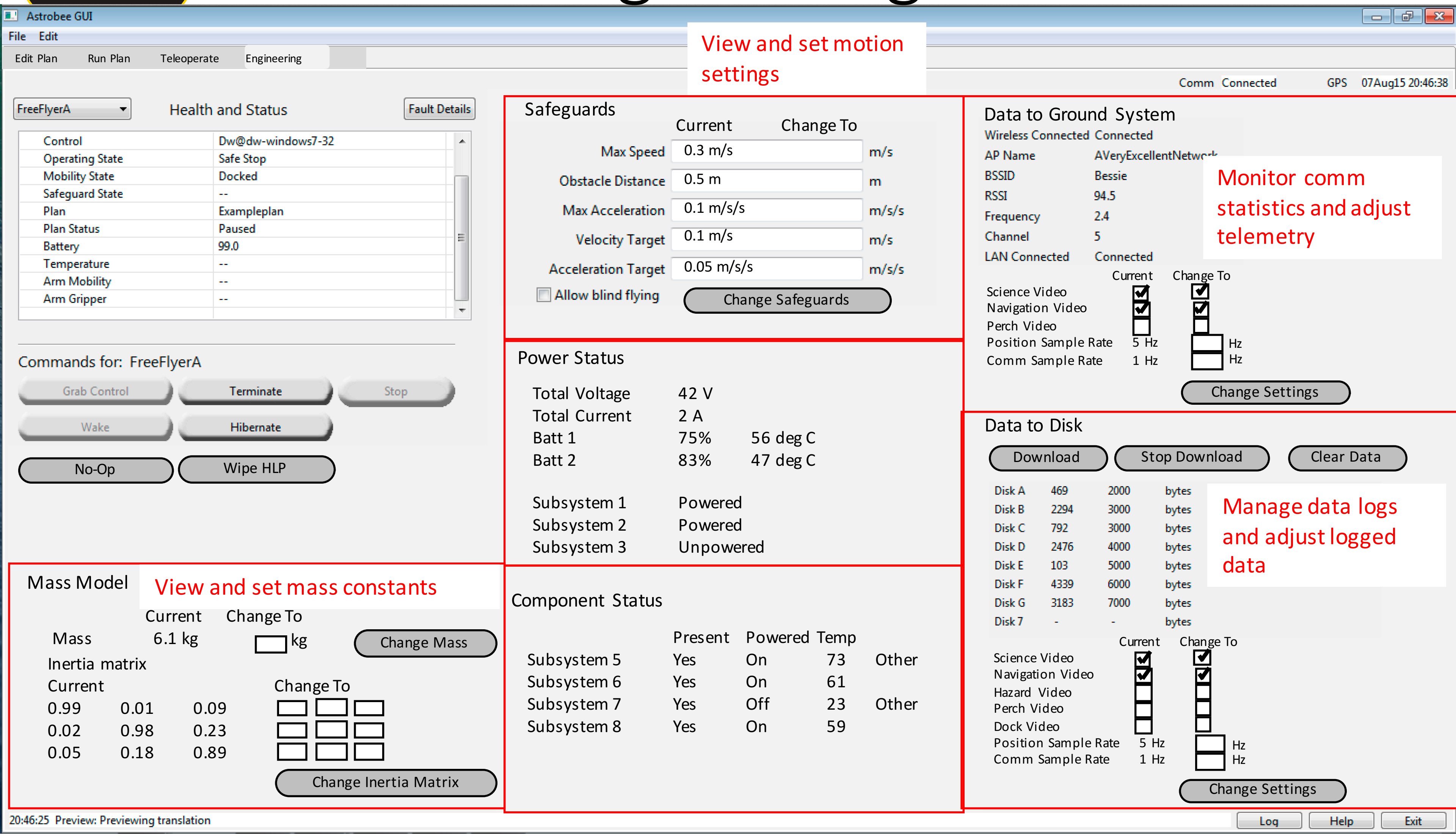
Teleoperation



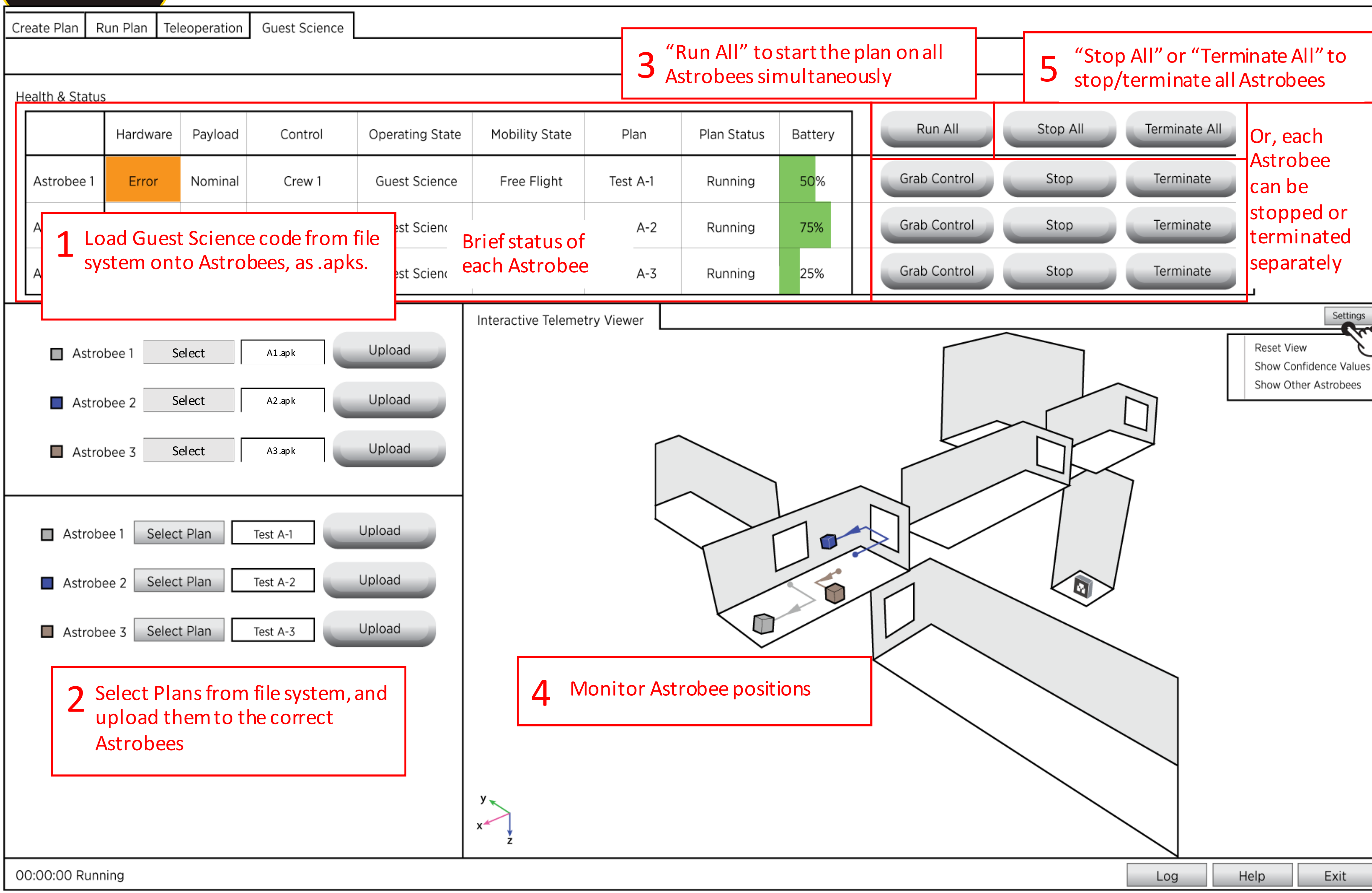
Teleoperation



Engineering



Guest Science



Agenda

Time	Duration	Presenter	Topic
9:00	1:00		Demo
10:00	0:45	Terry Kevin Chris	Welcome & Introduction
10:45	1:45	Trey Team Leads	Design
12:30	0:15		*Working Lunch*
12:45	2:15	Team Leads	Design
15:00	0:15		*Break*
15:15	0:30	Trey	TPMs, Trades, FM
15:45	0:30	Jonathan	I&T
16:15	0:15	Ernie	Safety
16:30	0:30	Chris	Technology Infusion, schedule, cost, risk
17:00	0:30	Chris	Conclusion