Human Exploration Telerobotics 2 (HET2) Astrobee

Delta Periodic Technical Review 3

February 1, 2017

Agenda

Time	Duration	Presenter	Topic
8:30	0:30	Terry, Chris	Welcome/Intro
9:00	1:30	Trey, Team Leads	Design
10:30	0:15		*Break*
10:45	1:15	Team Leads	Design
12:00	0:45		*Lunch*
12:45	0:30		*Demo*
13:15	1:15	Team Leads	Design
14:30	0:15		*Break*
14:45	0:30	Trey	Systems Engineering
15:15	0:30	Jonathan	Integration & Test
15:45	0:30	Ernie	Safety
16:15	0:15	Chris	Project Management
16:30	0:15	Maria	Operations
16:45	0:15	Chris	Conclusion

Welcome !

- Final design review of **Astrobee**
  - Delta Periodic technical review #3 (PTR 3)
- Logistics
  - Emergency exits
  - Rest rooms, lunch, demo
- (A few) introductions
  - **GCD** / **HET2** / **Astrobee** key people
  - **HEOMD/SPHERES** (Crusan, Martinez, Benavides)
  - **PTR board** (Fong, Provencher, Smith, Barlow, Smith, Crusan, Benavides)

Periodic Technical Review
(HET2 Project Plan)

- Periodic Technical Review (PTR)
  - Monitor and communicate technical and programmatic progress against the approved baseline
  - Review plans for upcoming work
- The **PTR board** consists of (or an assigned delegate):
  - HET2 PM: Terry Fong
  - Astrobee management: Chris Provencher, Trey Smith, Jonathan Barlow, Ernie Smith
  - AES Director/SPHERES PM: Jason Crusan, Jose Benavides
- All stakeholders who contribute or are interested in the project are invited to participate

Delta PTR 3

- Demonstrate that the design has sufficiently matured and has an acceptable level of risk
  - Hardware expected to be more mature (with known design gaps)
  - Software maturity expected to follow, with planned design beyond PTR 3
- Examine the results of Prototype testing (and any impact on the Certification Unit).
- Today's objectives :
  - **Focus on new/changed design since PTR 3 (June 2016)**
  - Ensure a thorough review of the products identified for PTR 3
  - Ensure Prototype 4D activities to date do not adversely impact forward plans
  - Ensure issues raised during the review are appropriately documented and a plan for resolution is prepared
- Following △PTR 3, Astrobee will:
  - Complete design for flight (any open items)
  - Complete Prototype 4D testing
  - Proceed with Certification Unit procurements

PTR 3 Entrance Criteria

- ✓ The element has successfully completed the previous planned milestone reviews, and responses have been made to all issues and actions, or a timely closure plan exists for those remaining open.
- ✓ The PTR 3 agenda, success criteria, and instructions to the review board have been agreed to by the technical team, element lead, and review chair prior to the review.
- ✓ The PTR 3 data package (IRG-FFRP-003) with the following products are available to the participants:
  - ✓ IRG-FF017 Astrobee Design Document with a design overview (to subsystem level) that can be shown to meet requirements and key technical performance measures
  - ✓ Astrobee document tree
  - ✓ Technical resource margins
  - ✓ Updated PTR 3 technical products
  - ✓ Updated schedule, cost, and risks

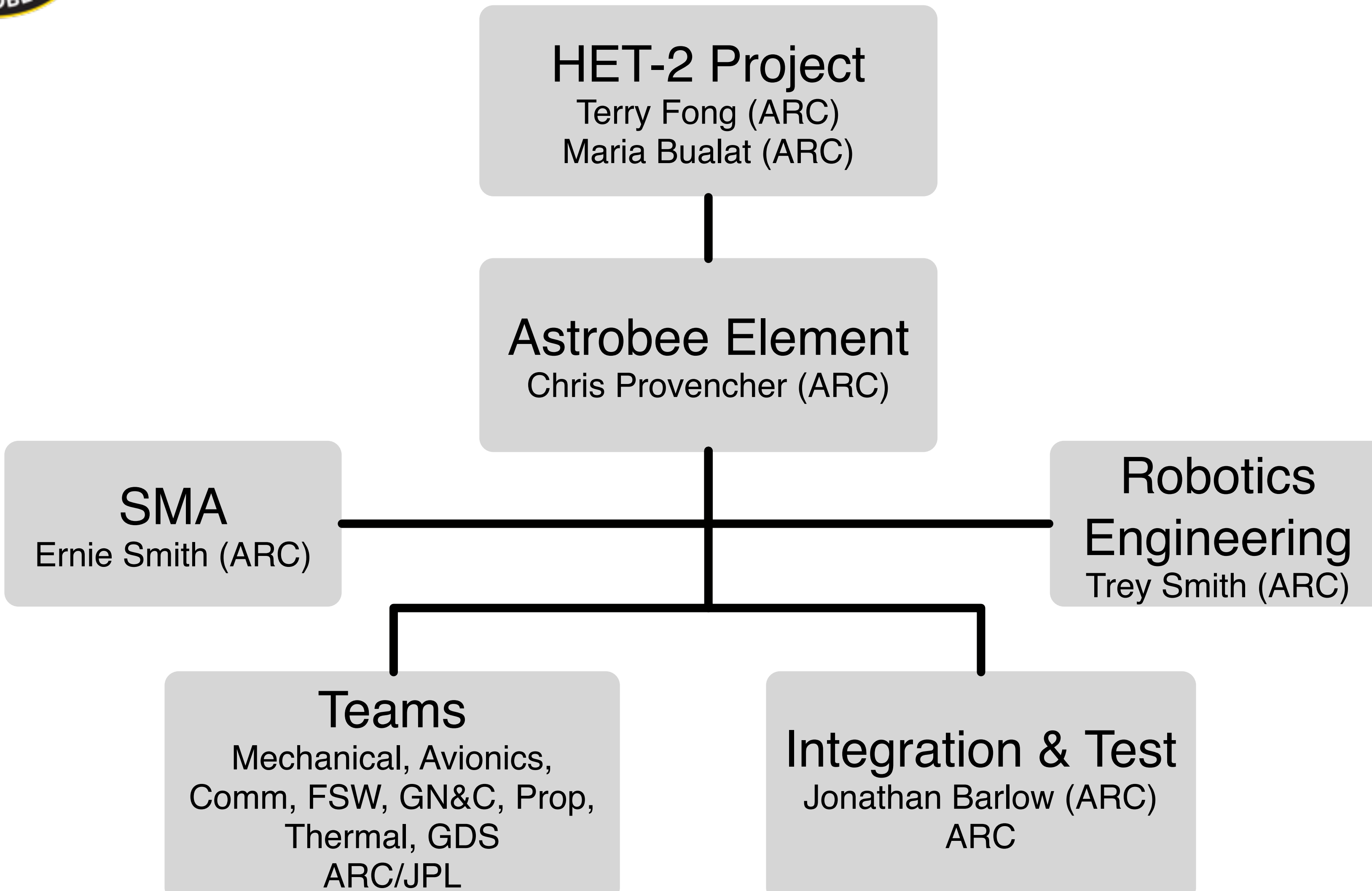
PTR Board + Reviewers

- We want your feedback !
  - Identify what we are doing well + what we can do better
  - Identify new issues or concerns
  - Suggest improvements
  - Recommend how and when Astrobee should move into the next lifecycle phase
- Please keep in mind…
  - Astrobee is an **element** within the HET2 **project**
  - PTR objectives
  - Astrobee is 7120.8 (Research & Technology) with ISS certs
  - Astrobee is **not** a spaceflight project

Overview

- Develop, test, deliver 2 free flying robots for ISS IVA use
- 4 year project (FY15-FY17) under Human Exploration Telerobotics 2 (HET2)
- Sponsor: Space Technology Mission Directorate, Game Changing Development Program
- Technology infusion to ISS payloads & operations

Astrobee Organization



Systems Engineering Team

- Trey Smith (ARC-TI, Lead)
- Jonathan Barlow (ARC-TI)
- Maria Bualat (ARC-TI)
- Estrellina Pacis (ARC-TI)
- Hugo Sanchez (ARC-RE)
- Allison Zuniga (ARC-TI, alumna)

I&T Team

- Jonathan Barlow (ARC-TI, Lead)
- Max Feinberg (Univ. of Illinois, OSSI intern)
- John Love (ARC-RD)
- Corey Snyder (ARC-SCF)
- Olivia Formoso (ARC-RE, alumna)

Avionics Team

C&DH, EPS, Dock, Perching Arm, Propulsion

- Vinh To (ARC-TI, Lead)
- Dmitriy Arbitman (Univ. of California San Diego, intern, alumnus)
- Steve Battazzo (ARC-RE)
- Jon Dewald (ARC-RE, alumnus)
- Brandon Gigous (Univ. of Illinois, OSSI intern, alumnus)
- Jason Lum (ARC-TI, alumnus)
- Nghia Mai (ARC-RE)
- In Won Park (ARC-TI)
- Cedric Priscal (ARC-TI)
- Jongwoon Yoo (ARC-TI)
- Shang Wu (ARC-RE)

Communications Team

Free Flyer Comm, E2E comm standards

- Ted Morse (ARC-TI, Lead)
- Vinh To (ARC-TI)
- Jason Lum (ARC-TI, alumnus)

Flight Software Team

Flight software, GNC software

- Lorenzo Flückiger (ARC-TI, Lead)
- Oleg Alexandrov (alumnus)
- Katie Browne (ARC-TI)
- Brian Coltin (ARC-TI)
- Phil Cooksey (Carnegie Mellon Univ., OSSI intern)
- Ravi Gogna (ARC-TI, alumnus)
- Dong-Hyun Lee (ARC-TI)
- Zack Moratto (ARC-TI, alumnus)
- Ted Morse (ARC-TI)
- Andrew Symington (ARC-TI)
- Mike Watterson (Univ. of Pennsylvania, NSTRF intern)

Ground Data Systems Team

- DW Wheeler (ARC-TI, Lead)
- Maria Bualat (ARC-TI)
- Ryan Goetz (JPL-397J)
- Connor Hitt (Univ. of Texas, intern, alumnus)
- Jessica Marquez (ARC-TH, collaborator)
- Andy Martinez (ARC-TI, Education Associates intern, alumnus)
- Jay Torres (JPL-397G, alumnus)

GN&C Team

GNC software, Prop software

- Jesse Fusco (ARC-RE, Lead)
- Michael McIntyre (ARC-RE, alumnus)
- Robert Nakamura (ARC-RE)

Mechanical Team

Structure, Propulsion, Dock, Perching Arm

- Hugo Sanchez (ARC-RE, Lead)
- Jeff Blair (ARC-RE)
- Earl Daley (ARC-RE)
- Brian Koss (ARC-RE, alumnus)
- Alex Langford (ARC-RE, alumna)
- Alberto Makino (ARC-RE)
- Travis Mendoza (Univ. of Southern California, intern, alumnus)
- Mike McIntyre (ARC-RE)
- Blair McLachlan (ARC-AOX)
- In Won Park (ARC-TI)
- Troy Shilt (Ohio State Univ., OSSI intern)
- Rafael “Omar” Talavera (ARC-RE)
- Watson Attai (ARC-RE)

Thermal Team

Free Flyer, Dock

- Jeffrey Feller (ARC-RE, Lead, alum)
- John Love (ARC-RD, Lead)
- Earl Daley (ARC-RE)
- Ali Kashani (ARC-RE)
- Blair Mclachlan (ARC-AOX)
- Vinh To (ARC-TI)

Human-Robot Interaction Team

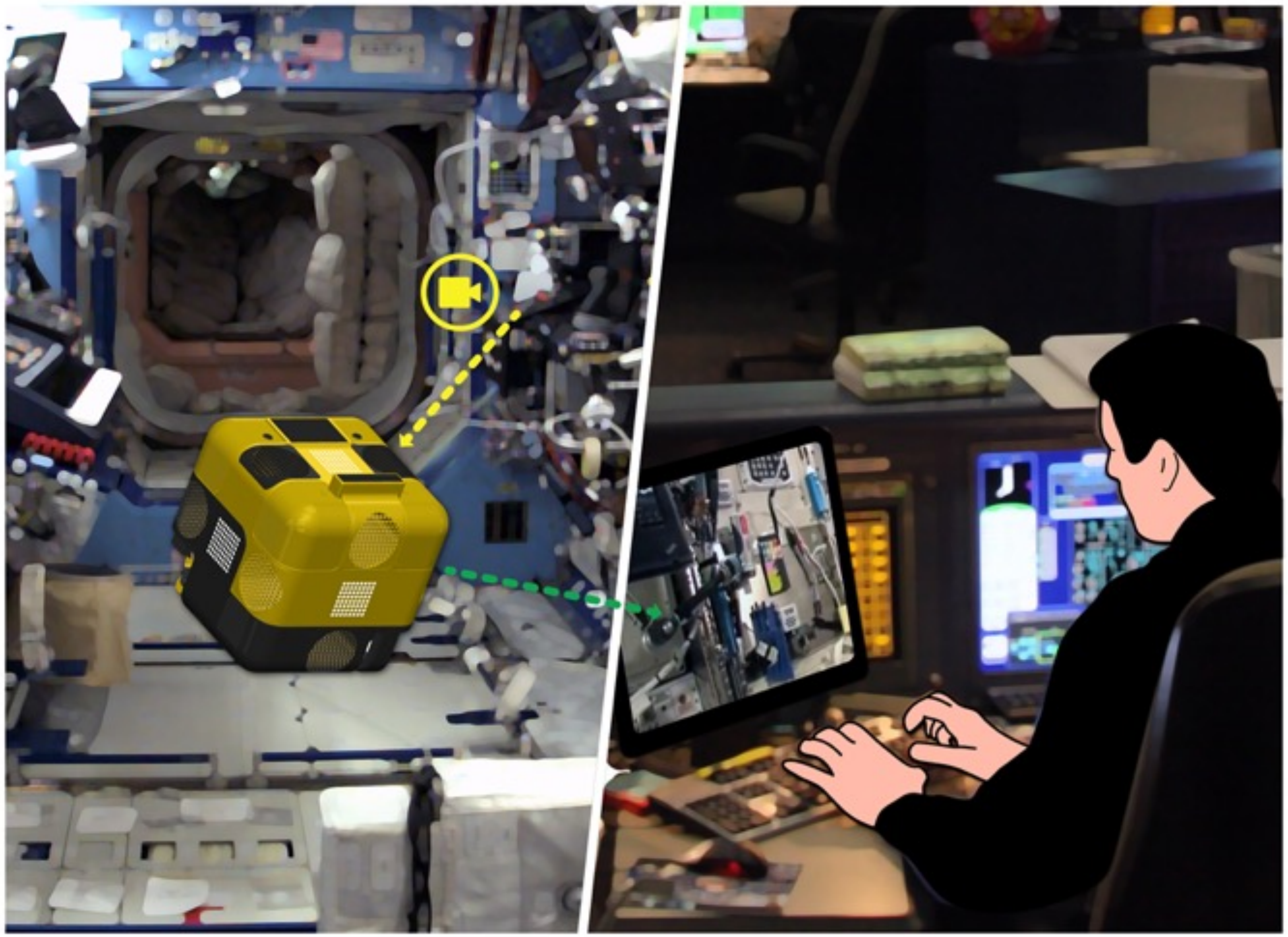
Free Flyer, Control Station

- Yunkyung Kim (ARC-TI, Lead)
- Liz Cha (Univ. of Southern California, NSTRF intern)
- Terry Fong (ARC-TI)
- Hyunjung Kim (ARC-TI, alumna)
- Pem Lasota (MIT, NSTRF intern)
- Youngwoo Park (ARC-TI, alumnus)
- Dan Szafir (U-Wisc, NSTRF intern, alumnus)

0g Robotics Research Facility

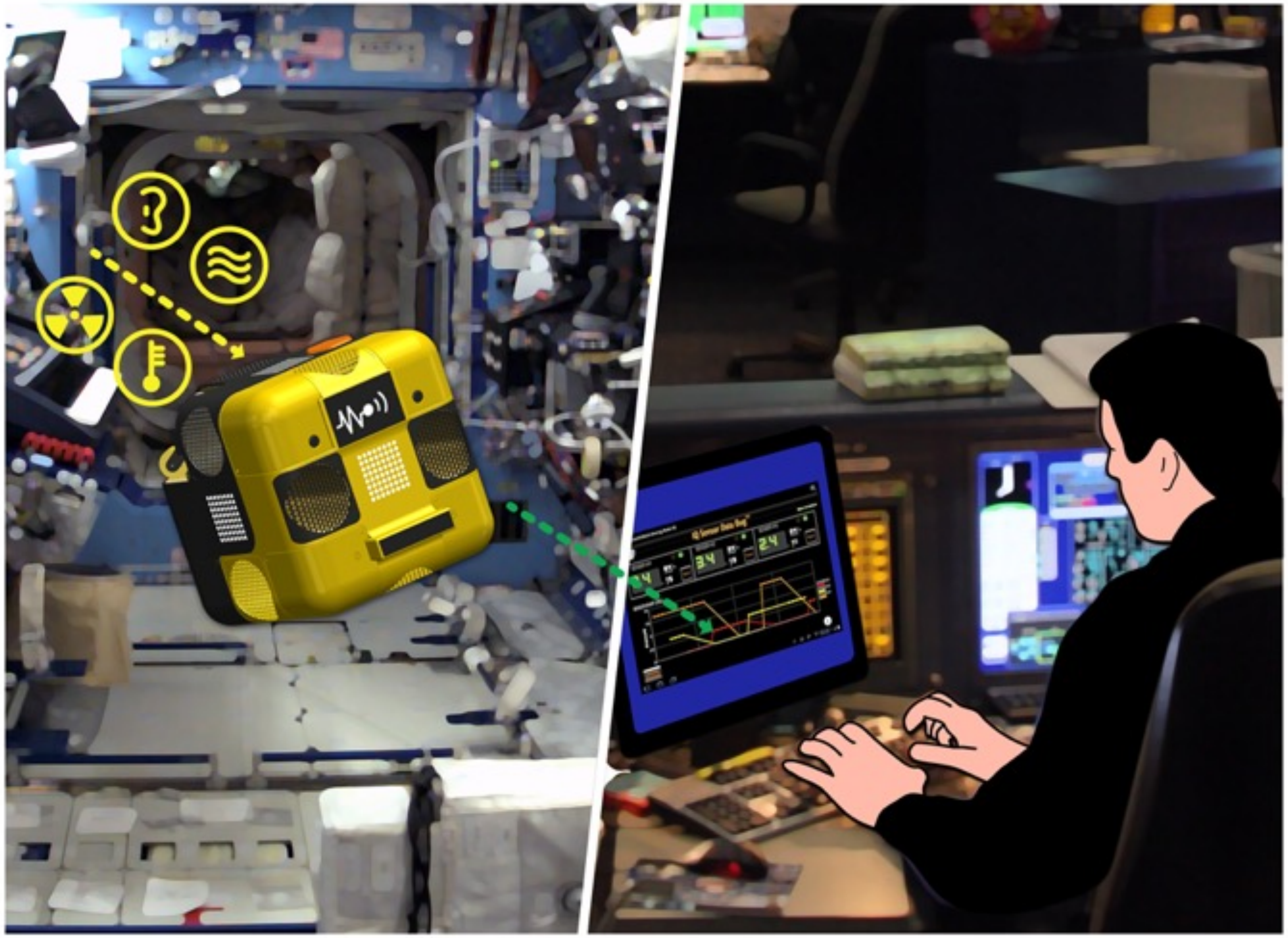
AES, SPHERES Program, Researchers

Mobile Camera Tasks



ISS Program, FOD, POIC

Mobile Sensor Tasks



ISS Program, FOD, POIC

Dock & Resupply

Agenda

Time	Duration	Presenter	Topic
8:30	0:30	Terry, Chris	Welcome/Intro
9:00	1:30	Trey, Team Leads	Design
10:30	0:15		*Break*
10:45	1:15	Team Leads	Design
12:00	0:45		*Lunch*
12:45	0:30		*Demo*
13:15	1:15	Team Leads	Design
14:30	0:15		*Break*
14:45	0:30	Trey	Systems Engineering
15:15	0:30	Jonathan	Integration & Test
15:45	0:30	Ernie	Safety
16:15	0:15	Chris	Project Management
16:30	0:15	Maria	Operations
16:45	0:15	Chris	Conclusion

Backup

ISS ROBOTIC FREE FLYER
ASTROBEE

SPHERES Payloads

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)

Free Flyer Key Requirements

- Holonomic control
- Navigate USOS
- Multiple peripheral ports
- Reconfigure parameters per payload
- Open API for payloads
- Position: +/- 20 cm, +/- 2 cm
- Angle: +/- 20 deg, +/- 8 deg
- Max acceleration: 10 cm/sec^2
- Max velocity: 50 cm/sec
- Avoid hitting unexpected obstacles
- Avoid keep out zones
- Validate path against map
- Monitor battery charge
- Noise requirements
- Tolerate collisions
- Size: 12” x 12” x 12”
- Mass: 8 kg
- Stream and record HD video
- Sortie durations & energy storage
- Perch on handrails
- Autonomous docking
- Replaceable modules
- Upgradeable software
- ISS ICD & Safety

Presented and baselined at PTR1

Ground Data Systems Key Requirements

- Ground Control
- Manual Control
- Plan authoring
- Plan control (select, upload, run, pause, abort, skip)
- Provide PIs access to science data
- Software install (guest science)
- Monitor multiple robots
- Identify free flyer being controlled
- Remote Terminate
- Real-time telemetry display
- 2D and/or 3D telemetry visualization
- Simulation for plan visualization
- Control station health & status
- Provide data storage
- Minimal UI training for Crew and Operatory Stations
- Upgradable hardware/software
- ISS ICD

Presented and baselined at PTR1

Dock Key Requirements

- Free flyer and dock must be able to complete all physical connections without crew assistance
  - AR target to assist free flyer localization during dock approach
- ~~Recharge spare batteries~~
- Provide free flyer with high bandwidth wired connection to ISS LAN
- Dock provides two free flyer berths
- ISS ICD & Safety

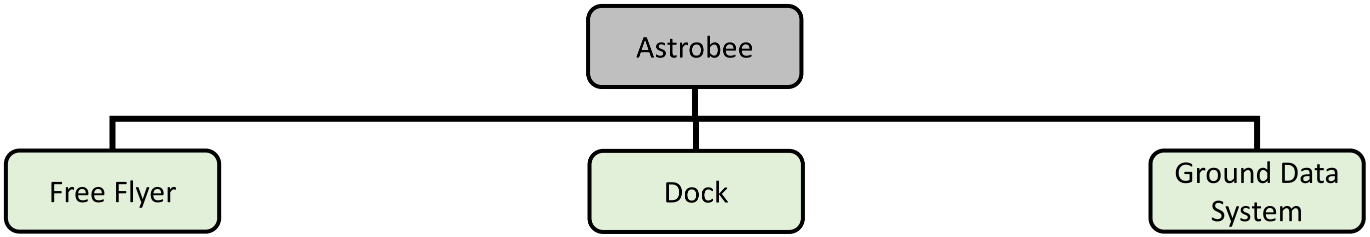
Presented and baselined at PTR1

System Design Overview

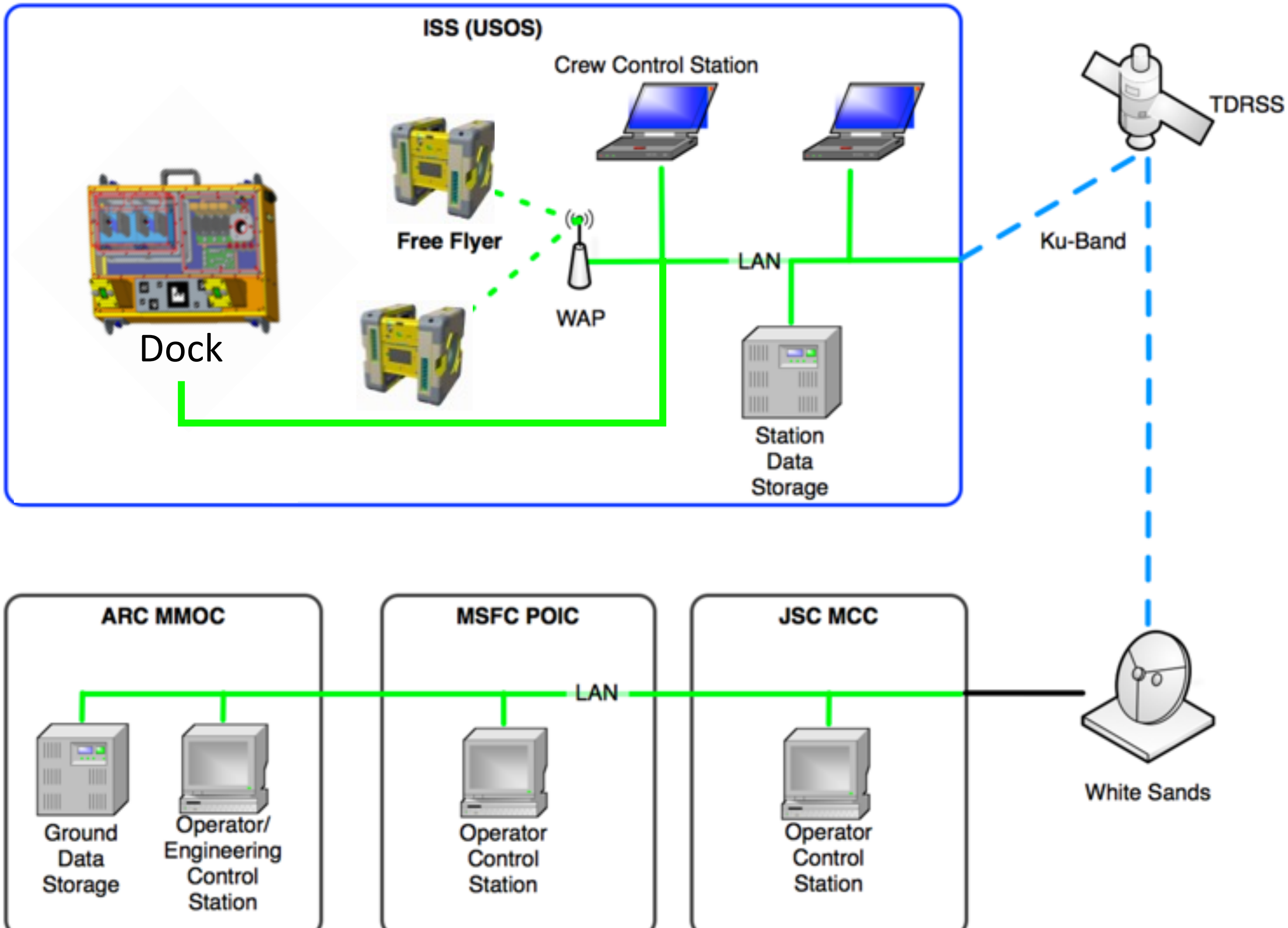
Delta Periodic Technical Review 3

February 1, 2017

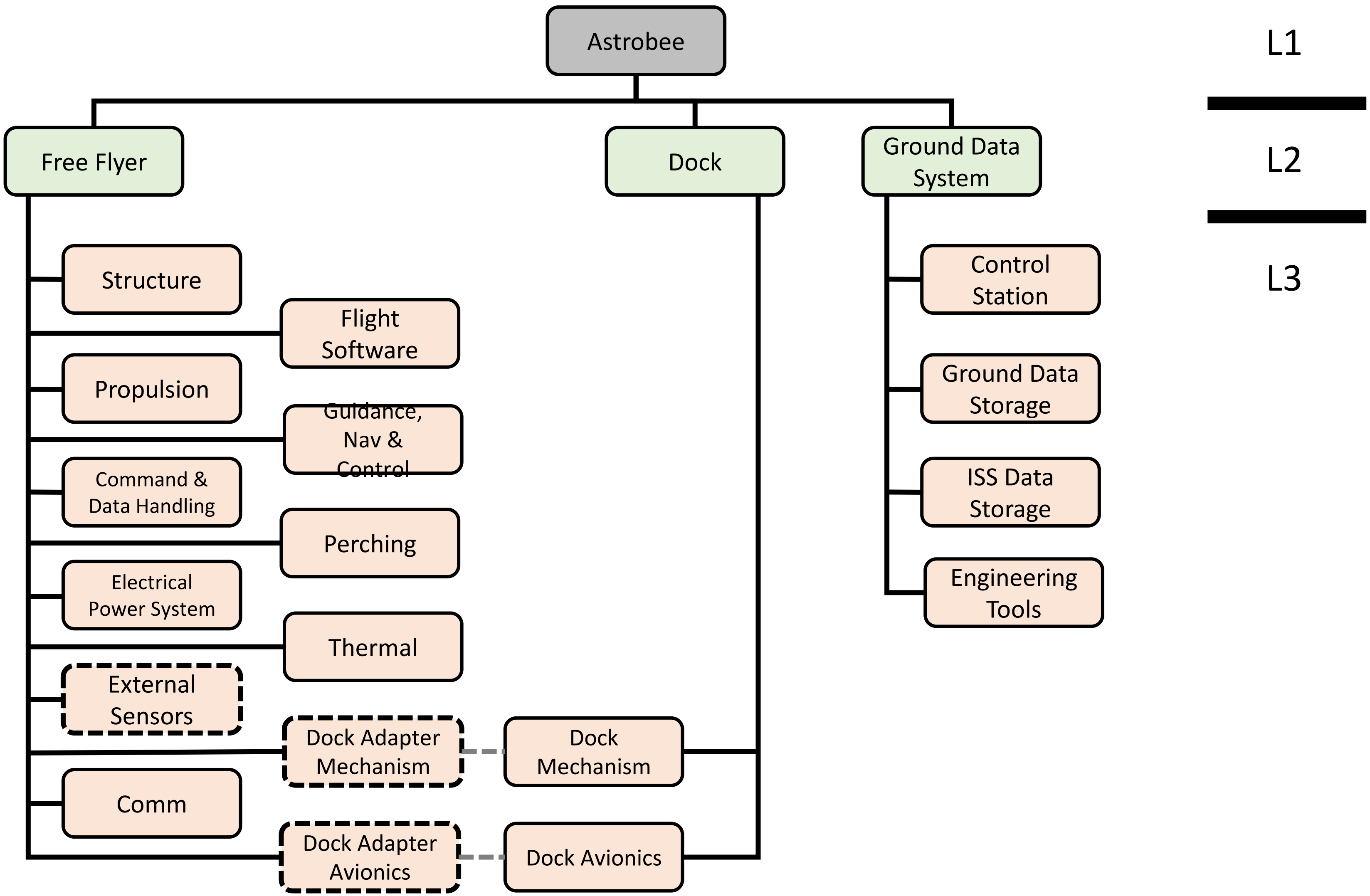
Astrobee Elements



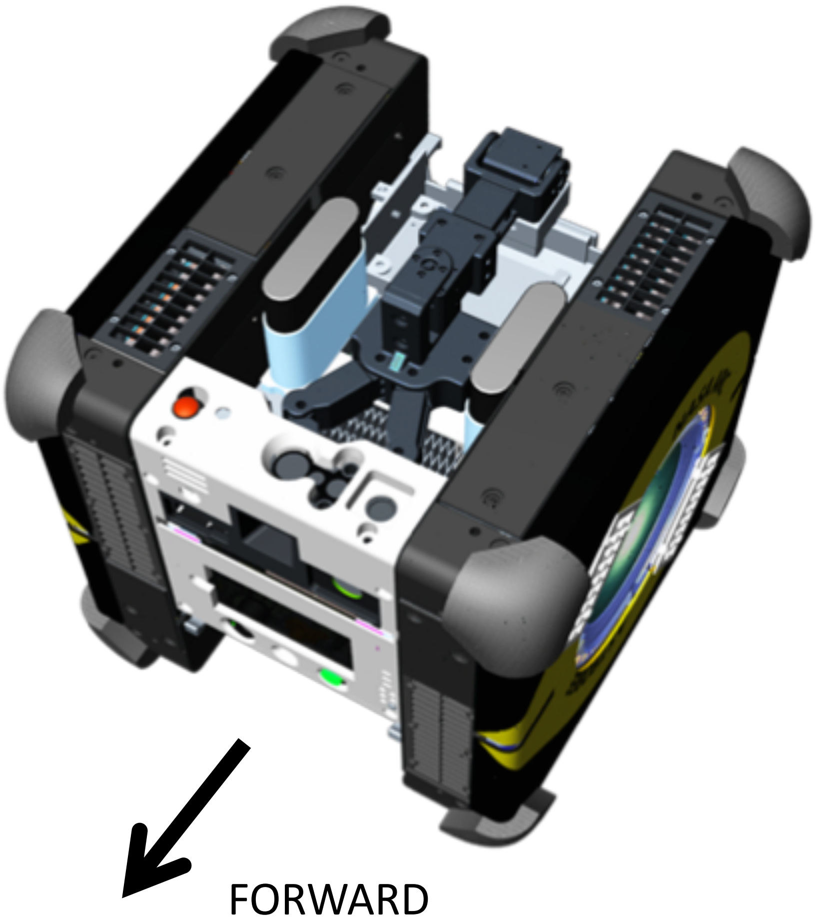
System Data Flow Diagram



Subsystems

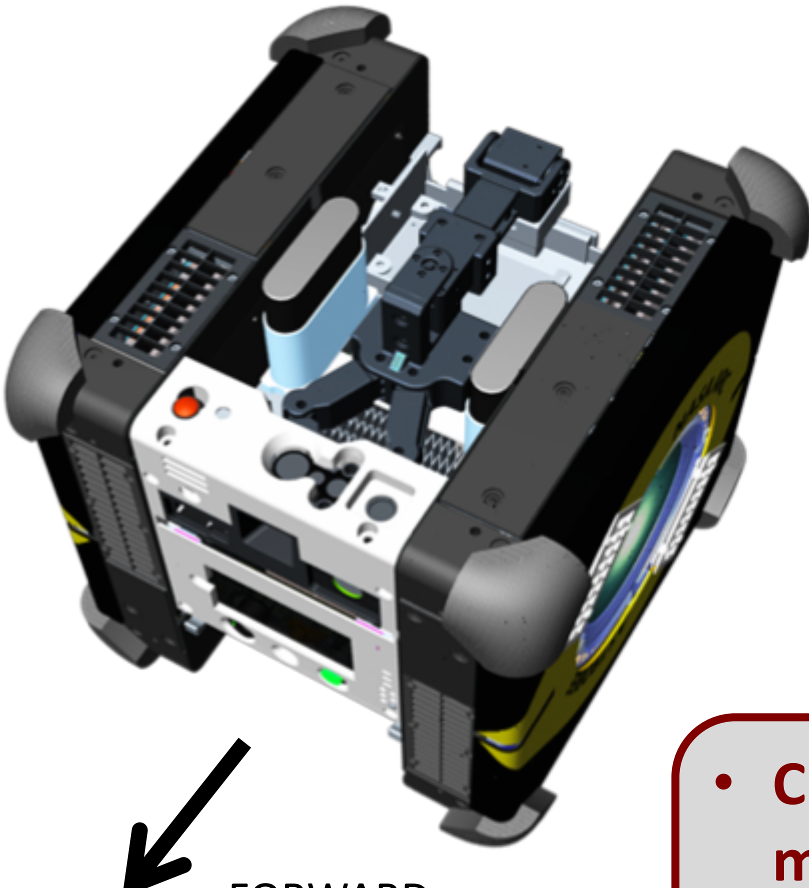

Astrobee
Free Flyer
Dock
Ground Data System
L1
L2
L3
Structure
Flight Software
Propulsion
Guidance, Nav & Control
Command & Data Handling
Perching
Electrical Power System
Thermal
External Sensors
Dock Adapter Mechanism
Dock Mechanism
Comm
Dock Adapter Avionics
Dock Avionics
Control Station
Ground Data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

Current Robot Design



12.5 x 12.5 x 12.5 inches
8 kg mass target

Current Robot Design



FORWARD

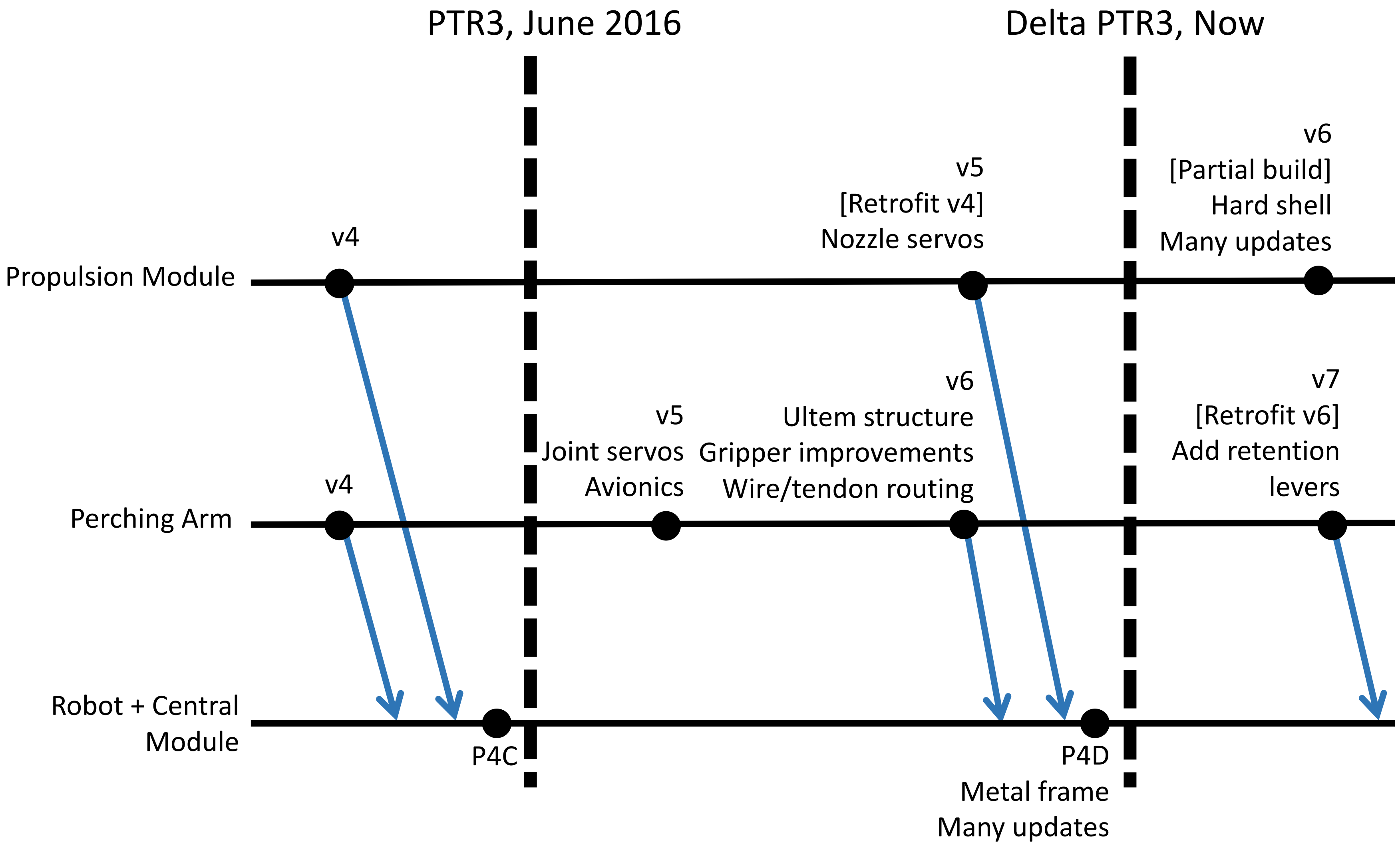
12.5 x 12.5 x 12.5 inches
8 kg mass target

- **Current best estimate of flight mass is 8.7 kg, above TPM threshold**
- **Will discuss this in detail later**

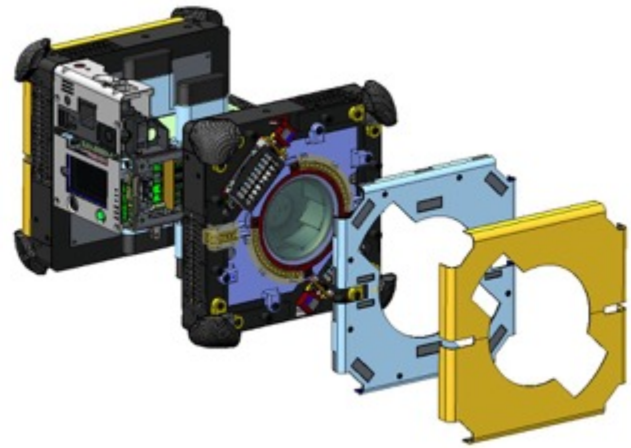
Project Response to PTR3 Feedback

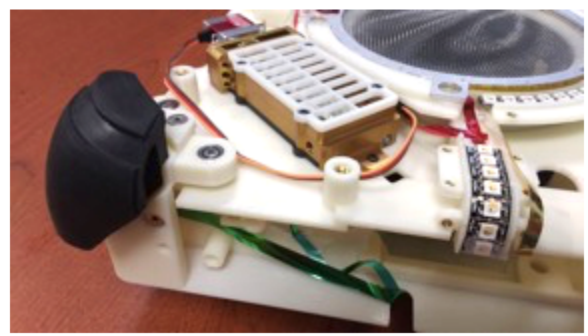
- Many design gaps and risks were identified at PTR3
- We judged the risk was too high to immediately proceed from Prototype 4C ("P4C") to cert unit build
- Therefore, do one more round of prototype testing prior to cert unit
  - Integrated P4D – Incorporates many of the post-PTR3 design changes
  - Stand-alone prototyping of some components – Used to save resources when we could retire the risk without integrated testing

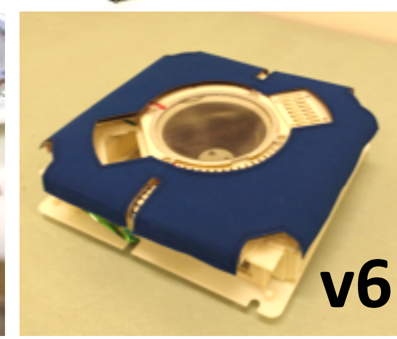
Robot Prototype Versions



Propulsion Module Versions







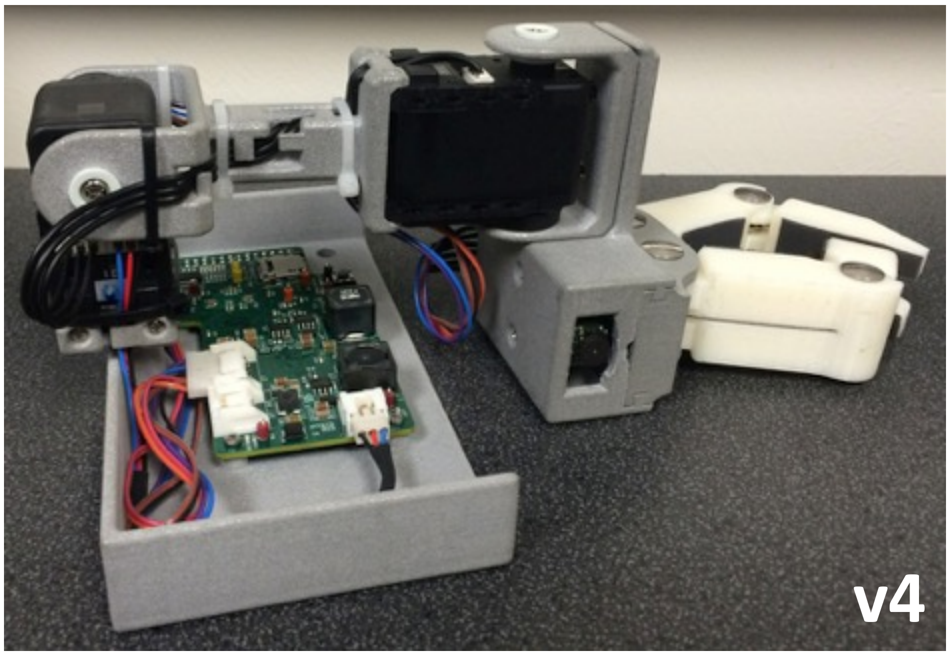
Propulsion Module

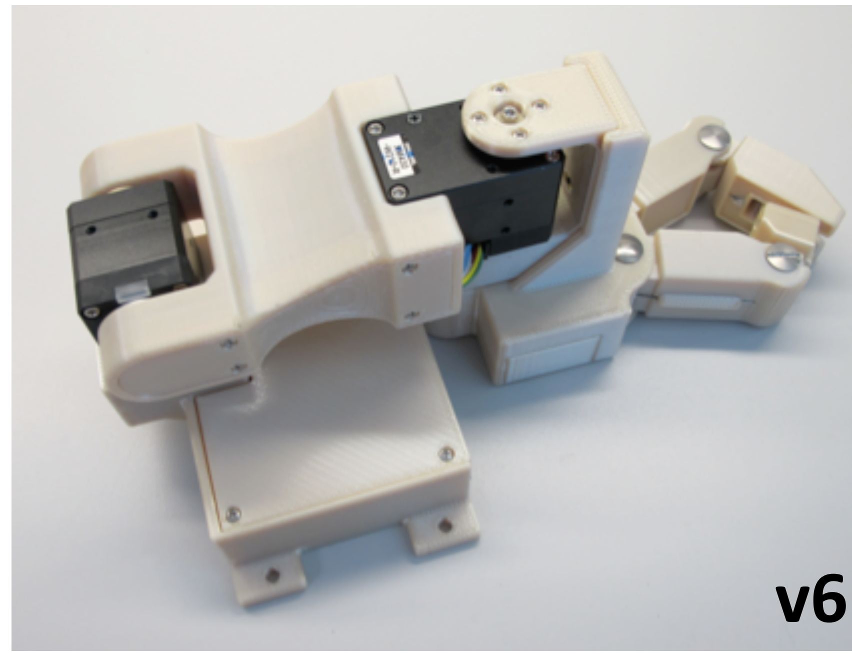
v4

v5
[Retrofit v4]
Nozzle servos

v6
[Partial build]
Hard shell
Many updates

Perching Arm Versions

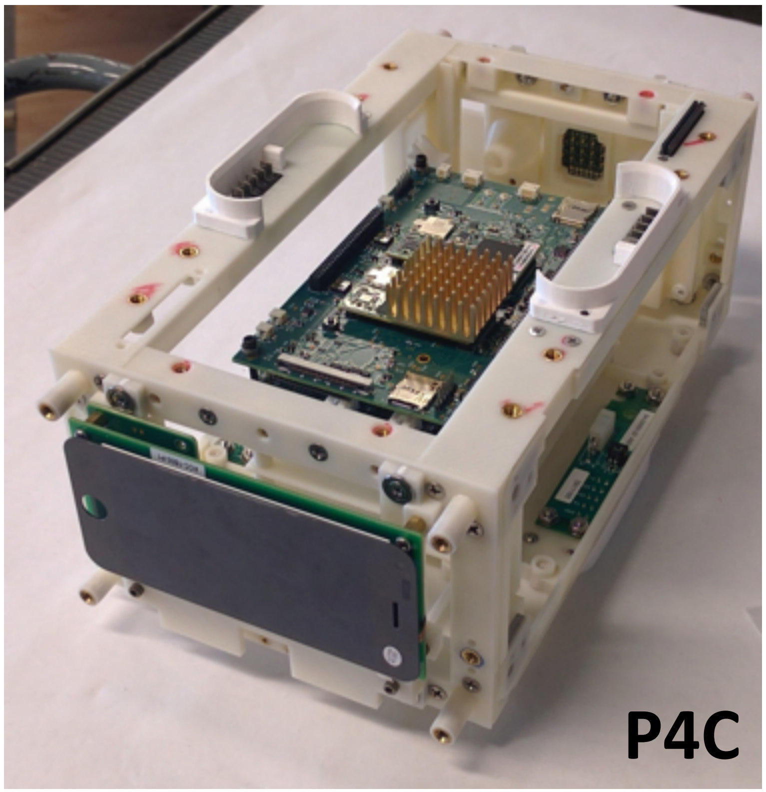


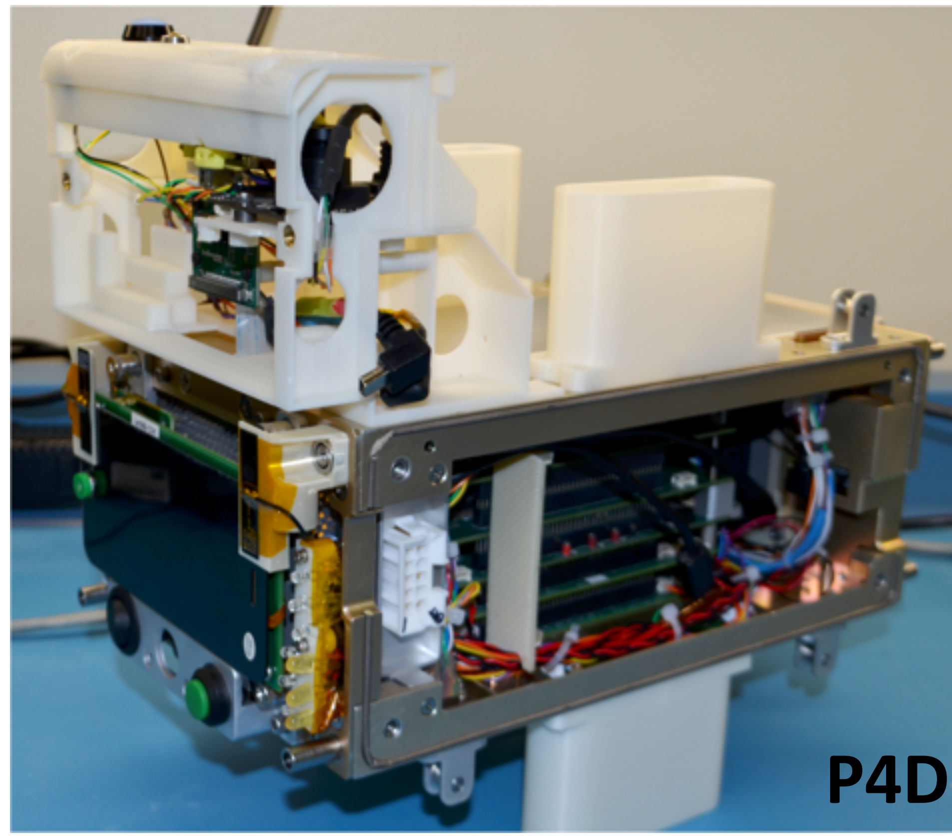


Perching Arm

- v4
- v5: Joint servos, Avionics
- v6: Ultem structure, Gripper improvements, Wire/tendon routing
- v7: [Retrofit v6] Add retention levers

Robot / Central Module Versions

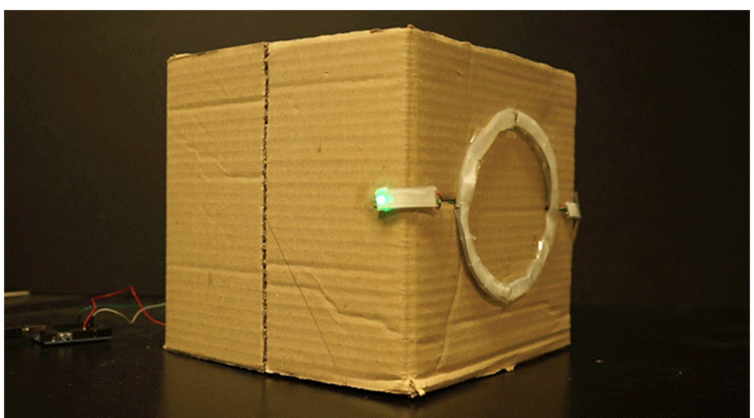




Robot + Central Module

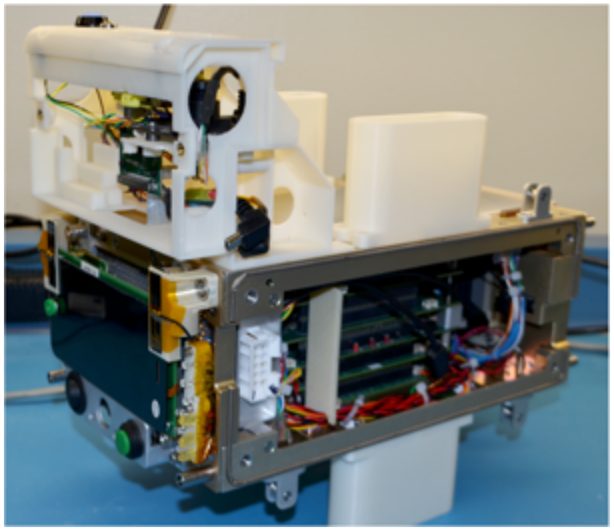
- P4C
- P4D
  Metal frame
  Many updates

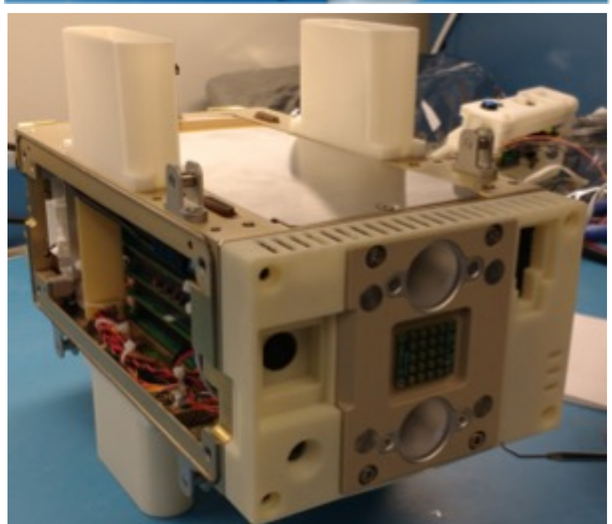
Human-Robot Interaction



- External appearance design
- Signal light design
- Human factors throughout (e.g. restraining straps)

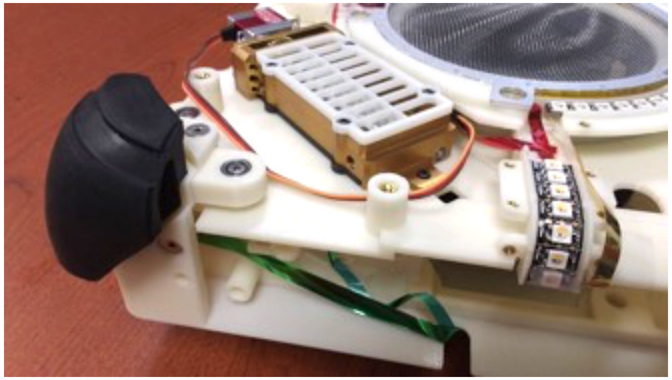
Structure

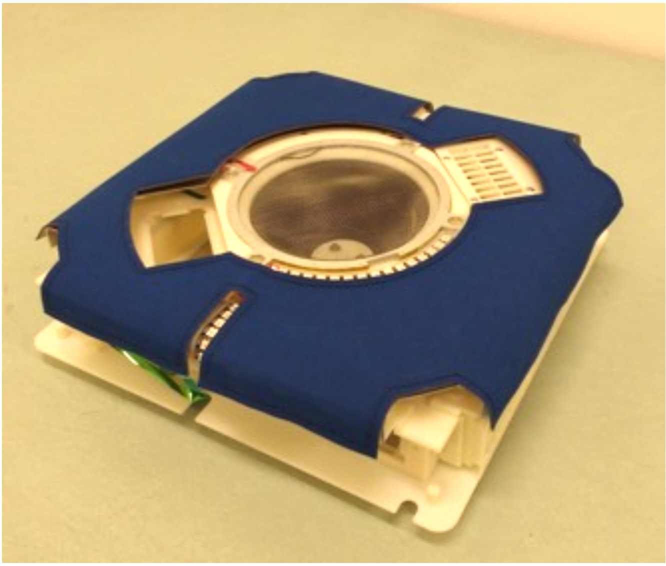




- Camera placement, servicing, lens protection
- Payload interface
- Wire routing and thermal air flow

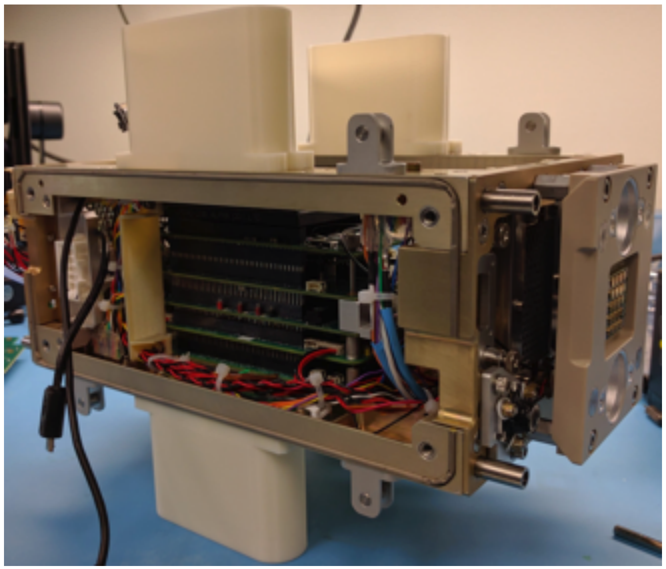
Propulsion

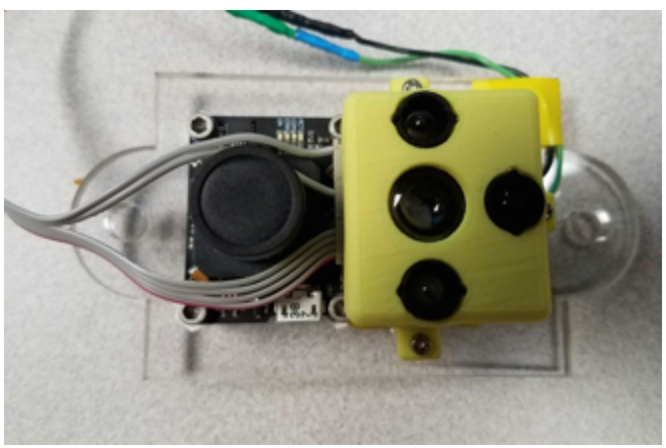




- Plenum lid / hard shell
- Corner bumpers
- Soft layer and skin

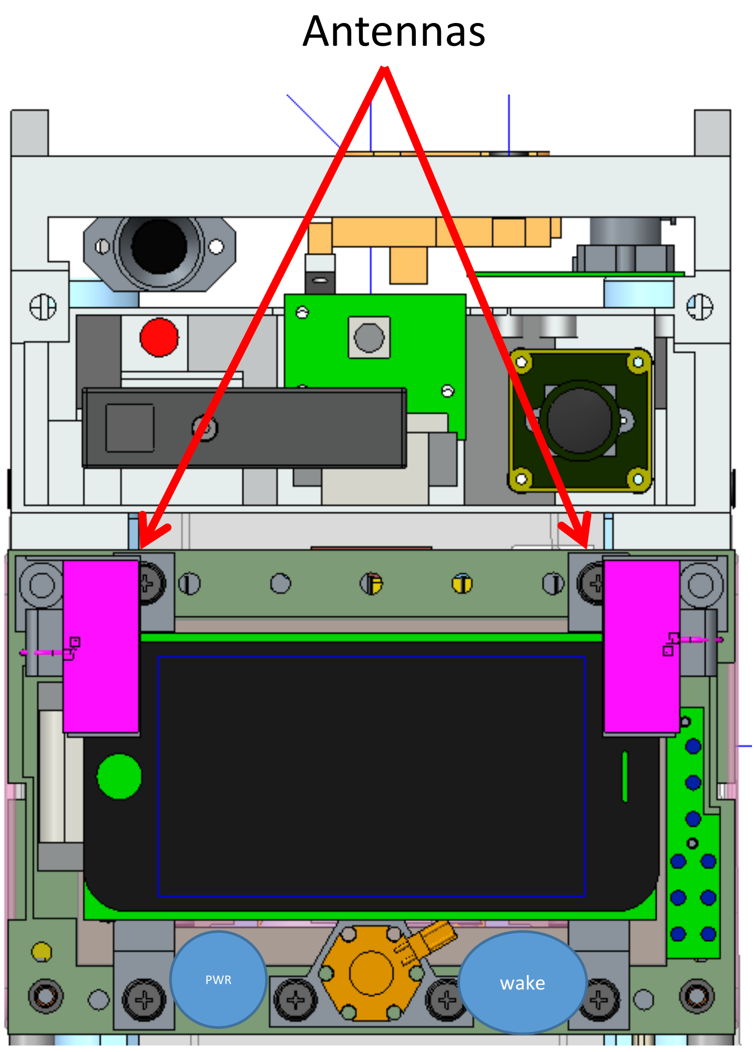
Avionics





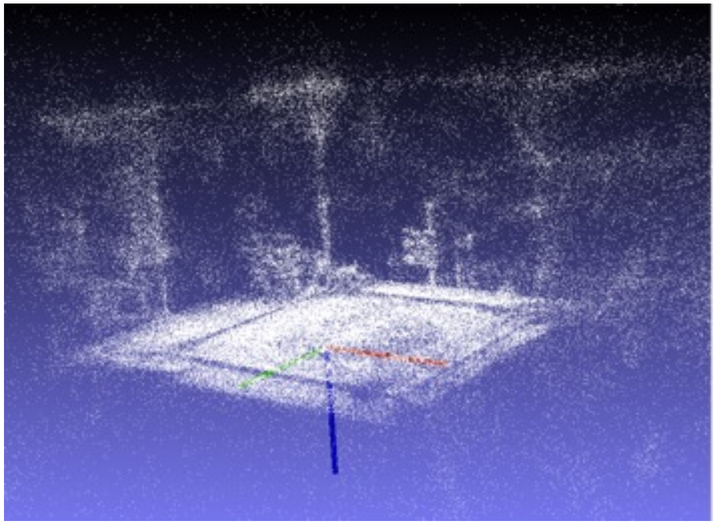
- Safety improvements (over-current, over-temperature controls)
- Improved support for software/firmware updates
- SpeedCam

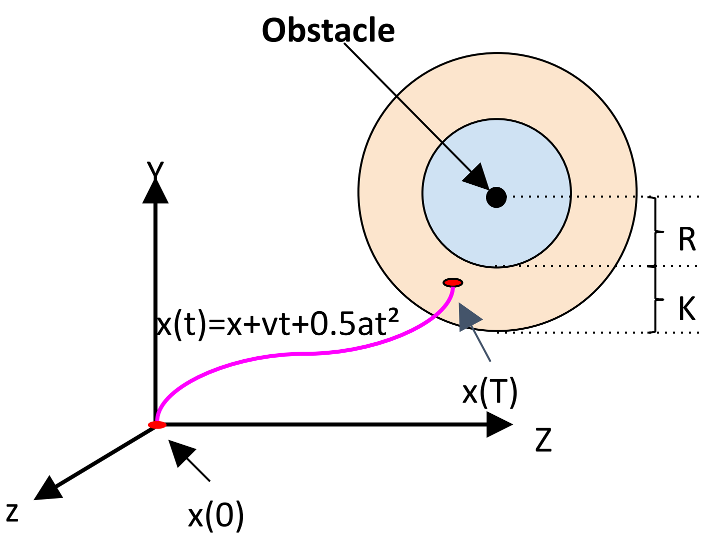
Comm



- Antenna placement
- Video distribution approach
- Telemetry recording and downlink management

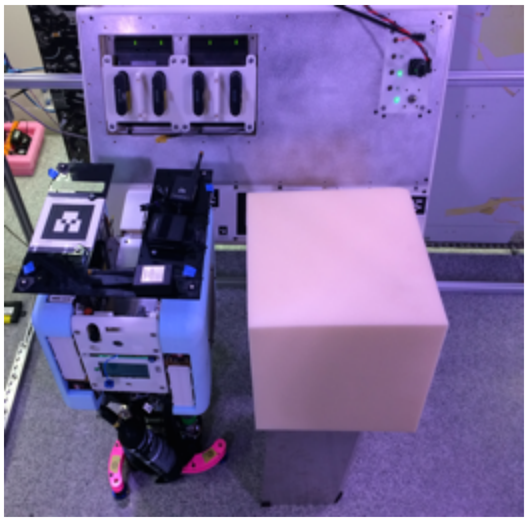
Flight Software



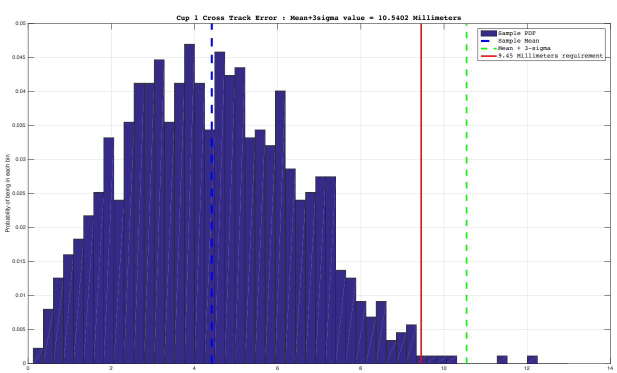


- Mode management and sequencing
- Onboard trajectory generation and collision detection
- Fault management infrastructure

Guidance, Navigation, and Control



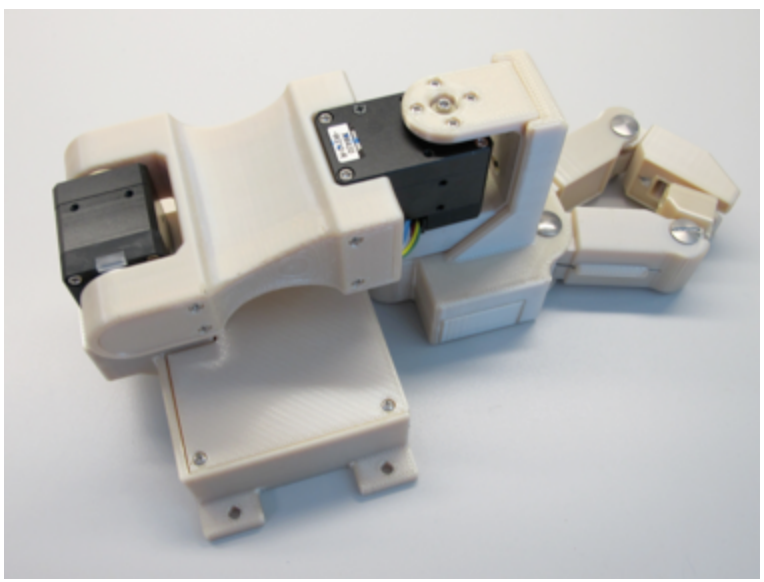
Ground effect test setup



Monte Carlo error distribution

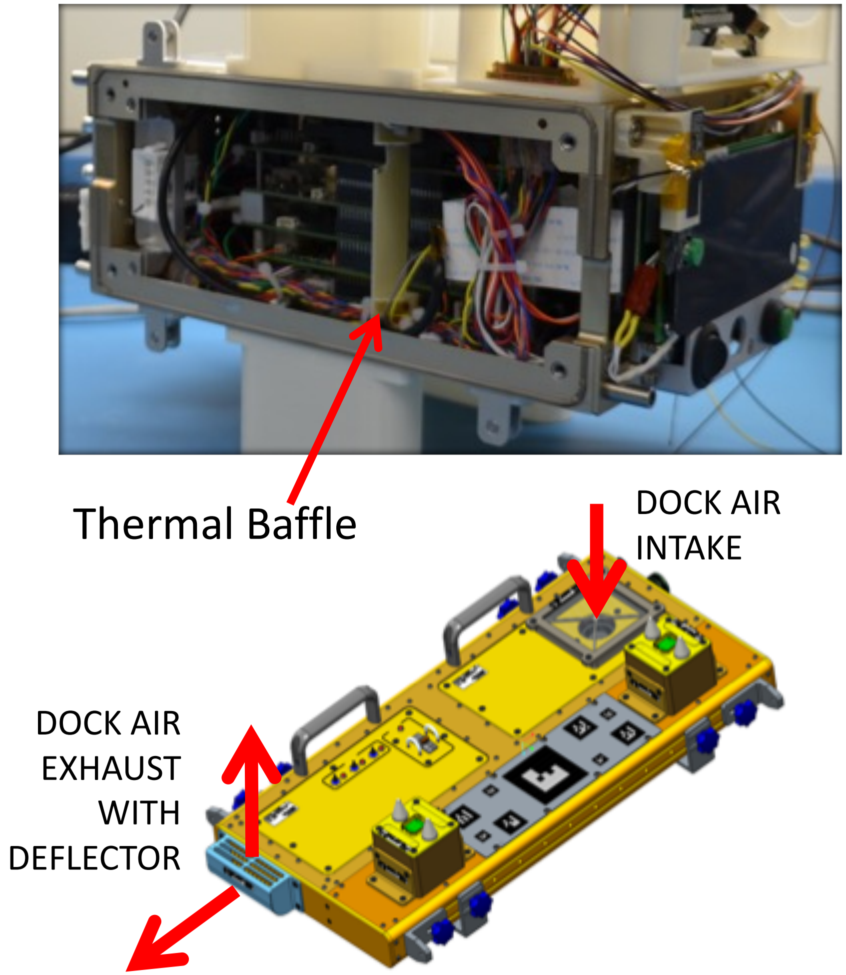
- Visual odometry
- 6 DOF gantry testing in 1g
- Fault management

Perching Arm



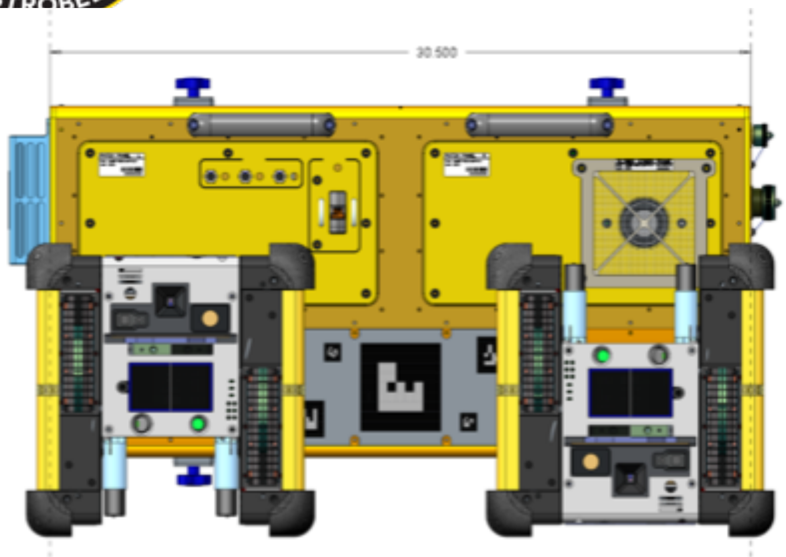
- Joint servo motor
- Wire and tendon routing
- On-orbit gripper swap/upgrade

Thermal



- Thermal testing and safety analysis for peripheral heat sources (e.g. arm motors)
- Arm gripper motor
- Dock thermal intake screen / minimize crew cleaning

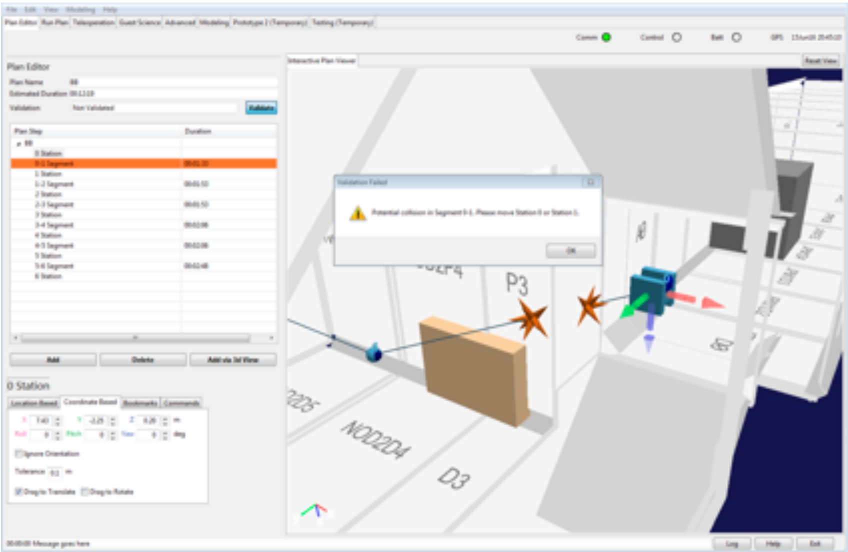
Docking Station

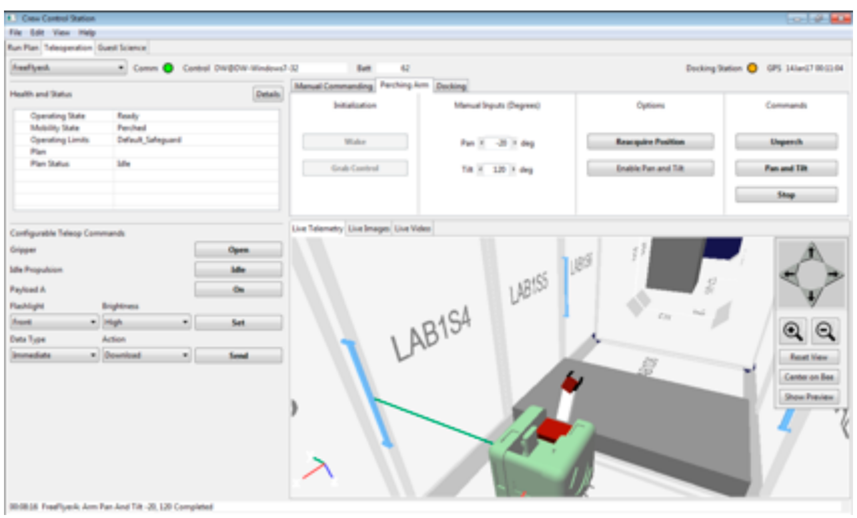


Dock Processor (same as LLP)

- Flexible ISS placement / attachment approach
- New remote wake function (requires “smart dock”)
- Separated COTS battery chargers from docking station to reduce volume / ease placement concerns

Ground Data System





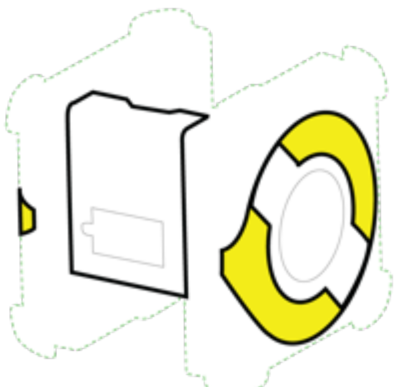
- Guest science interface
- Config file management
- Fault management

Astrobee
Human-Robot Interaction (HRI)

Design Overview

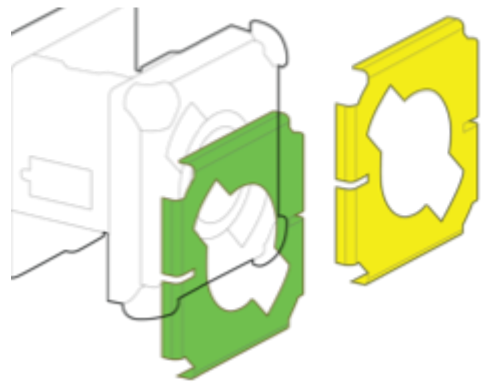
Design Goal

Characteristics

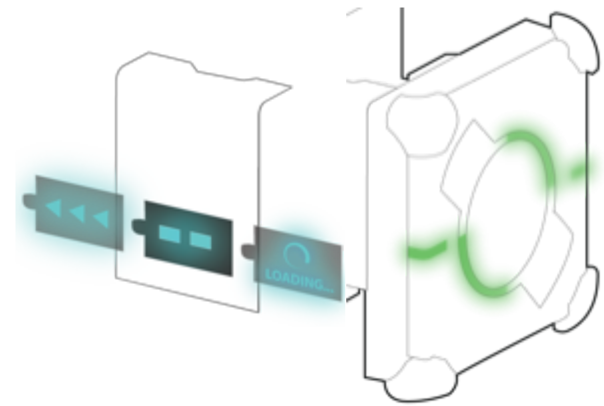


Sleek, not bulky

Attractiveness

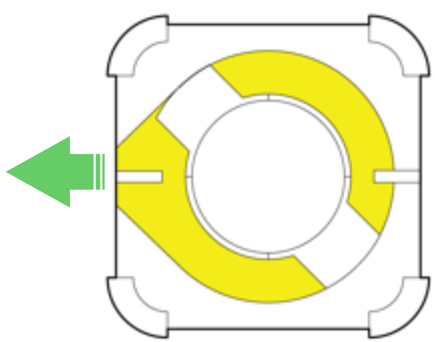


Engagement by identification

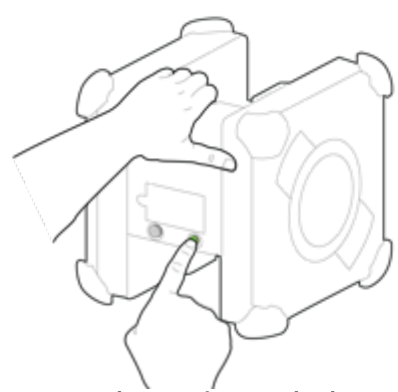


Affective & intuitive signals

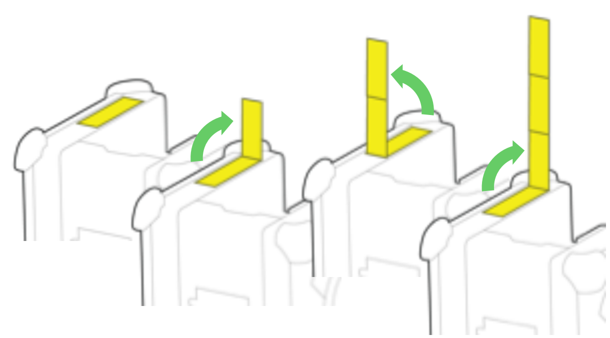
Functional Affordance



Clear indication of orientation



One-hand usability



Adjustable Velcro length

Design Maturity

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

Component	Maturity / Risk	Forward Work
Signal LEDs	High / Low	-
Light signaling pattern	Med / Low	Follow up with crew office
Sound signal	Low / Low	Design sound & follow up with crew office
Touch screen	Low / Low	Not started yet

New/Changes from PTR3

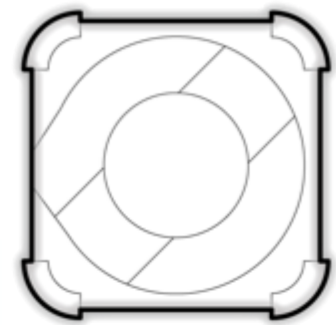
Component	New / Changes
Signal LEDs	- New signal LED arrays on each prop module
Light signaling pattern	- New signaling LED patterns for each robot state
Sound signal	- Define useful situation
Touch screen	- Define useful situation as signal modality

Purpose of HRI

Human Perspective

- Proximal user (Crew): Aware robot states **without annoyance** and **task disruption**
- Distant user (Ground Operator) : **No latency** for signaling states

Human



Astrobee

- Represent various state having different **criticality, urgency, and amount of information**

Robot Perspective

ISS ROBOTIC FREE FLYER
ASTROBEE

Non-verbal Signal

- Representing information that is important but not critical
- Provide subtle changes to reflect updates without distraction
- Moving from the periphery to the focus of attention

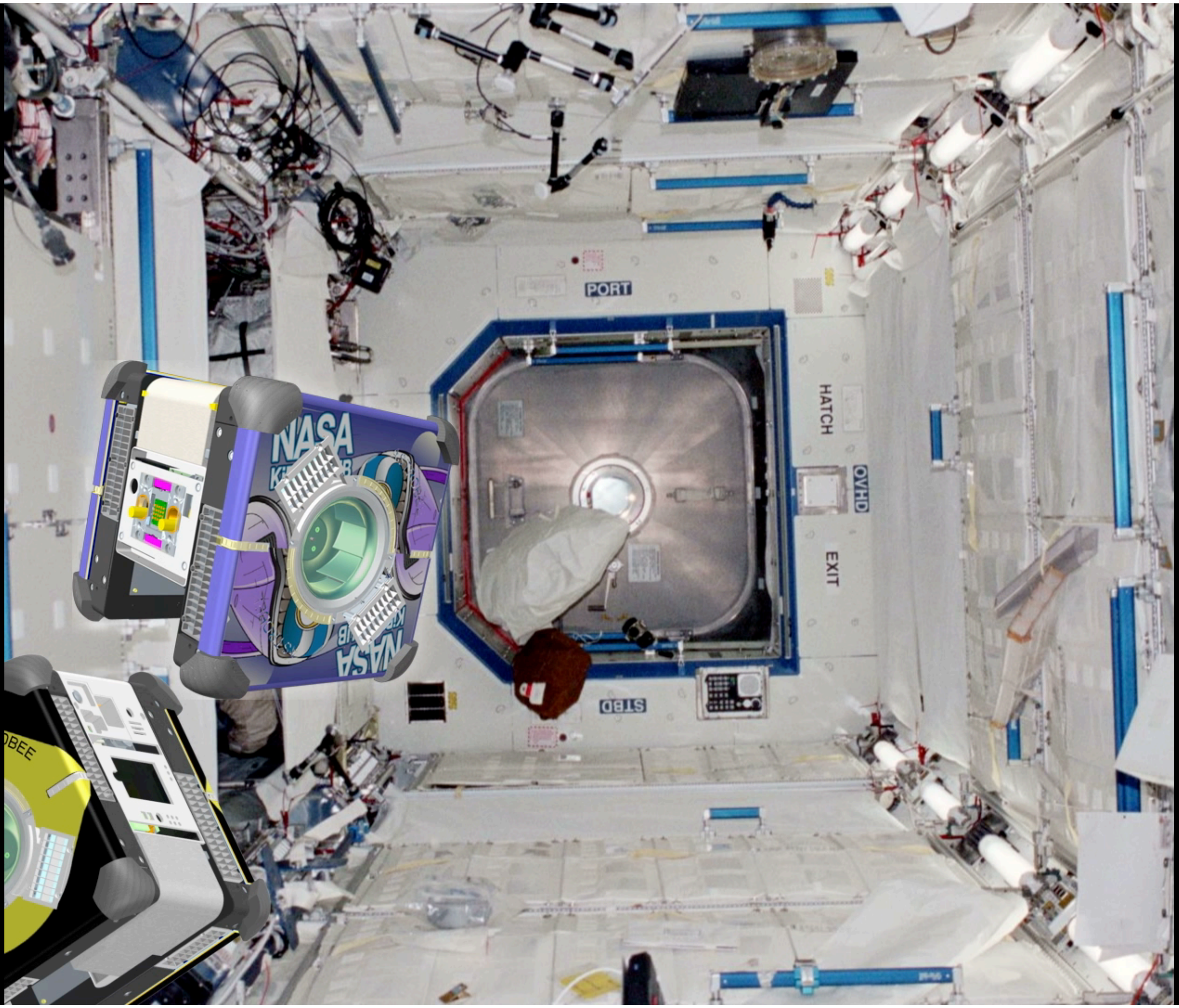
	Light	**Sound**
Strength	• Visually perceived before consciously attention • Sophisticatedly express states	• Convey information without visibility restriction • Strong focus of attention
Weakness	• Requires line of sight • Interference from natural and artificial sources	• Can be perceived as interference or annoyance • Masked by other sound

Interaction Modality

Physical Distance

	Separate (invisible)	Distant	Close
Sound	Alerting a state	Alerting a state	Alerting + voice command
Movement		Motion	Orientation, Gesture
Light		Conveying intent	Conveying intent
Touch Screen		Conveying intent	Conveying intent / information
Touch (Haptic)			Receiving crew's input

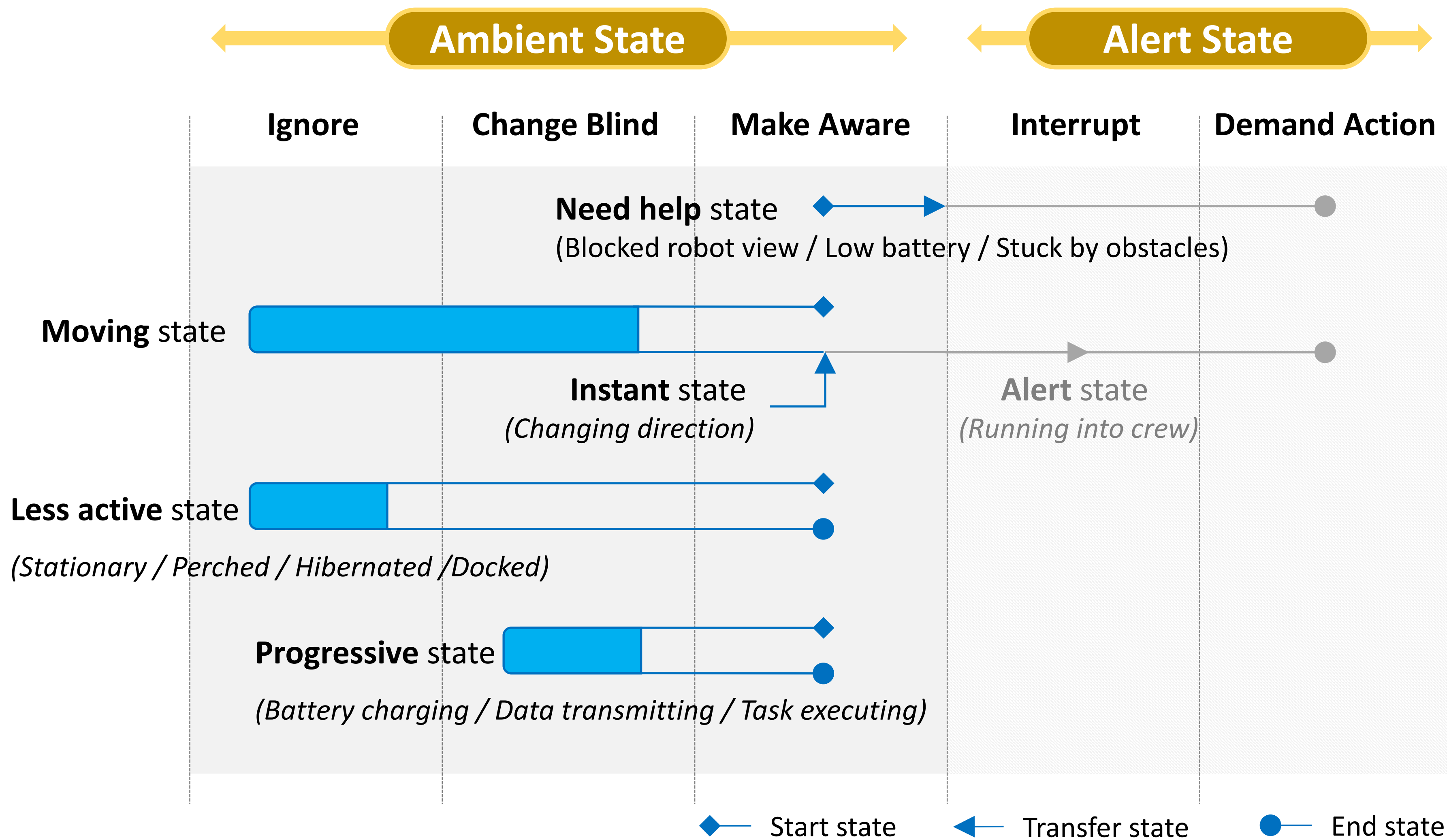
Signal Light Concept



Notification Level

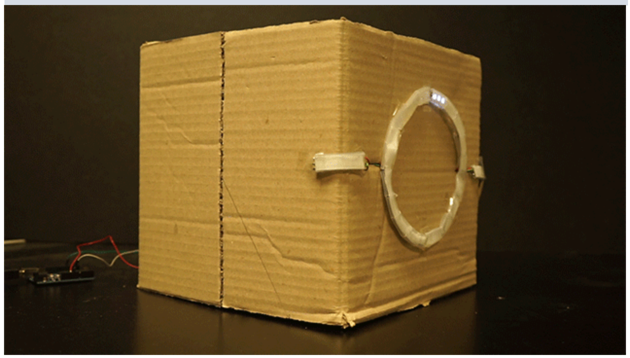
High awareness	**Demand Reaction**	Interrupt until user does action
	Interrupt	Demand attention (flashing, beeping, vibration, etc.)
	Make Aware	to help people decide their further action
	Change Blind	tiny updates, slow, fade (help people expect robot's overall action)
Low awareness	**Ignore**	no change (let people aware of why robot is awaken / whether the robot is awaken)

Notification Level & Robot States



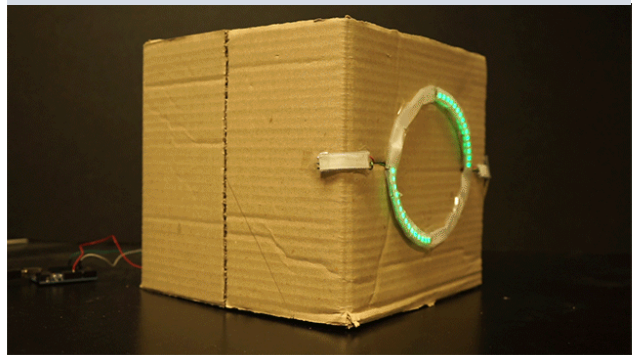
Signal Light Design

Hibernating



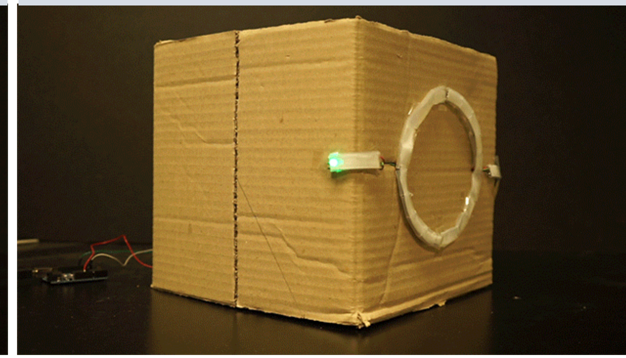
Blink, White

Stationary



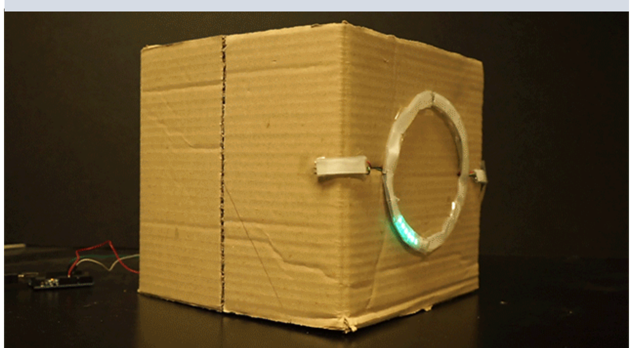
Blink, Green

Moving



Flowing, Green

Data Transmit / Task Execute



Spinning, Cyan

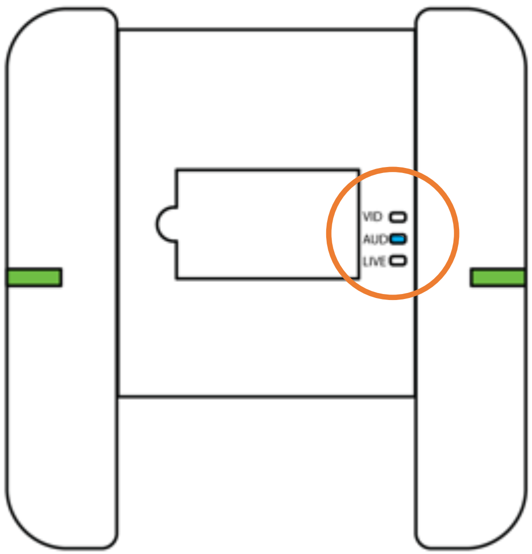
Stuck by Obstacle

Running into Crew

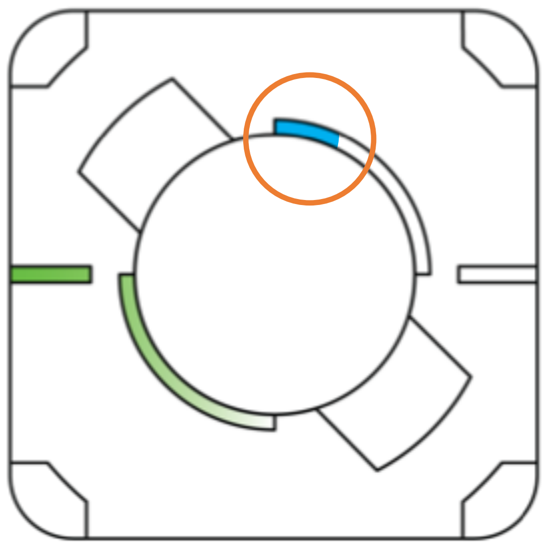
Blink, Amber

Crew Privacy

- Using **blue color** only for indicating *Audio Recording* state
- Representing *Audio Recording* states on **all side of Astrobee**
  - status LEDs on front/aft face & signal LEDs on both props



Front face



Prop

Audio Recording
while **Moving**

Astrobee Structure Subsystem

Design Overview

Design Maturity

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.

Component	Maturity / Risk	Forward Work
Core Module	High / Low	- Implement P4D findings - Finalize battery retention system
Top Forward Module	High / Low	- Implement P4D findings - Incorporate Al. Structure - Incorporate NavCam protection
Forward Group	High / Low	- Implement P4D findings
Aft Group	High / Low	- Implement P4D findings
Forward and Aft Bezels	Medium / Low	- Implement P4D findings - Finalize inlet screen

New/Changes from PTR3

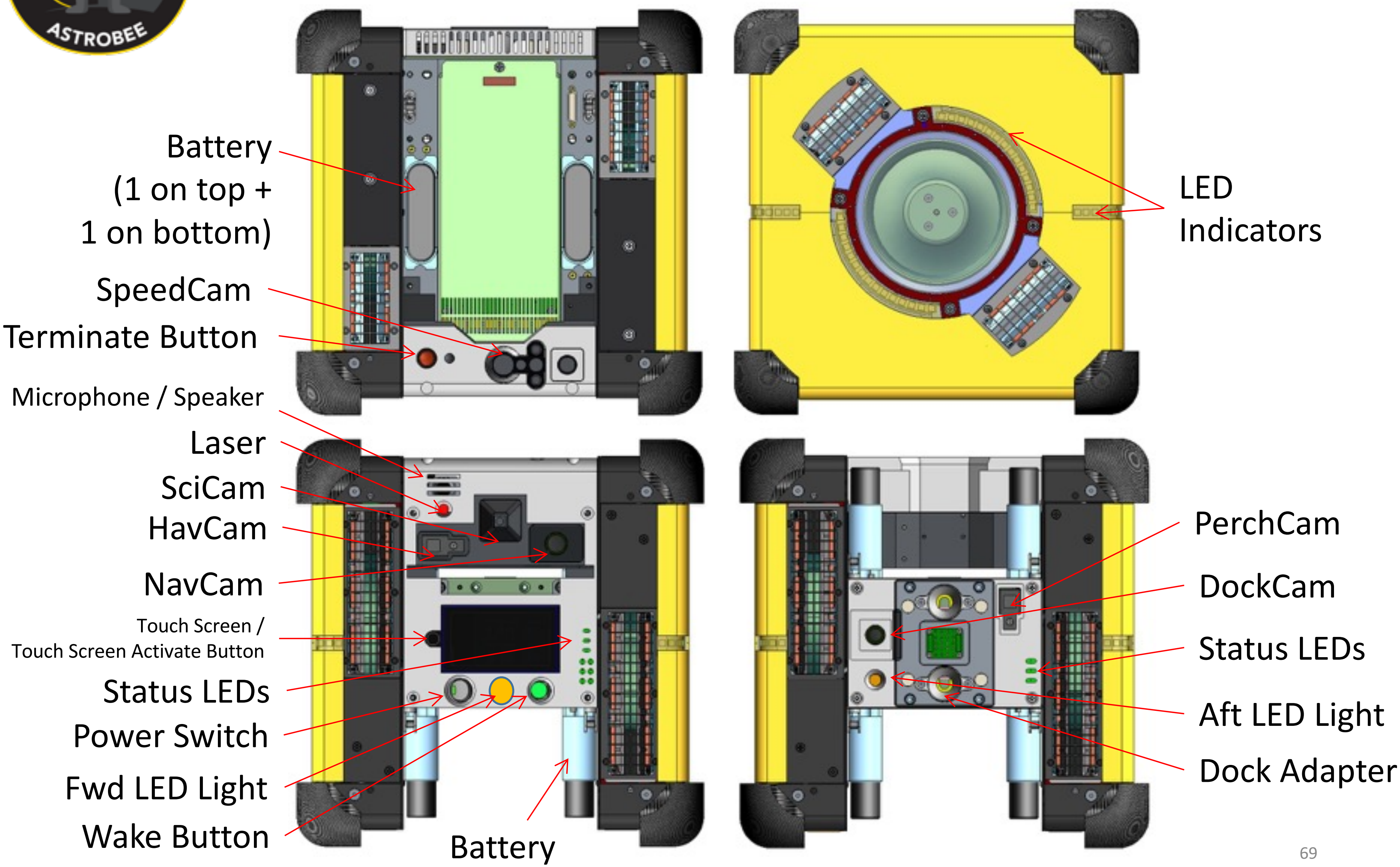
Component	New / Changes
Core Module	- Changed replaceable modules and incorporate designs - Changed fwd antenna locations - New camera locations - New button location and design - New status led designs - Changed Avionics location - New Payload attachment design - New top cover removal screw - New wire routing features
Top Forward Module	- Changed replaceable modules and incorporated designs - New camera locations - New wire cover design
Forward Group	- Changed touchscreen location
Aft Group	- Changed docking cups orientation and cup size - Changed aft antenna location
Forward and Aft Bezels	- Change fwd and aft cooling air vents - New forward bezel configuration

Astrobee Images

Forward Top

Aft Top

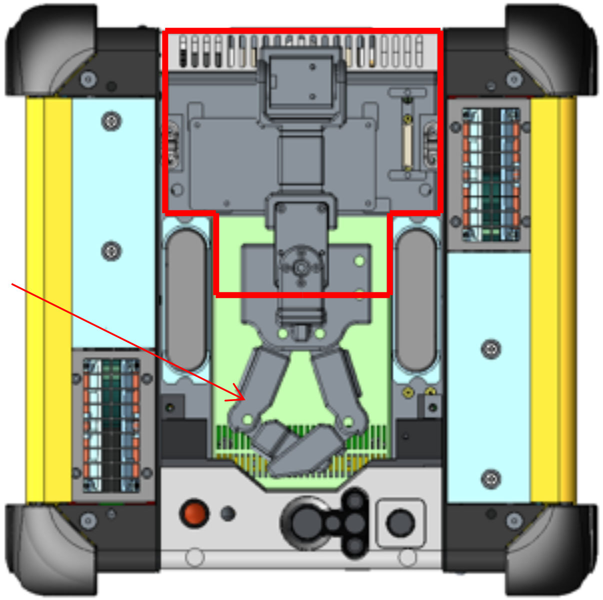
Base Layout

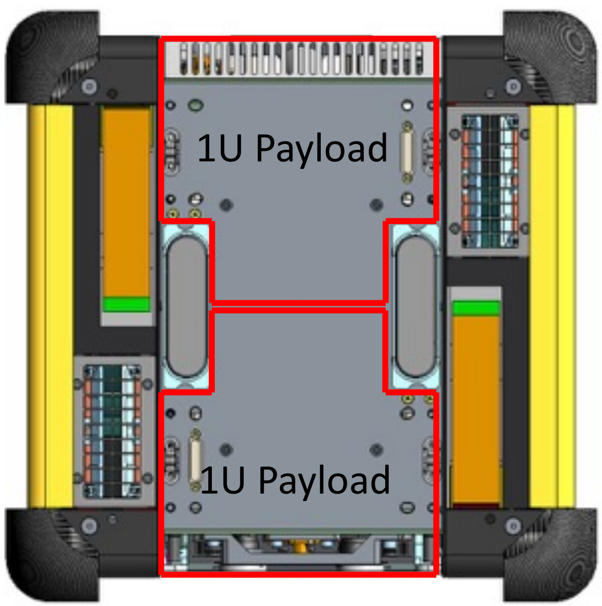


Battery
(1 on top +
1 on bottom)
SpeedCam
Terminate Button
Microphone / Speaker
Laser
SciCam
HavCam
NavCam
Touch Screen /
Touch Screen Activate Button
Status LEDs
Power Switch
Fwd LED Light
Wake Button
Battery
LED
Indicators
PerchCam
DockCam
Status LEDs
Aft LED Light
Dock Adapter

Payload Layout

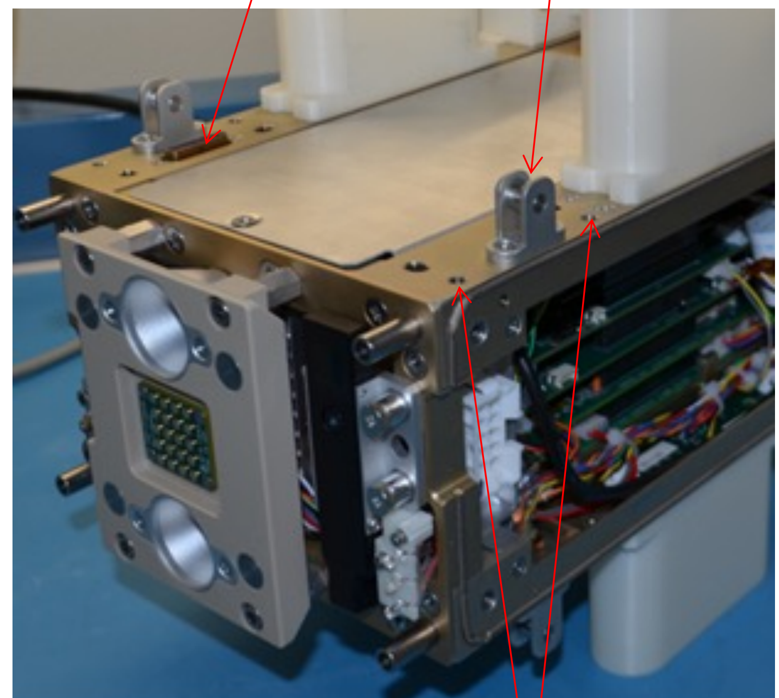
Perch Arm is larger than 1U





Core Connector
31 POS PLUG (M835130E03C)

2X Clevis

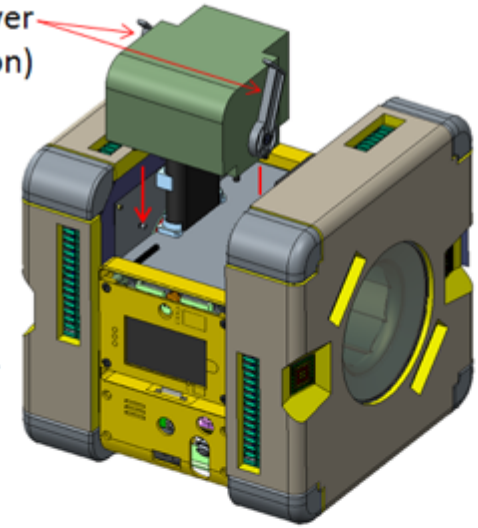


4X #8-32 Thread

Payload Mechanical Attachment Options

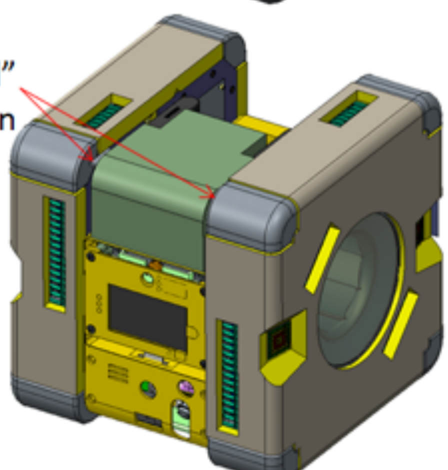
Quick "No Tool" Payload Attachment

2X Lever
(open position)



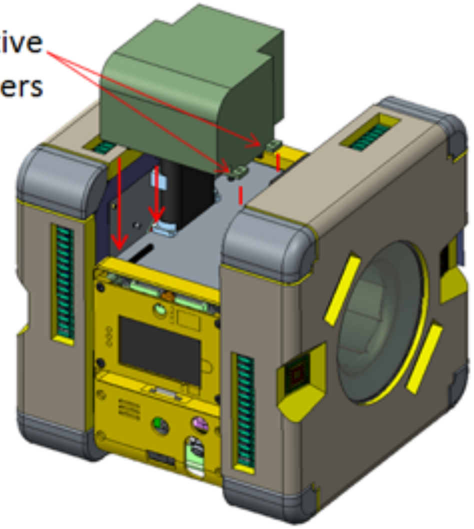
Lever engages and disengages payload connector and provides mechanical attachment

Lever in "Locked" position

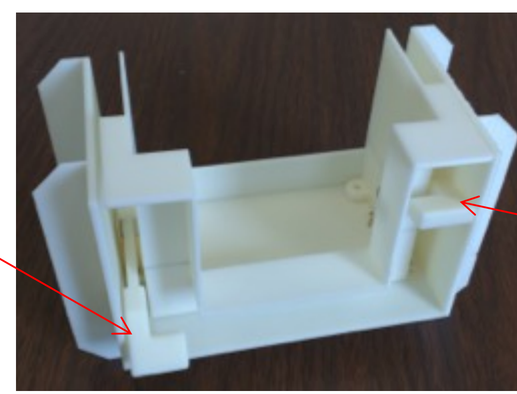


4X Fastener Payload Attachment

4X Captive Fasteners



"Un-Lock" Position

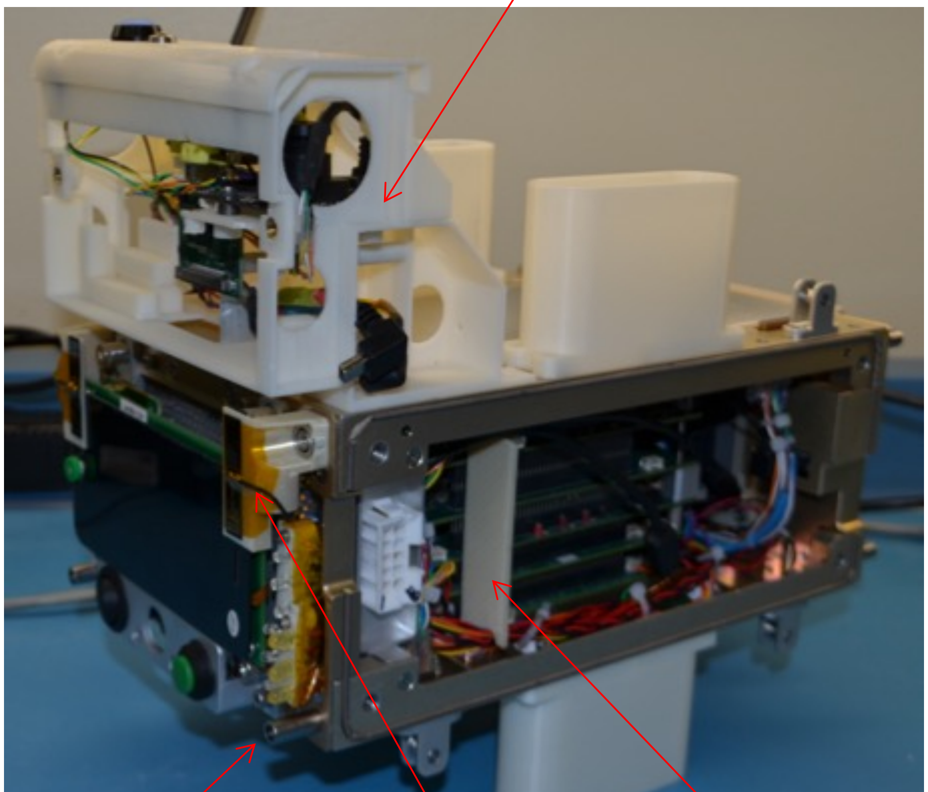


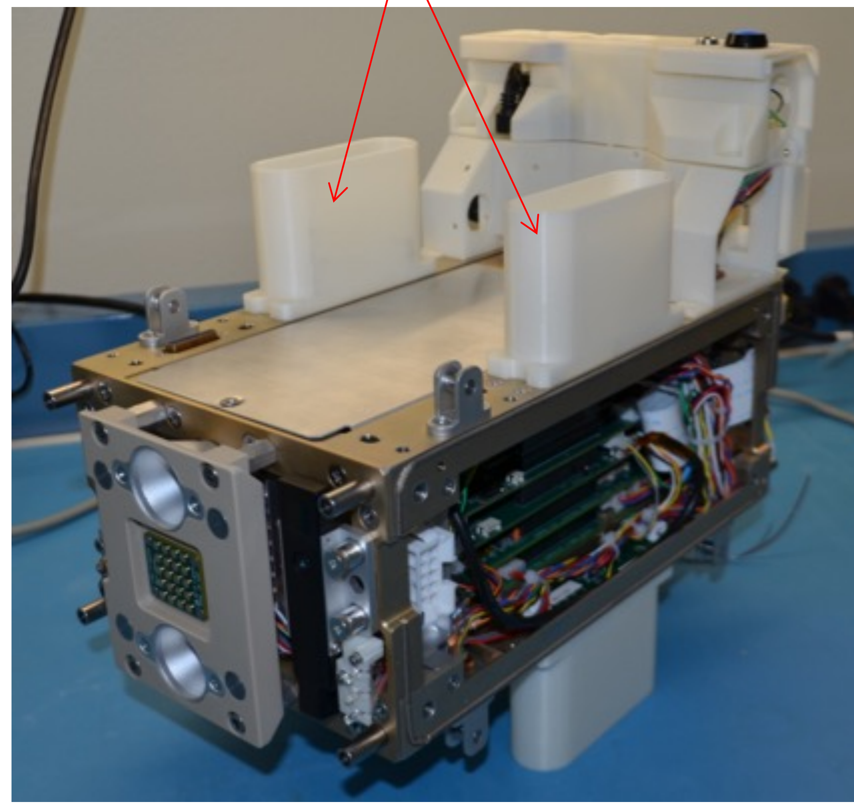
"Lock" Position

Core and Forward Module

Top Forward Module
(in ABS Prototype)

Battery Retainer



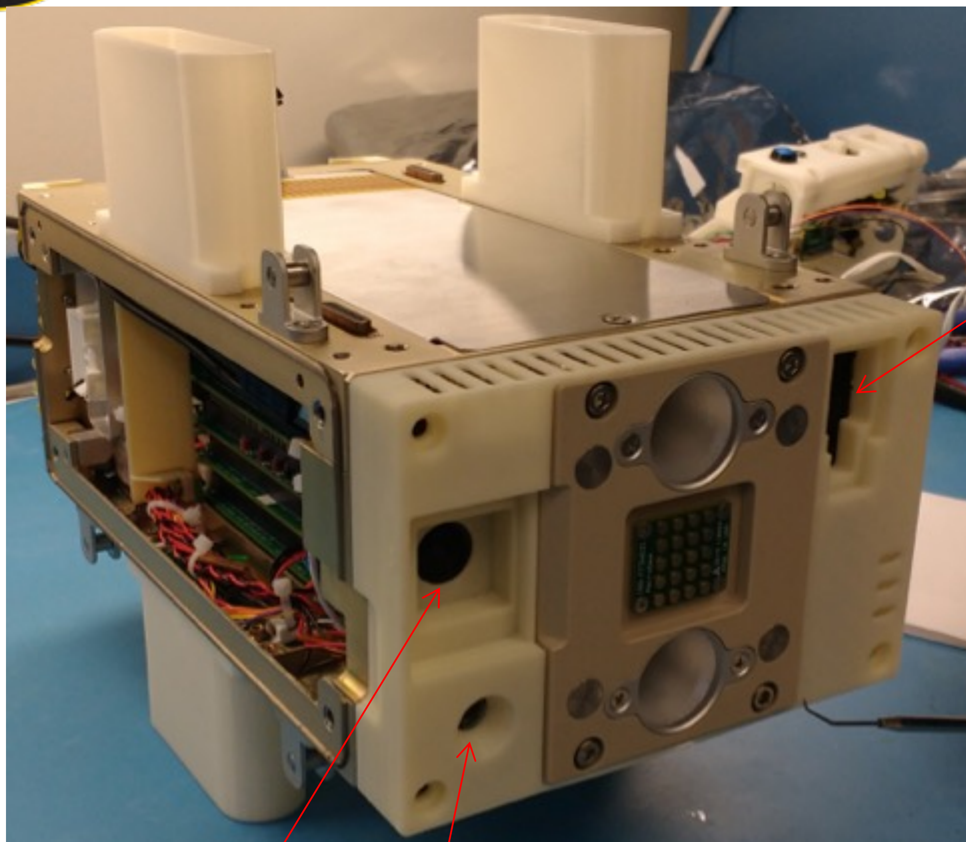


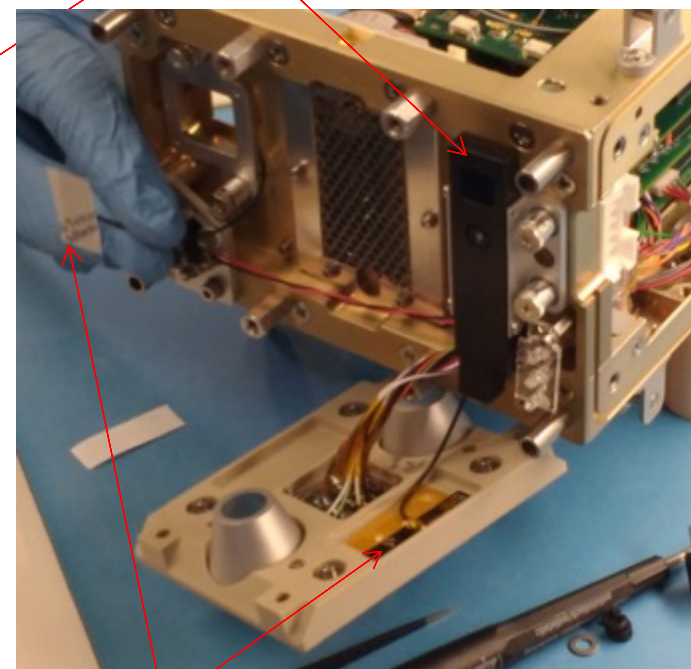
Forward Bezel
Not shown

Fwd Antennas

Air deflector

Aft Module





Perch Cam

DockCam

Aft LED Light

Aft Antennas

Astrobee Propulsion Subsystem

Design Overview

Design Maturity

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.

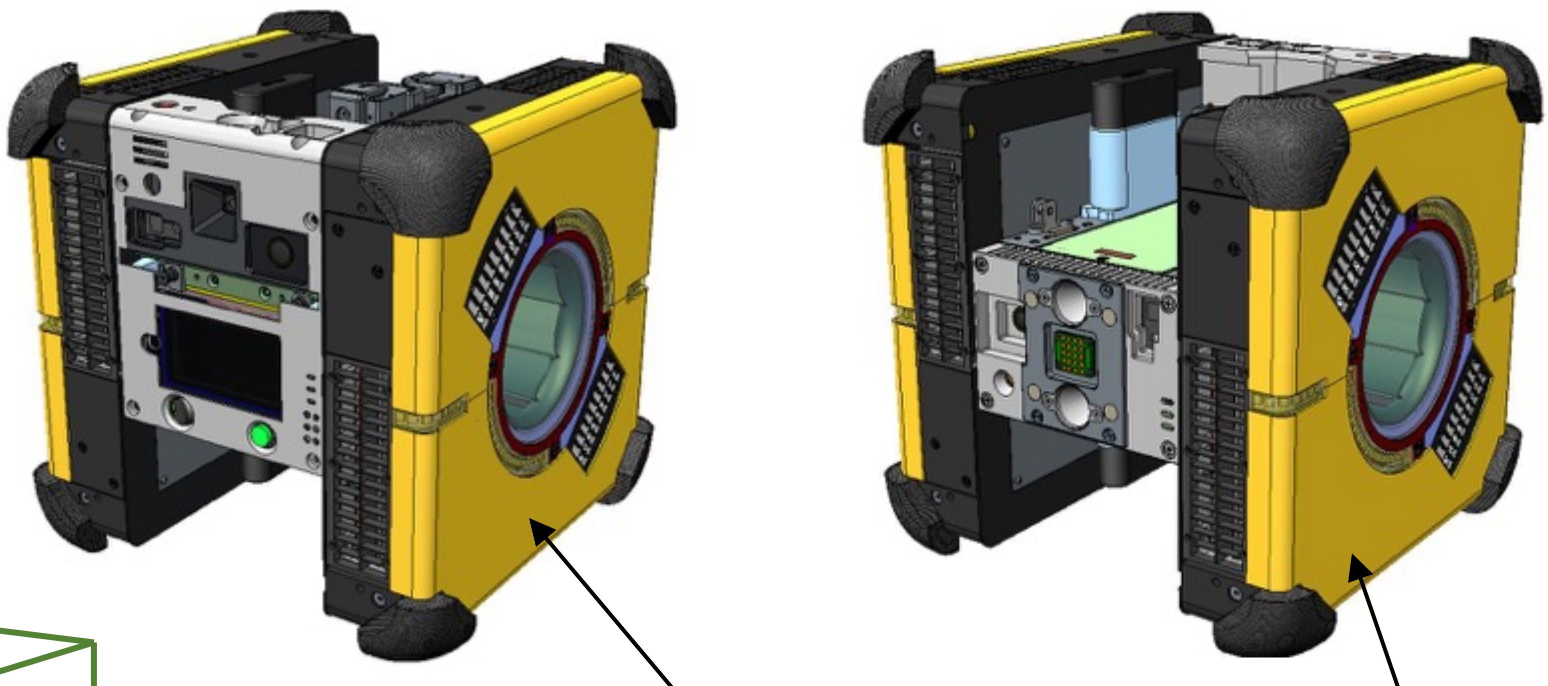
Component	Maturity / Risk	Forward Work
Plenum	High/Low	Improve strength
Top Cover and Skins	High/Low	Finalize skin attachment methods. See Yun's slides
Signal Lights	High/Low	See Yun's slides
Restraint Straps	High/Low	
Impact Mitigation	High/Low	Finalize bumper nomex cover design
Nozzles	High / Low	
Impeller/Motor	High/Low	

New/Changes from PTR3

Component	New / Changes
Plenum	- Added features for covers and nozzle changes
Top Cover and Skins	- New Al. Top Cover with softlayer - New skin design
Signal Lights	- New signal light design
Restraint Straps	- New restraint strap design
Impact Mitigation	- Finalized bumper materials - Confirm bumper force performance with testing - New softlayer design
Nozzles	- New vibration isolation and seal components - Change to servo spline drive shaft - Change drive shaft gear - New servo thermal sensor
Impeller/Motor	- New stiffened impeller

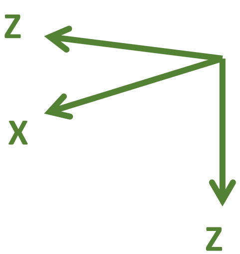
Astrobee Design

Two identical Propulsion Modules on Astrobee



Left Propulsion Module

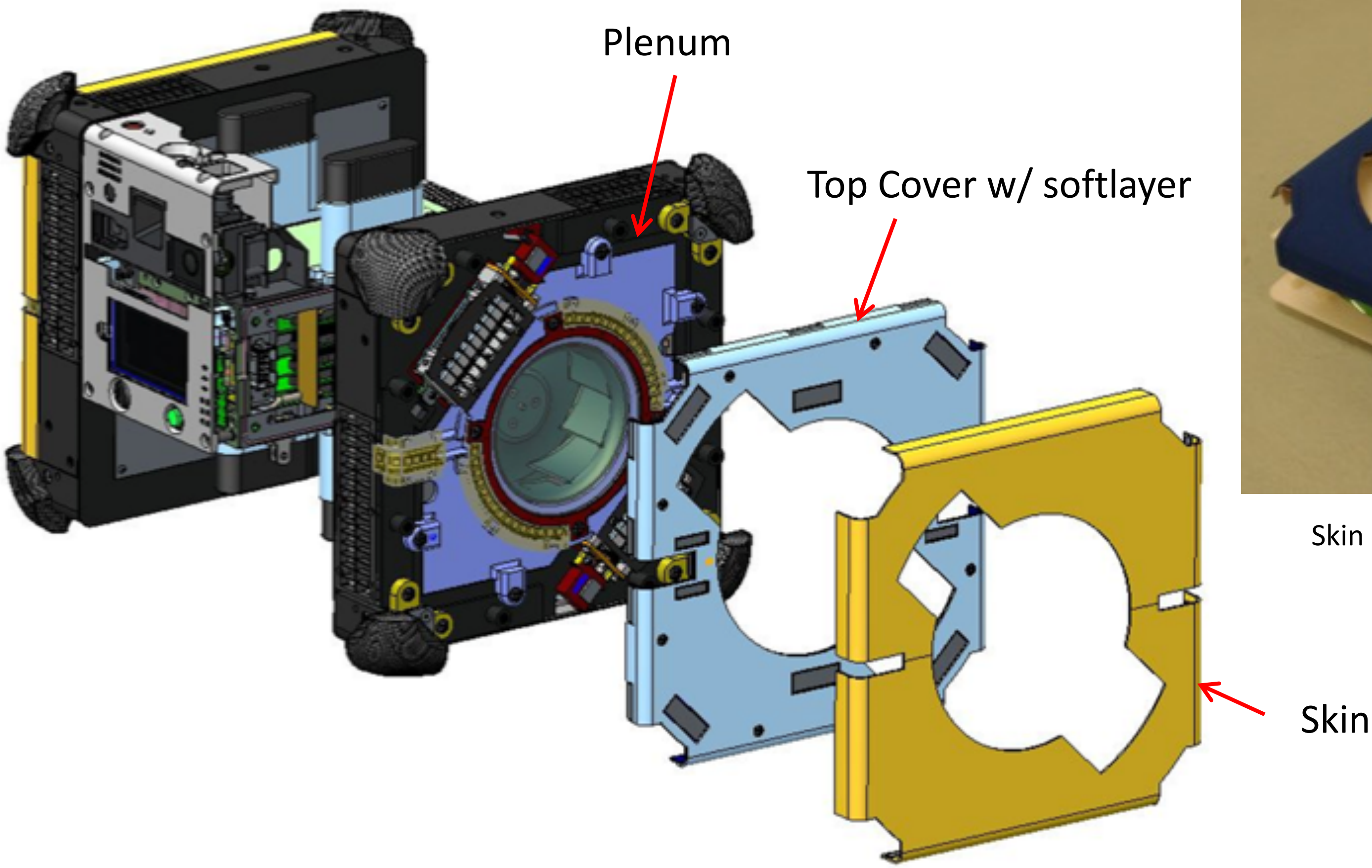
Right Propulsion Module

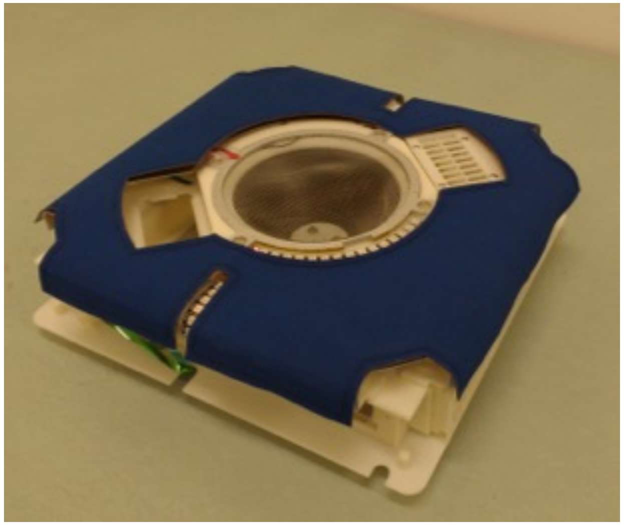


Front ISO View

Aft ISO View

Top Cover and Skins

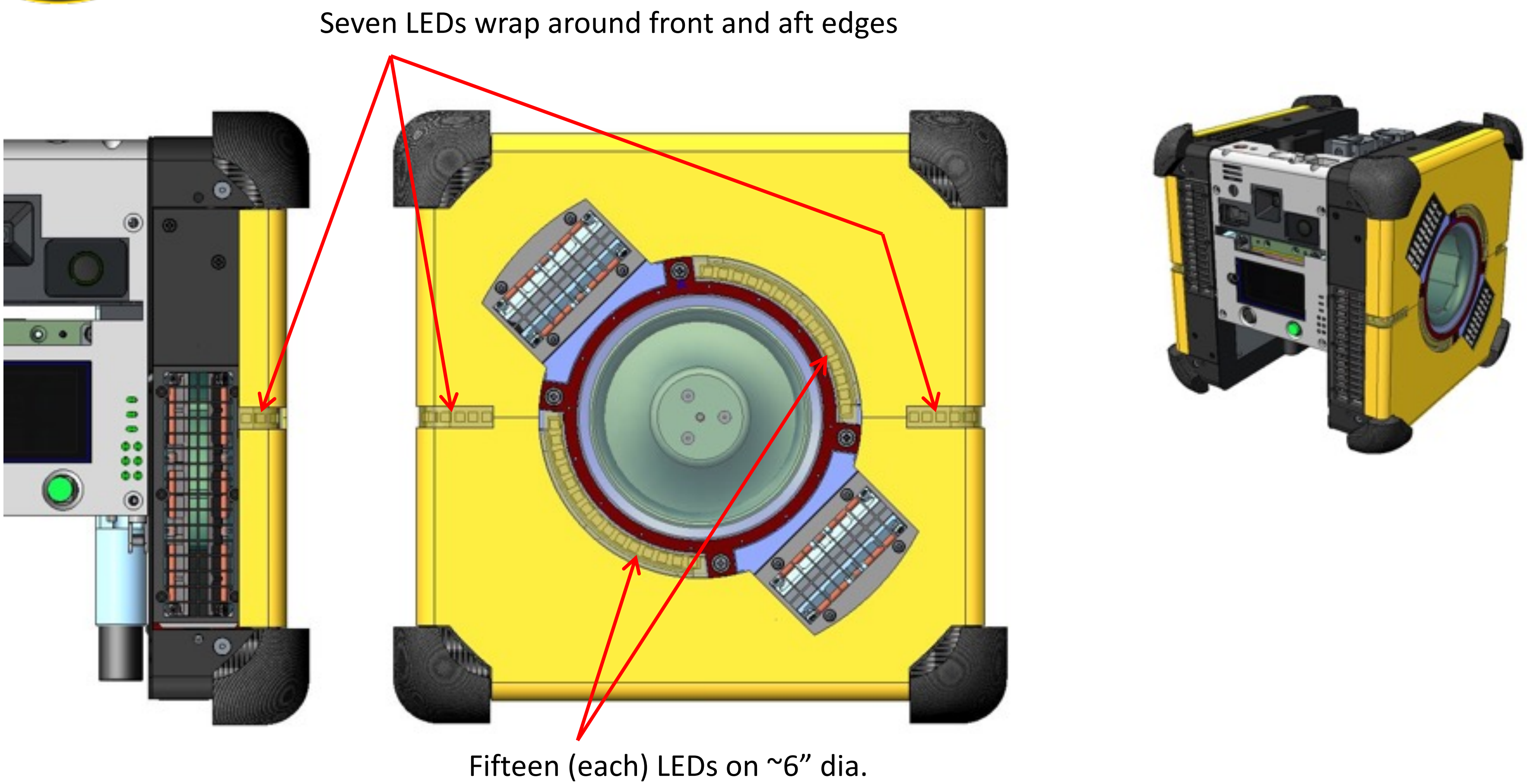




Skin Sample made in JSC Soft Goods

Top Cover: Aluminum sheet with soft layer and Velcro patches
Skin Material: Nomex / Chemglass w/ Velcro Hook and Loop patches
Graphics: Printed on Nomex

Programmable Signal Lights



LED: ¼” Square Multi-color Adafruit NeoPixel

Restraint Straps

Strap with Velcro hook allows Astrobee to be restrained to ISS loop patches

Two deployable straps for restraining Astrobee on station. Velcro Hook on ends of straps

Strap is unfolded 1 fold

Strap is unfolded 2 folds

Fully Deployed ~ 10” Strap

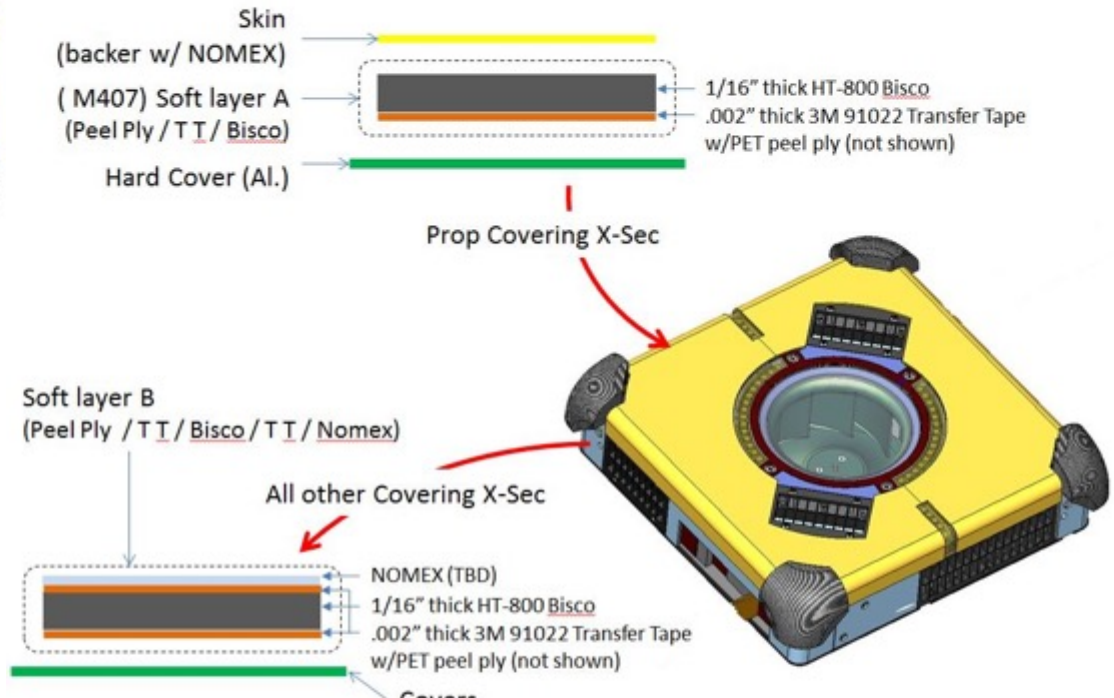
Strap Material: Nomex with Velcro Hook and Loop patches
Full Length: ~10 inches
Design Strength: 10 lbf

Impact Bumpers & Surfaces

“Soft Layers” 1/16” thick foam

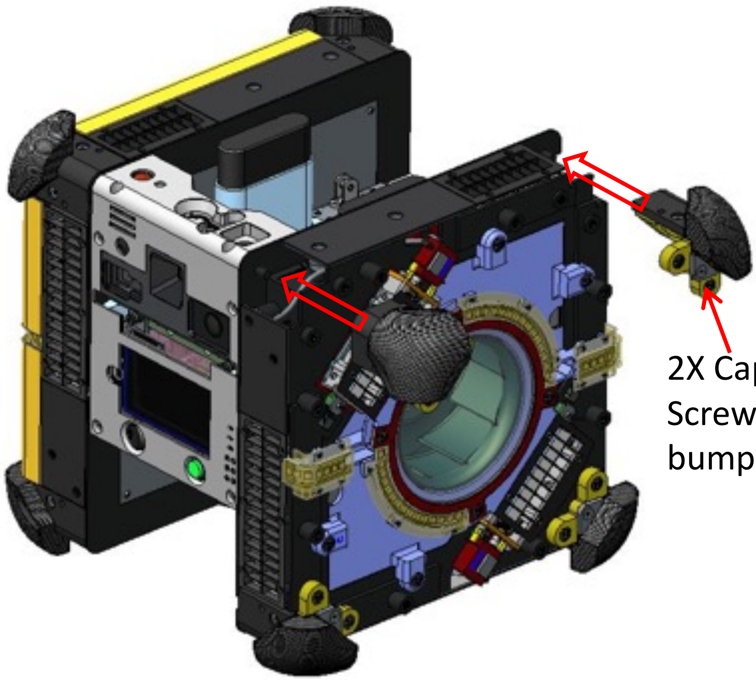
8X Corner Bumpers

Soft Layers Defined (Layer A and Layer B)

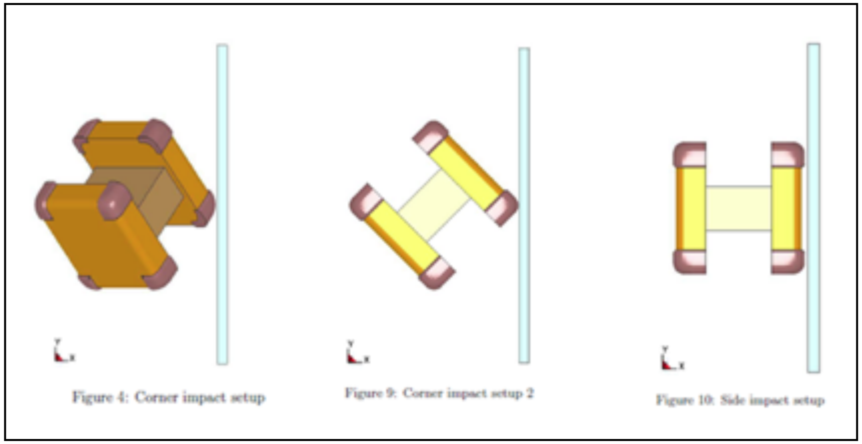


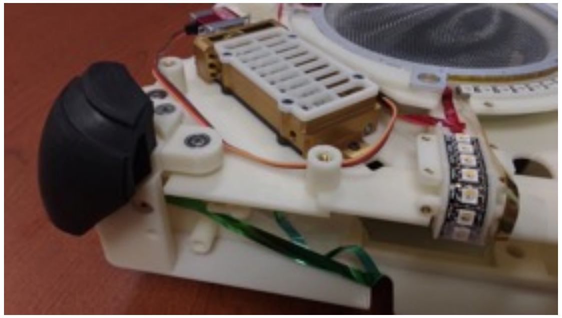
Impact Bumpers

Max operational resultant force < 125 lbf, Max force < 1000 lbf

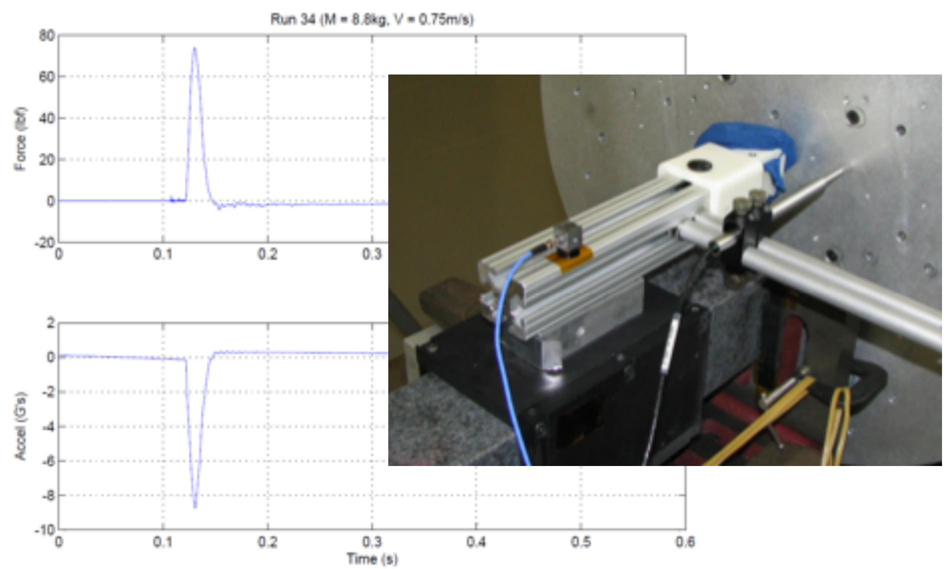


2X Captive Screws hold bumpers on



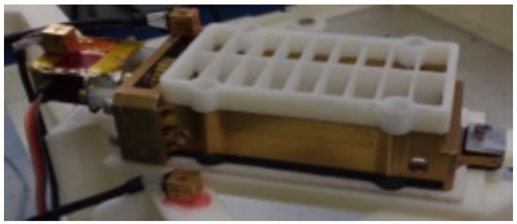


Bumper Material: Arti-lage SH28 PU energy absorbing foam w/ Nomex cover

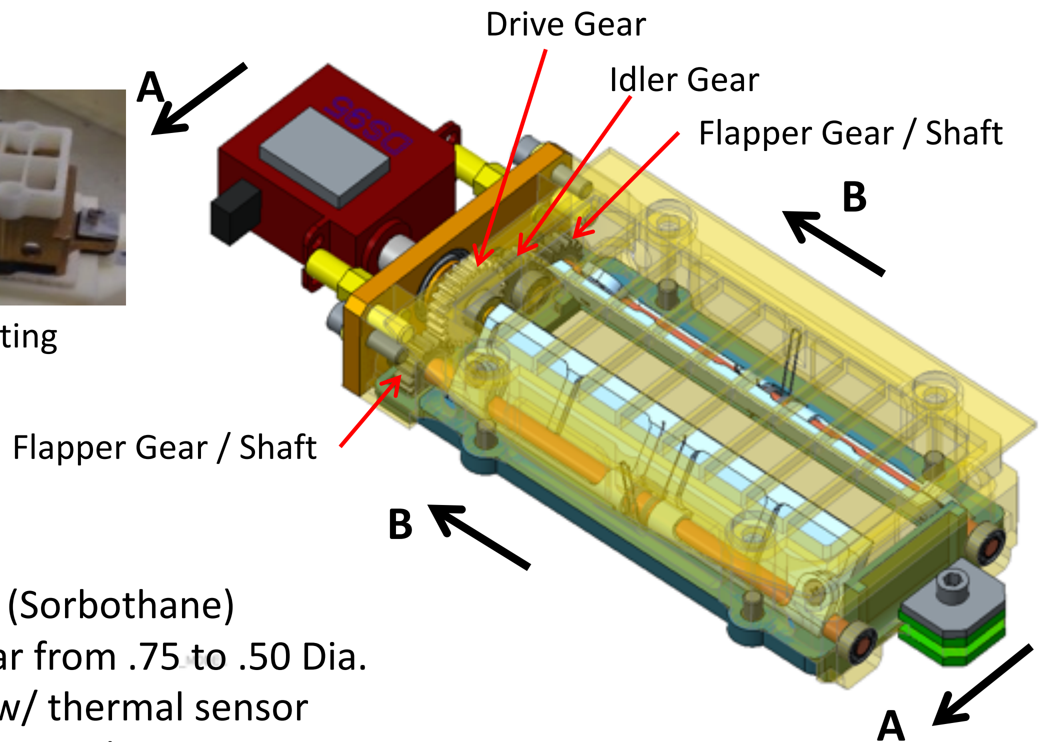


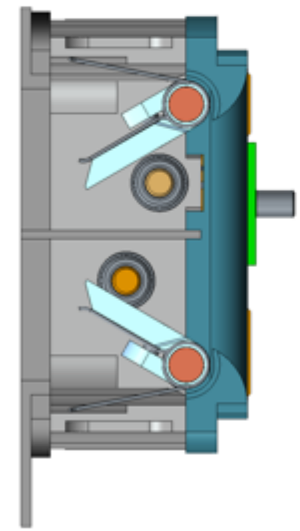
Impact Bumper Testing

Nozzle Subassembly



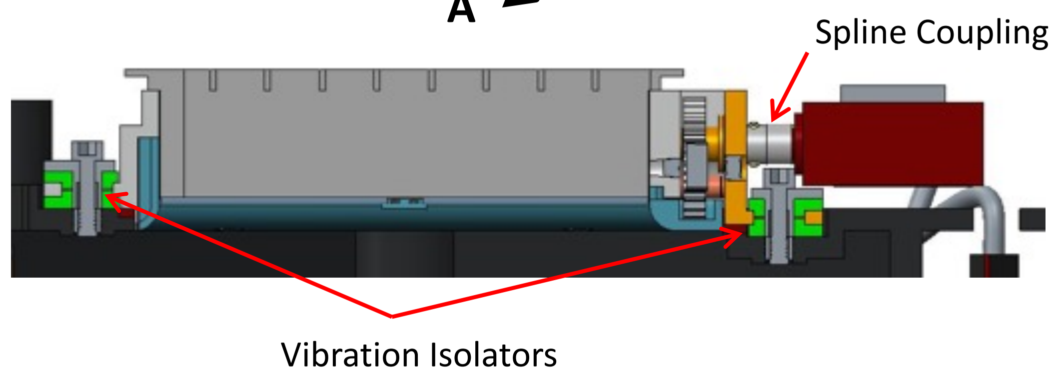
Nozzle Isolation Testing





Sec B-B

- Vibration Isolation (Sorbothane)
- Reduced Drive Gear from .75 to .50 Dia.
- COTS MKS Servos w/ thermal sensor
- Splined drive shaft (Cert/Flight)



Sec A-A

Astrobee Propulsion Subsystem Avionics and Software

Delta-PTR3 Design Overview

Design Maturity

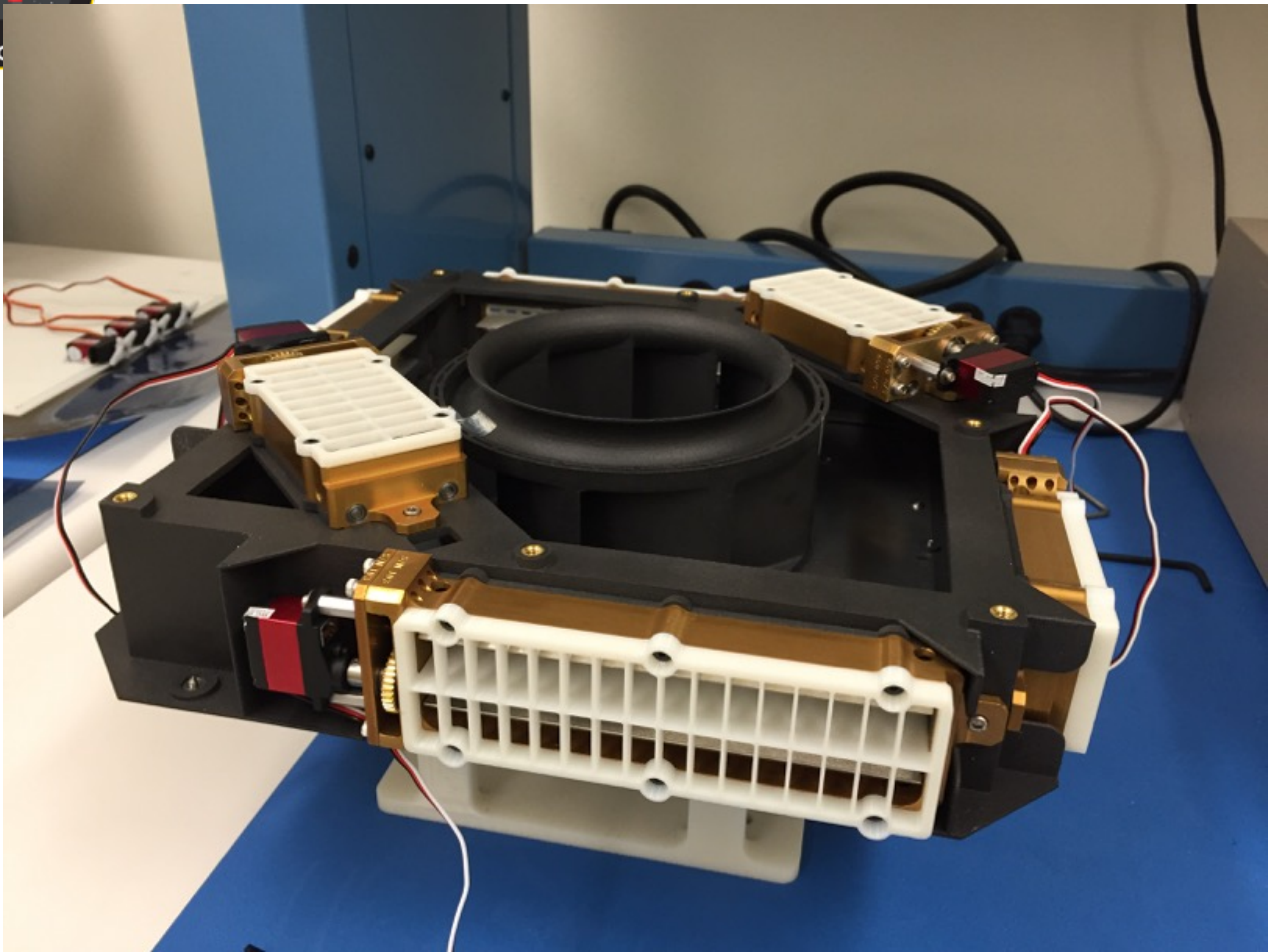
The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

Component	Maturity / Risk	Forward Work
Prop Avionics Hardware	High/Low	Board layout updates required before Cert build
PMC SW	High/Low	

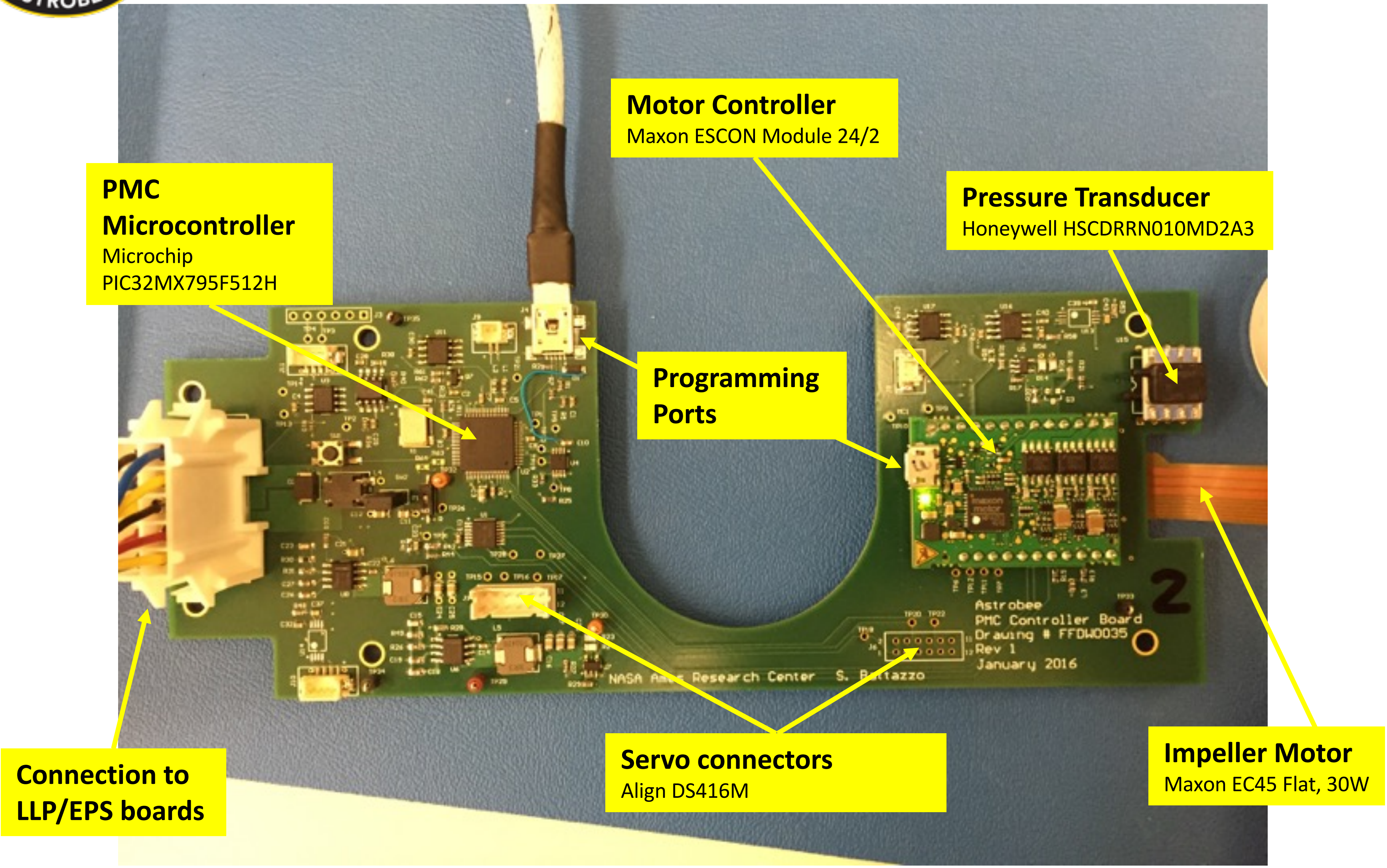
Summary of Changes from PTR3

Component	New / Changes
Nozzle Servos	Replaced MKS DS92 with DS95
PMC Board	Added PWM chip for nozzle servo control
PMC Board	Added LED processor (Independent circuit from prop control)
Temp Sensors	Temperature sensors (AD590) added to all servos and impeller motor

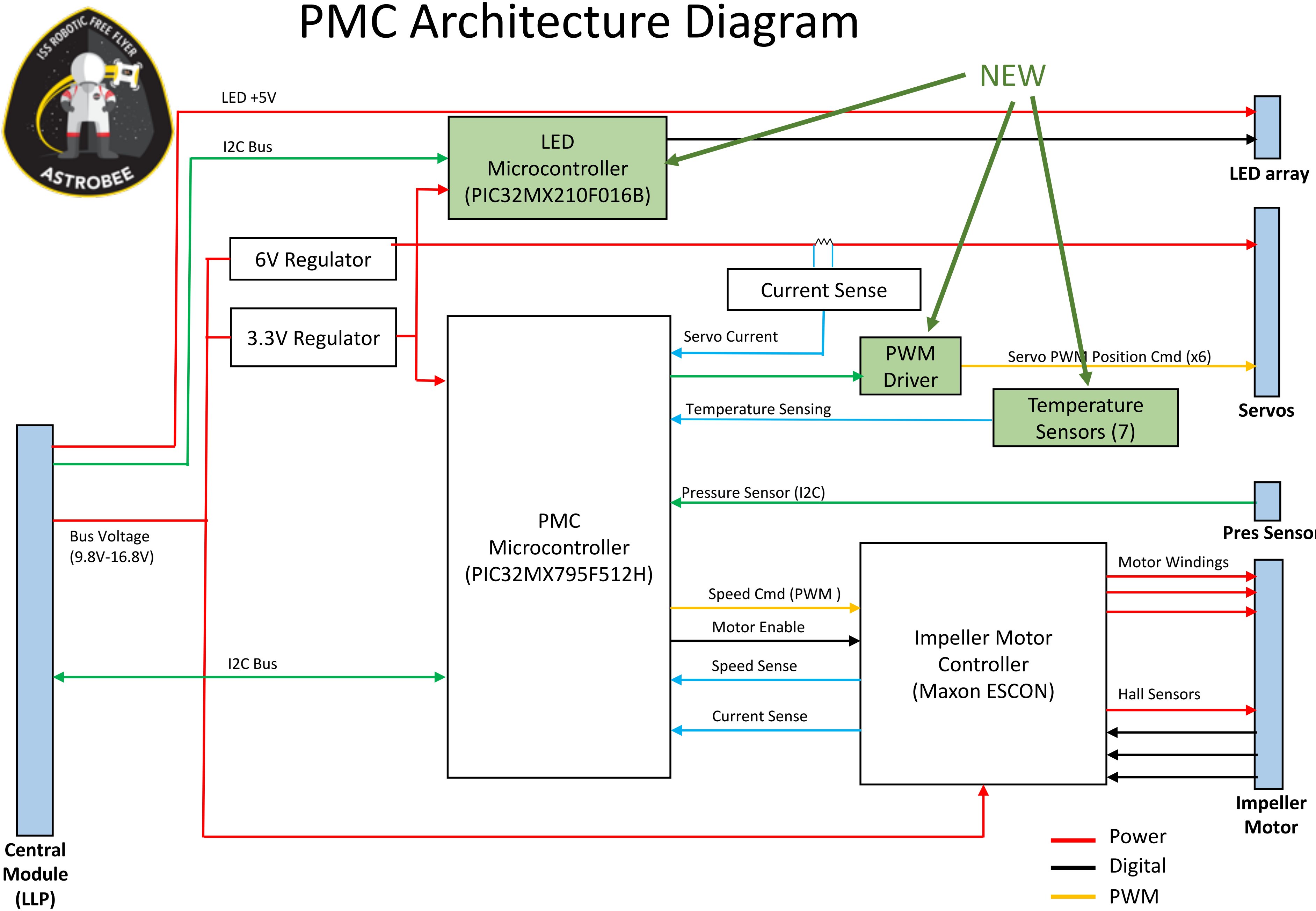
Propulsion Module: Impeller Design



Propulsion
Electronic Components



PMC Architecture Diagram



Propulsion
Software: PMC Functions

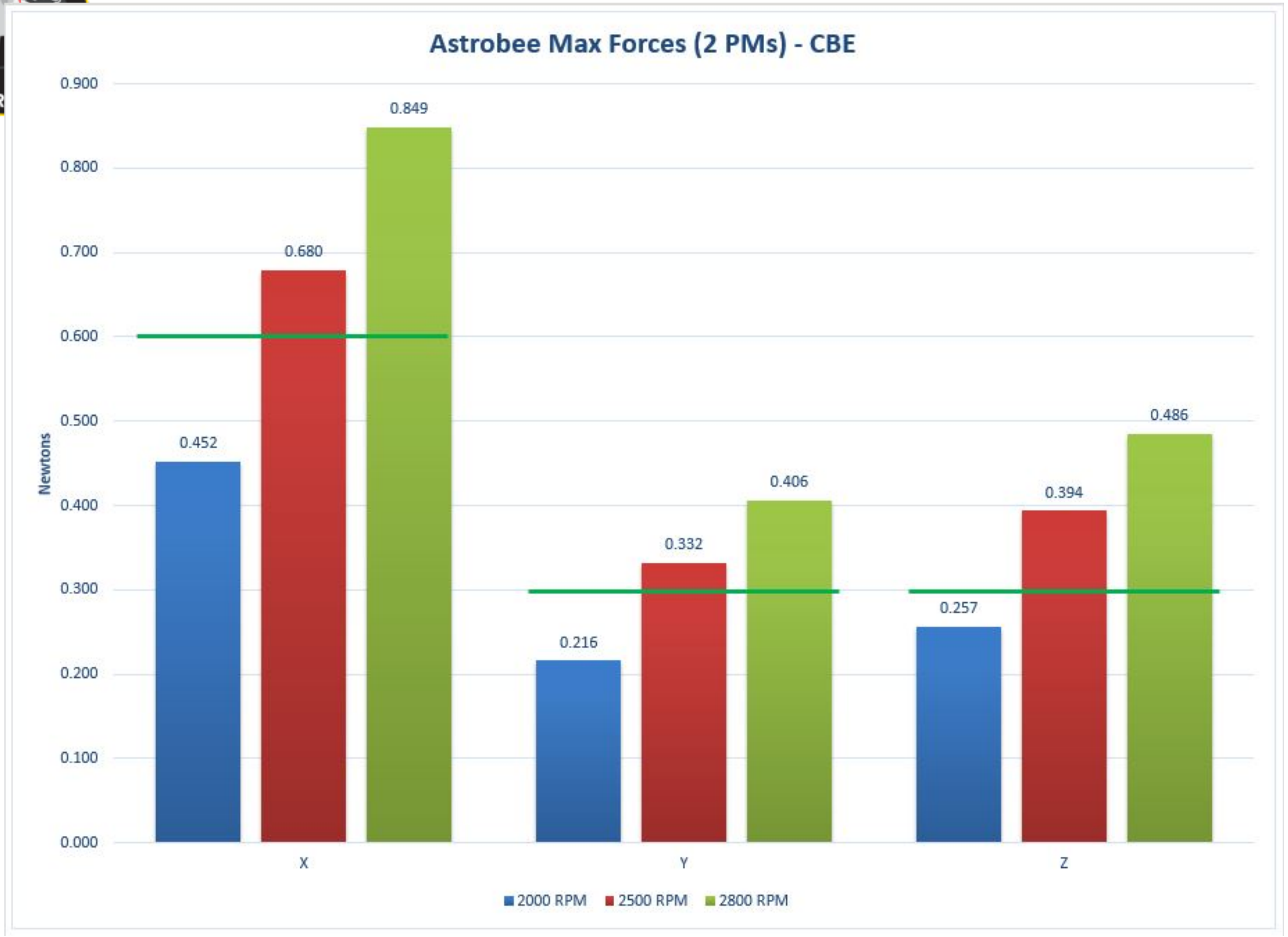
PMC Board Functions

1. Control impeller motor speed
2. Control nozzle servo motor positions
3. Mode management
4. Receive and execute commands from the LLP
5. Return telemetry to LLP
6. Read plenum pressure sensor
7. Read motor speed from motor controller
8. Read motor current from motor controller
9. (New) Read temps from 6 servos + impeller motor
10. Perform propulsion FM activities
11. (New) Control LED signal array

Propulsion Software

- Development environment
  - MPLAB X (v3.45)
  - XC32 Compiler (v1.42)
  - Harmony Configurator (v1.09)
- Programming
  - PMC/LED SW upload capability from ground
    - Updated via I2C Comm path
  - Directly to the PMC board via a mini-USB port
  - Motor controller firmware not to be updated on orbit

Performance



Astrobee CDH, EPS, & Sensors Subsystem

Design Overview

Design Maturity

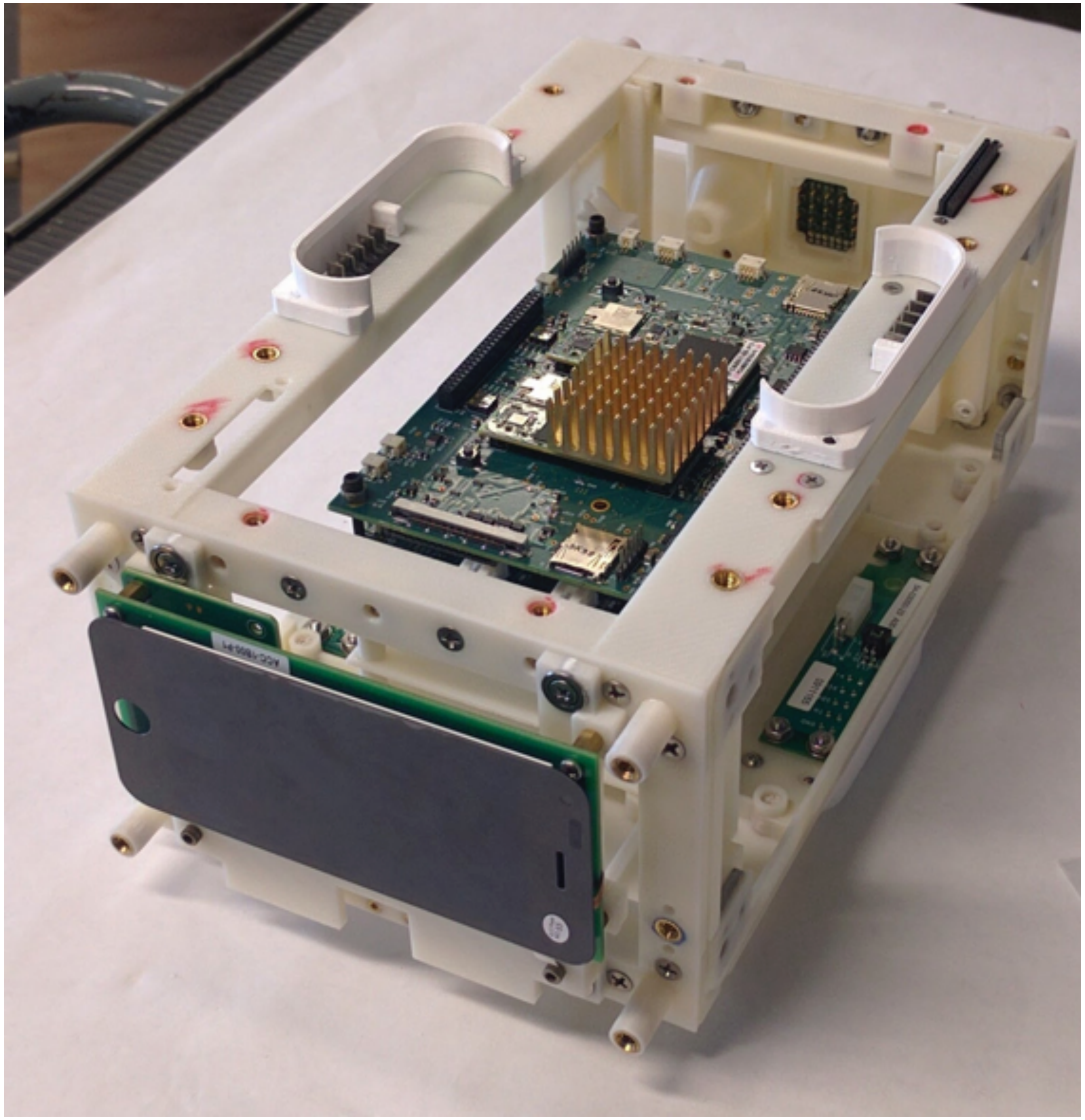
The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.

Component	Maturity / Risk	Forward Work
Backplane board	High / Low	HW payload over current
Data bus	High / Low	
Low level processor	High / Low	USB OTG support
Mid/High level processor	High / Low	Speaker+Mic, USB OTG support
Touchscreen	High / Med	Ribbon cable routing
Flashlights	High / Low	
Payload connector	High / Low	
Buttons/switches/LEDs	High / Low	
EPS	High / Low	HW over current, HW over temp
SpeedCam	Med / Low	More testing

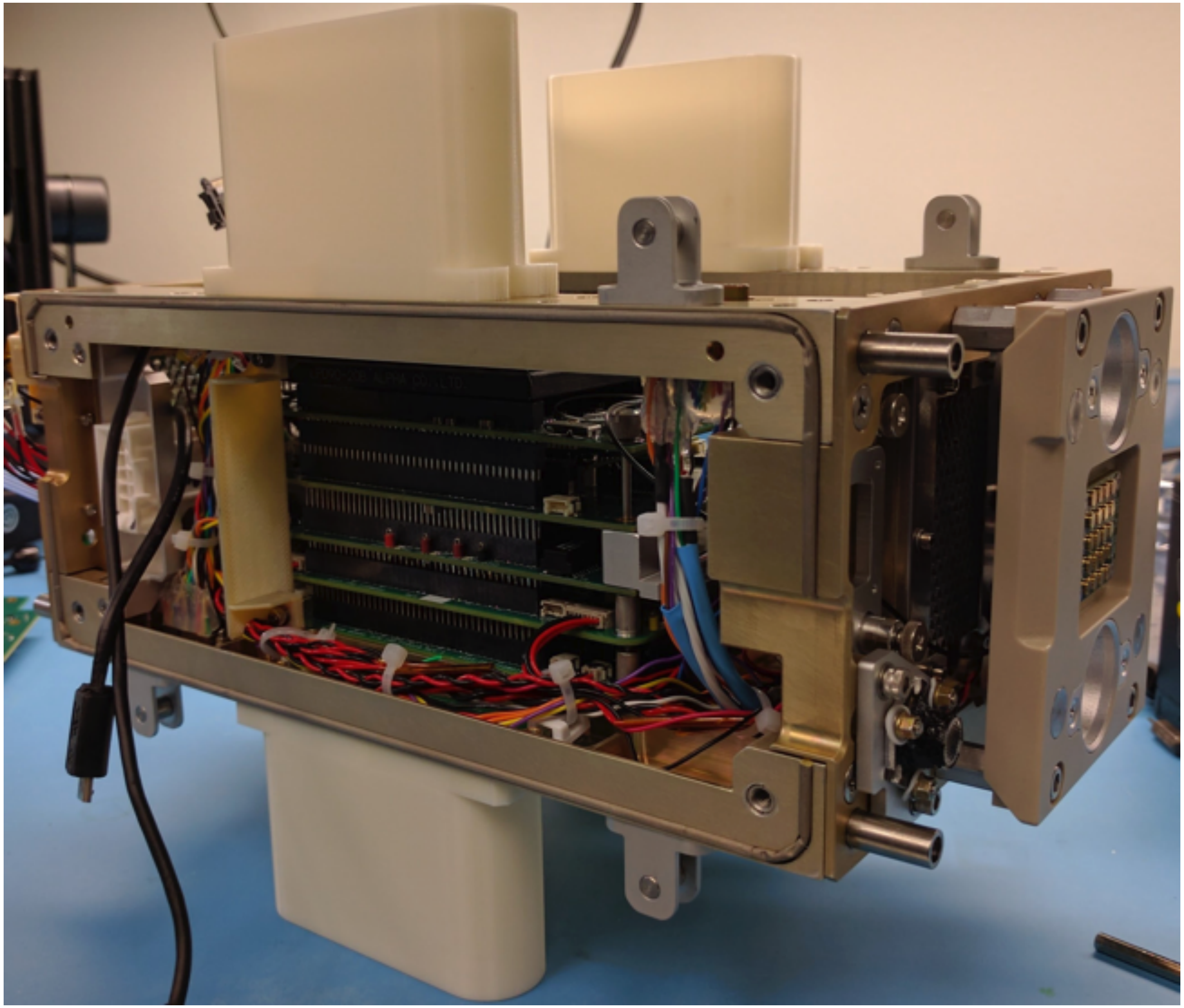
New/Changes from PTR3

Component	New / Changes
EPS	- HW current limit for payload power - HW over temperature protection - Improved battery charging
Backplane	- HW current limit for payload power
MLP/HLP	- Speaker and Microphone fix - Added Fastboot support - SMA connector for WiFi antenna - Additional mounting holes for heat sink
LLP	- GPIO line to MLP & HLP volume for Fastboot
SpeedCam	- Big redesign

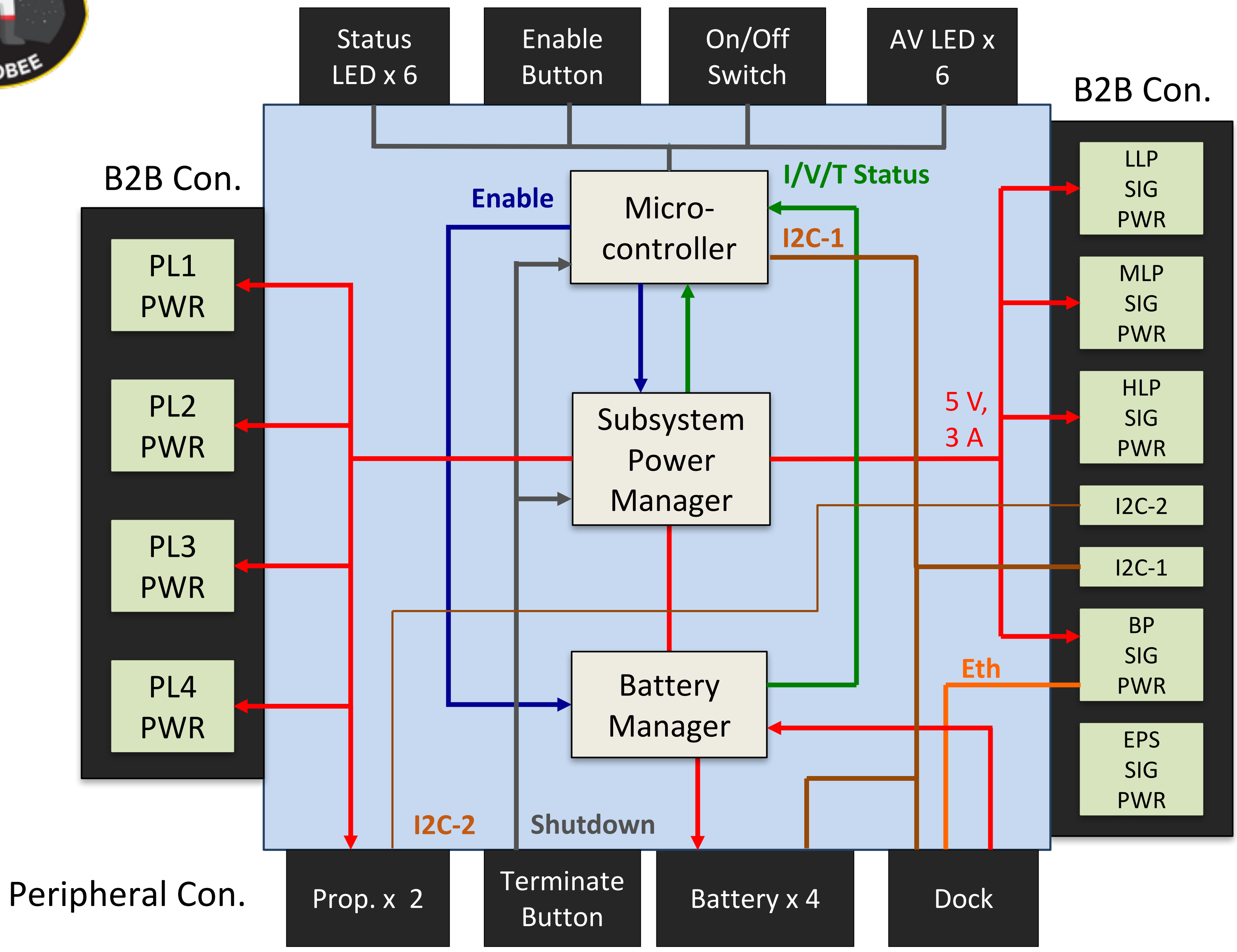
Avionics Stack



Avionics Stack



EPS Diagram

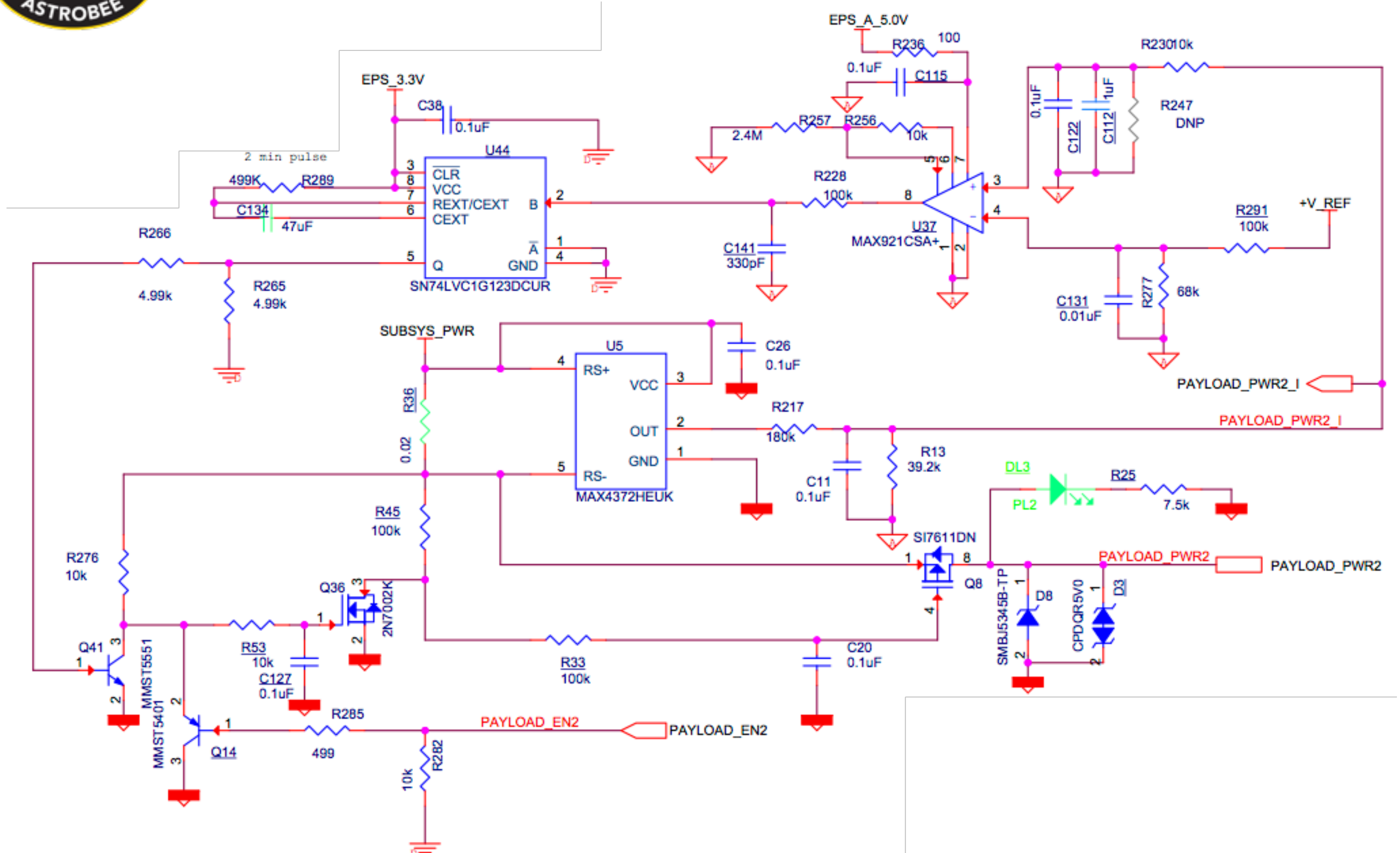


Status LED x 6
Enable Button
On/Off Switch
AV LED x 6
B2B Con.
B2B Con.
Enable
I/V/T Status
Micro-controller
I2C-1
PL1 PWR
PL2 PWR
PL3 PWR
PL4 PWR
Subsystem Power Manager
5 V, 3 A
LLP SIG PWR
MLP SIG PWR
HLP SIG PWR
I2C-2
I2C-1
BP SIG PWR
EPS SIG PWR
Eth
Battery Manager
I2C-2
Shutdown
Peripheral Con.
Prop. x 2
Terminate Button
Battery x 4
Dock

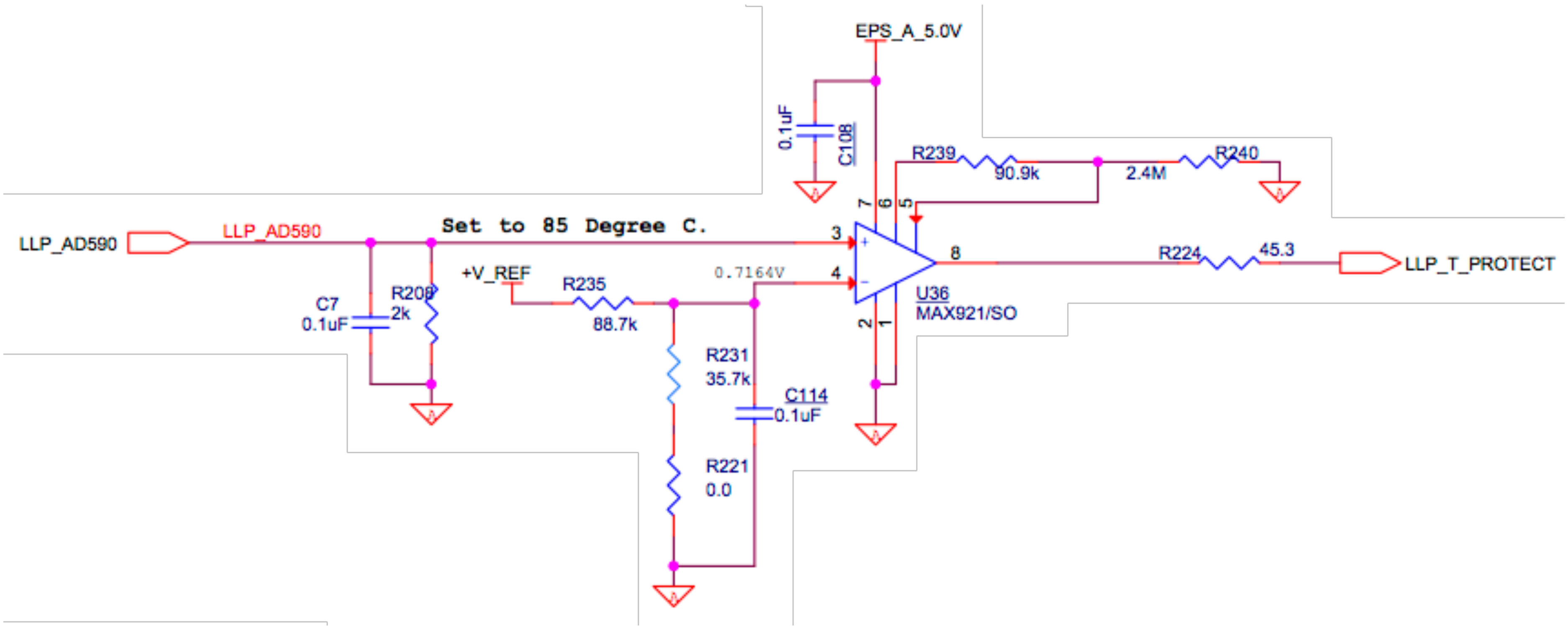
EPS

- HW over current protection
  - 4 Payloads
- HW over temperature protection
  - LLP
  - MLP
  - HLP
  - Flashlights
  - System
- Improved battery charging

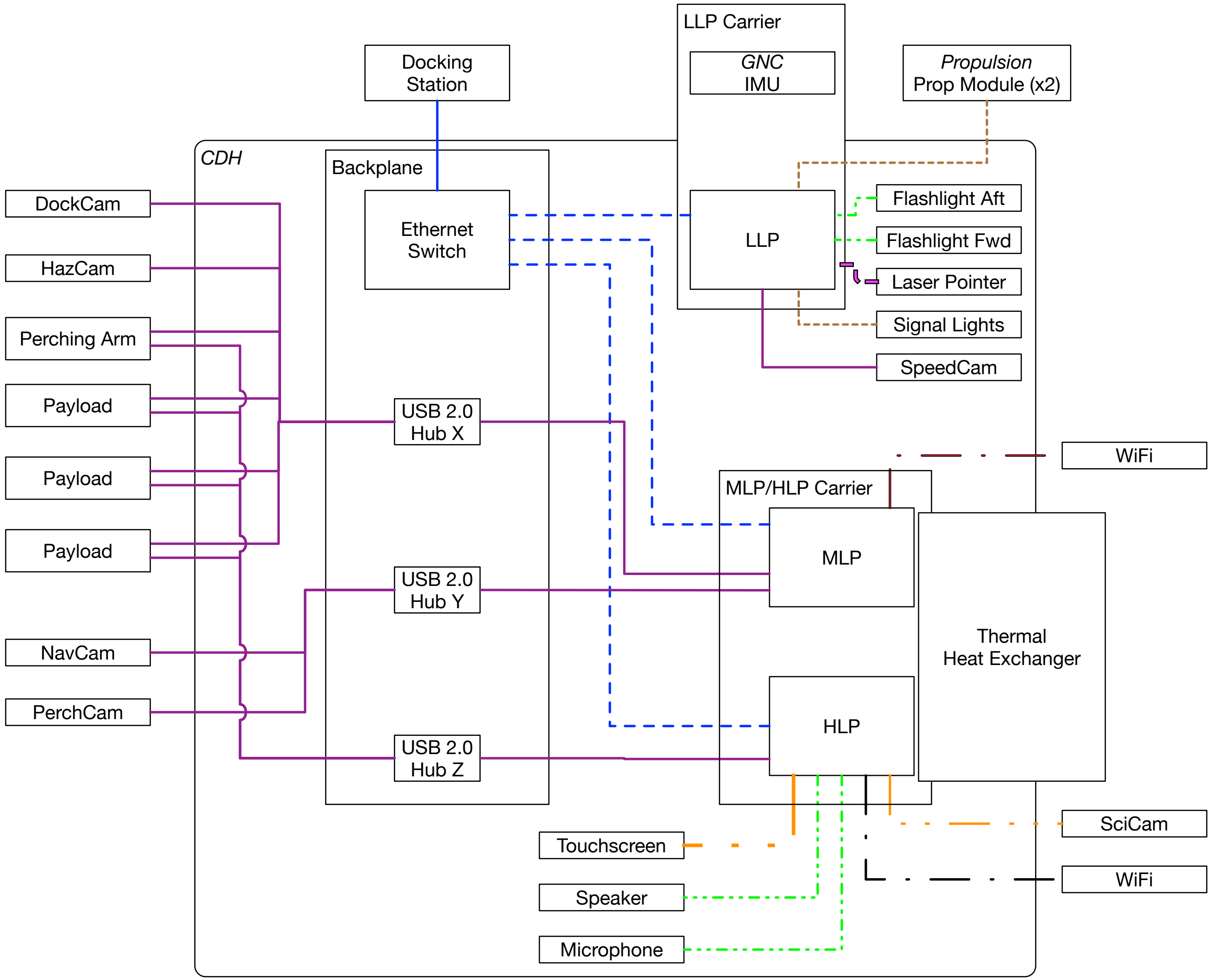
EPS HW over current



EPS HW over temperature

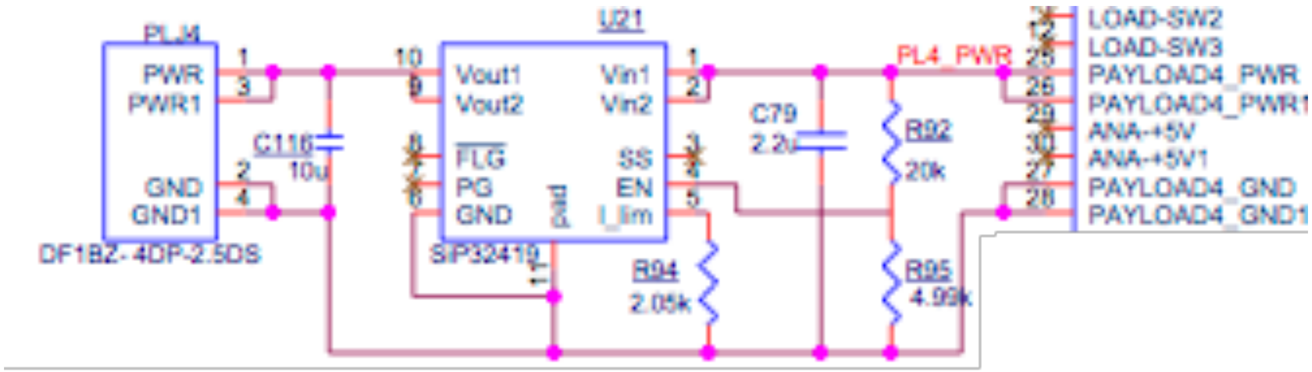


Avionics Diagram

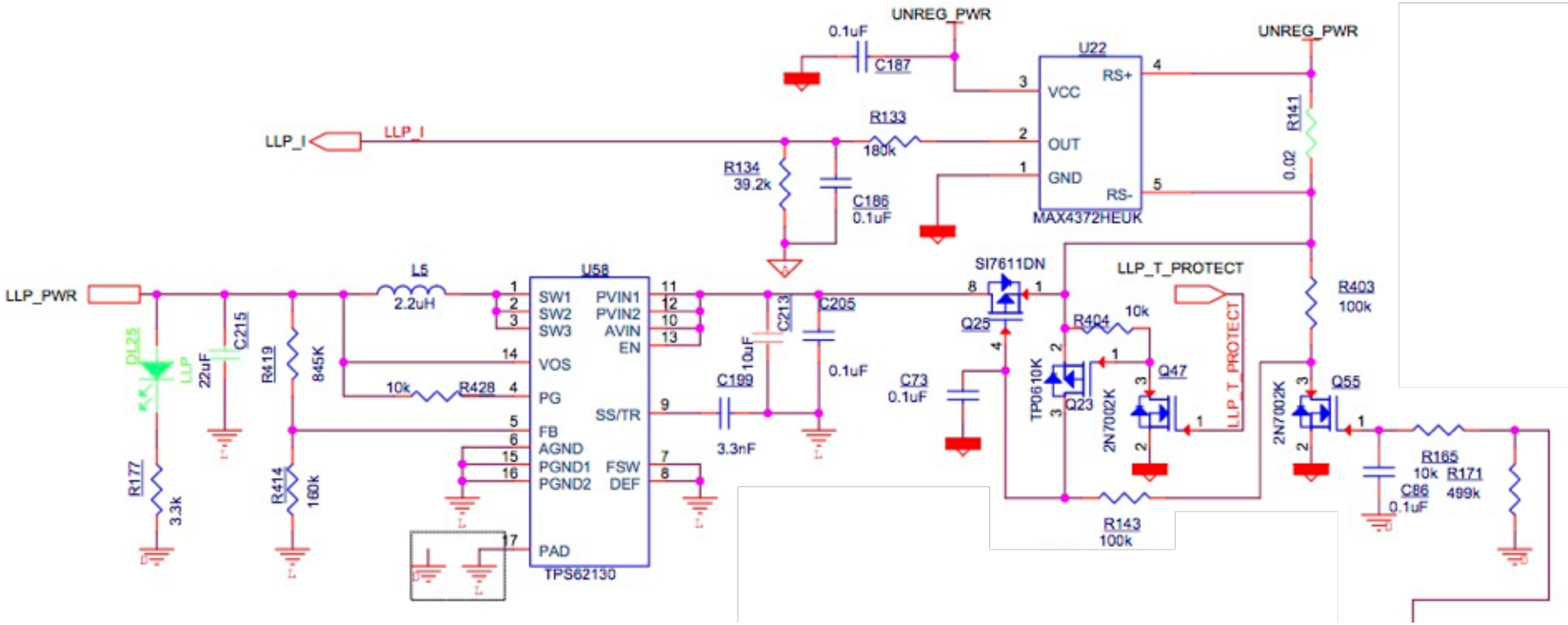


Backplane

- HW over current protection
  - 4 Payloads



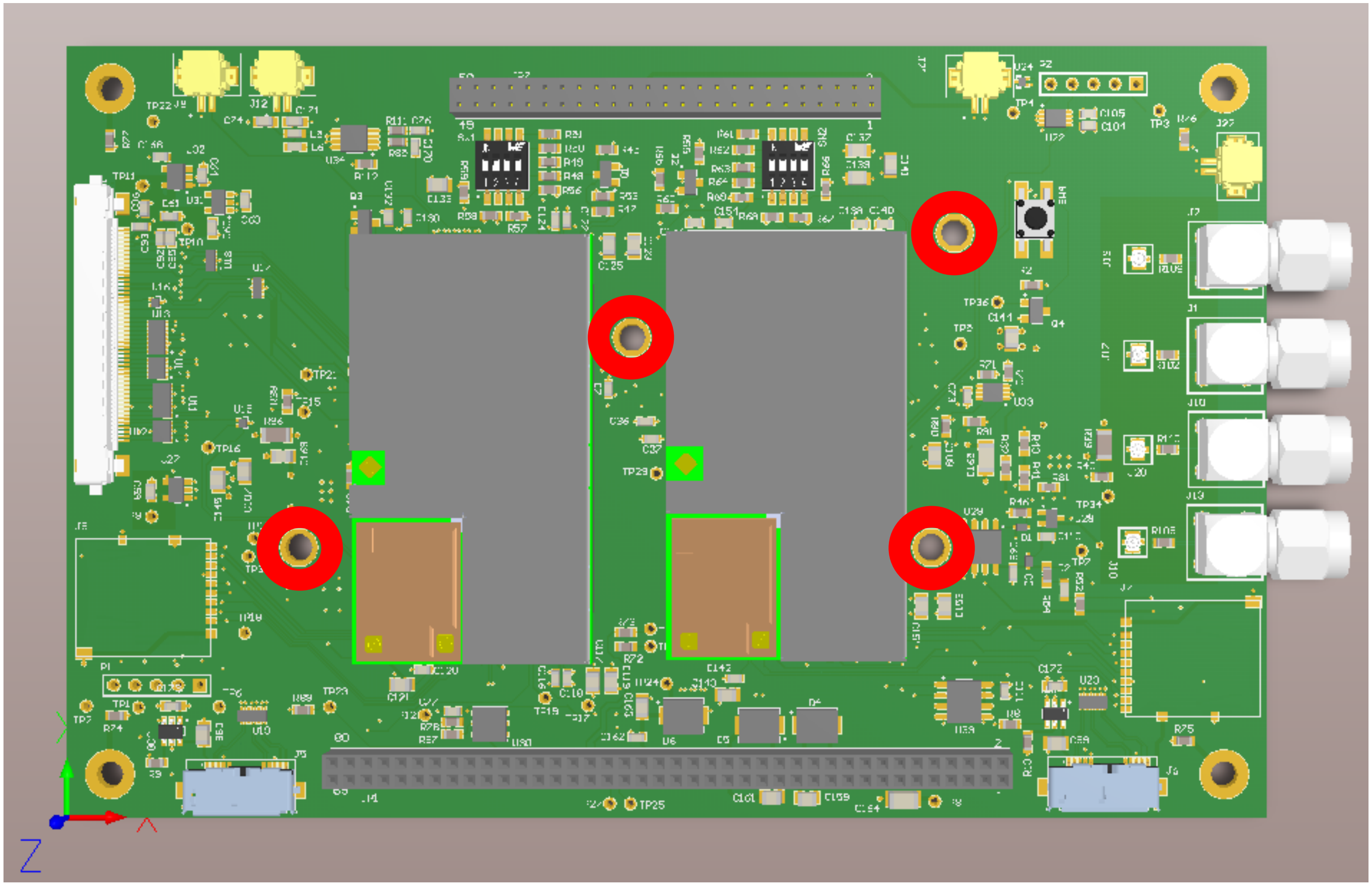
EPS HW over temperature



MLP+HLP Carrier

- Fix speaker and mic issues
- Added Fastboot support for MLP and HLP
- Changed Wifi antenna connector
- Added more mounting holes for heat sink

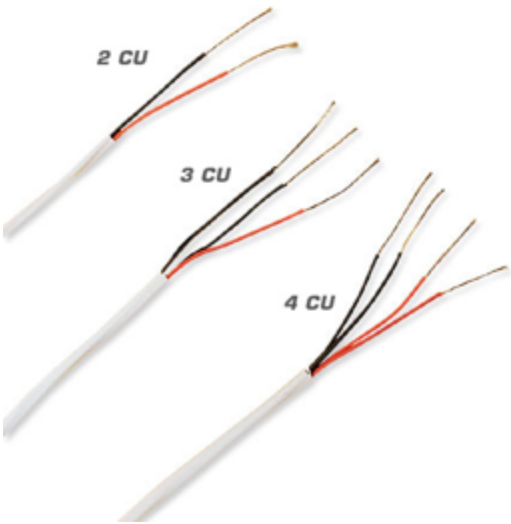
MLP+HLP Carrier



Payload Bay Connector

- 31 pin D-sub connector
- V_{batt}, GND
- USB 2.0
- More robust
- Premade harness
- Male side on Astrobee

Payload Bay Connector



- Pre-twisted pair cable for:
  - USB data
  - Ethernet
  - Power
- Reduces wire bundle size

SpeedCam

PX4Flow

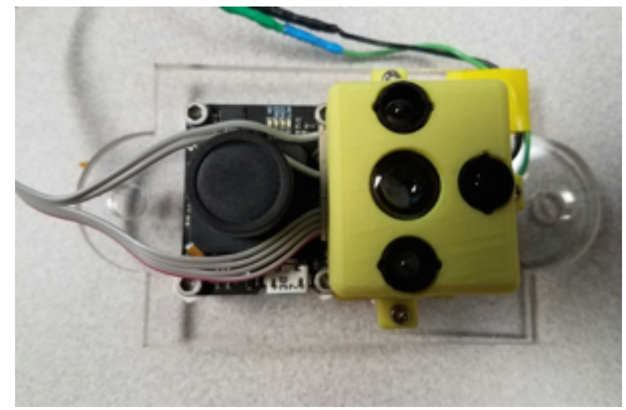
30 deg FoV lens

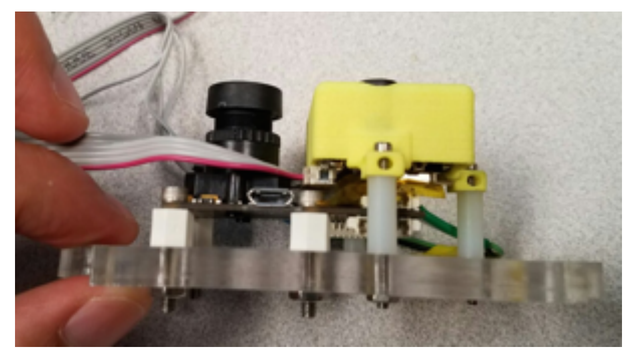
Accelerometer

TeraRanger

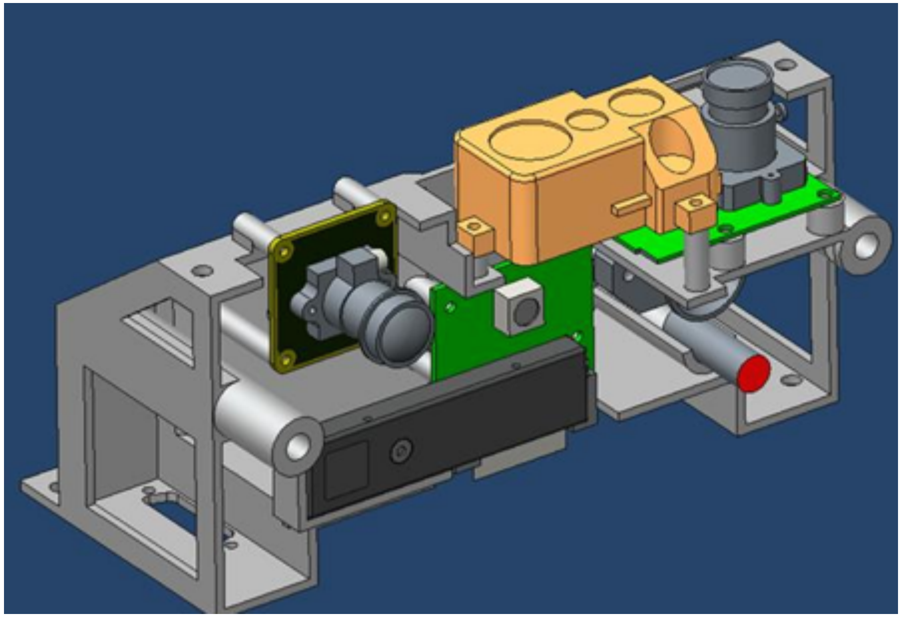
New Firmware

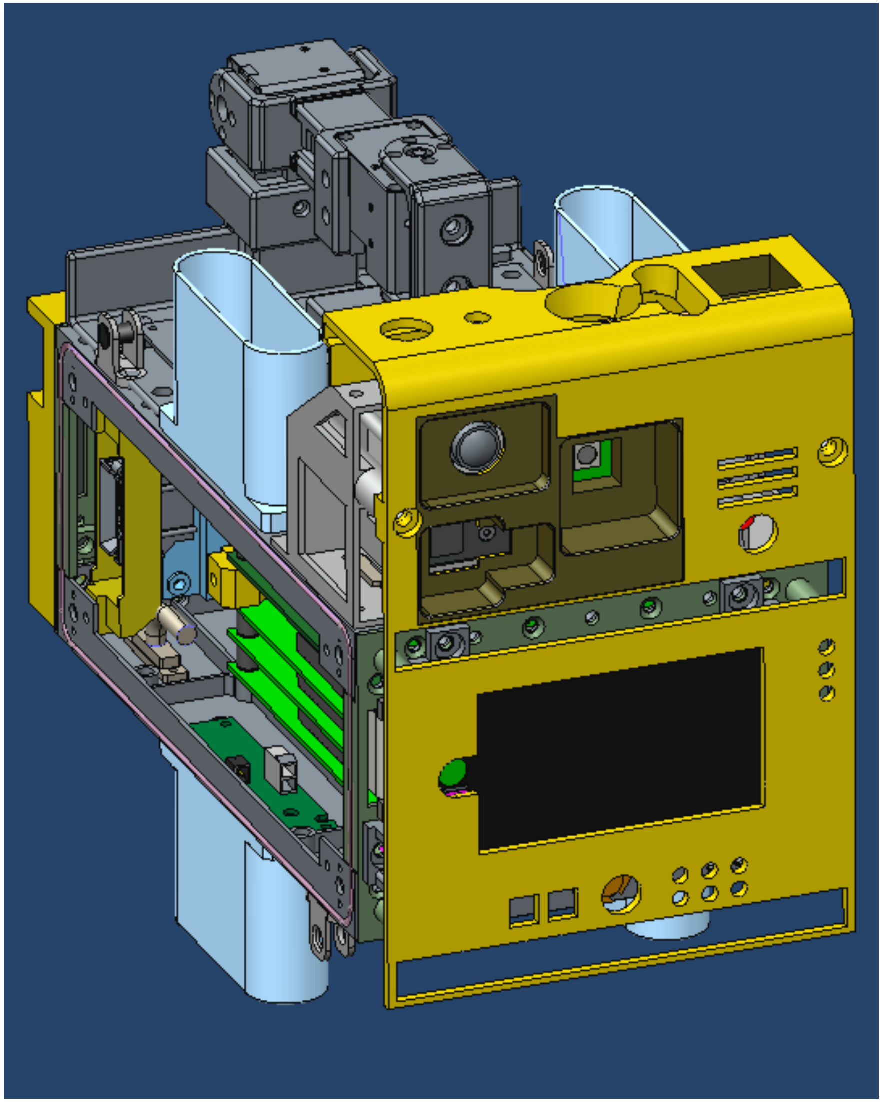
Astrobee SpeedCam!





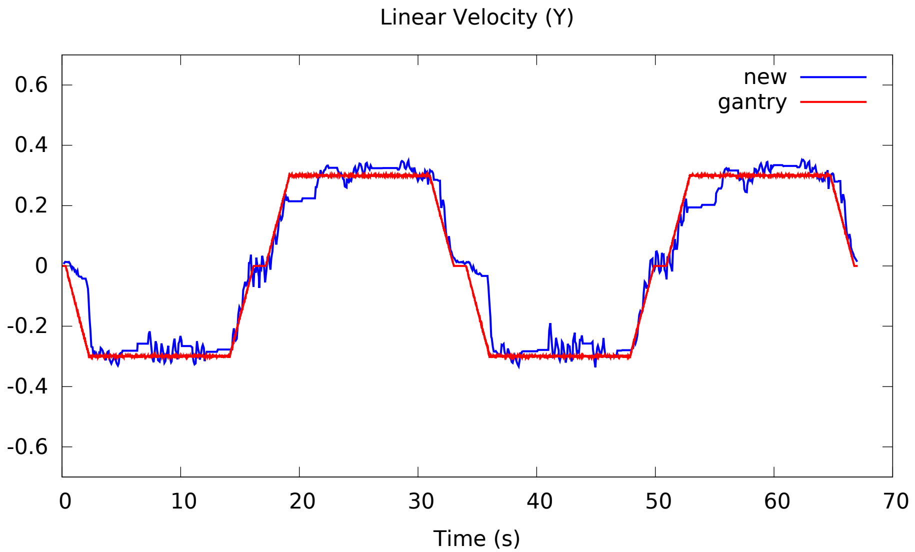
SpeedCam

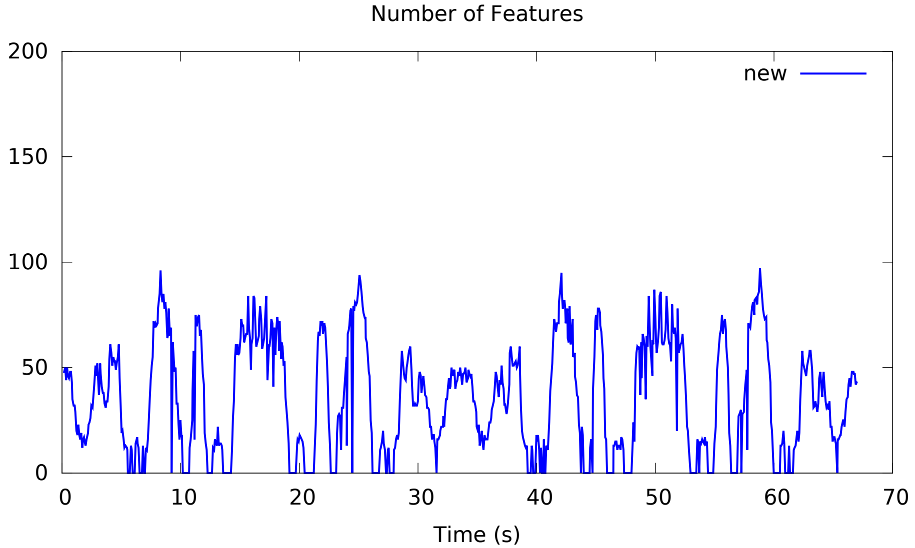




Test Setup I

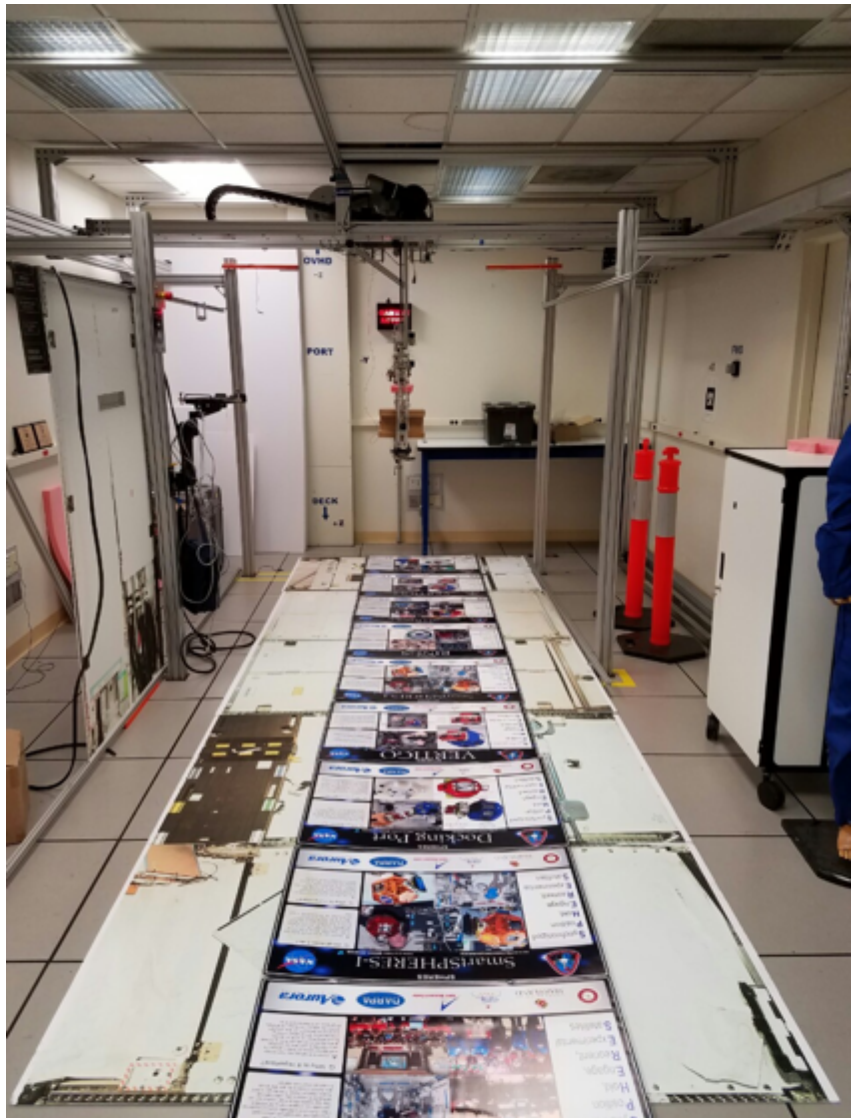
Result I


Linear Velocity (Y)
new
gantry
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
10
20
30
40
50
60
70
Time (s)

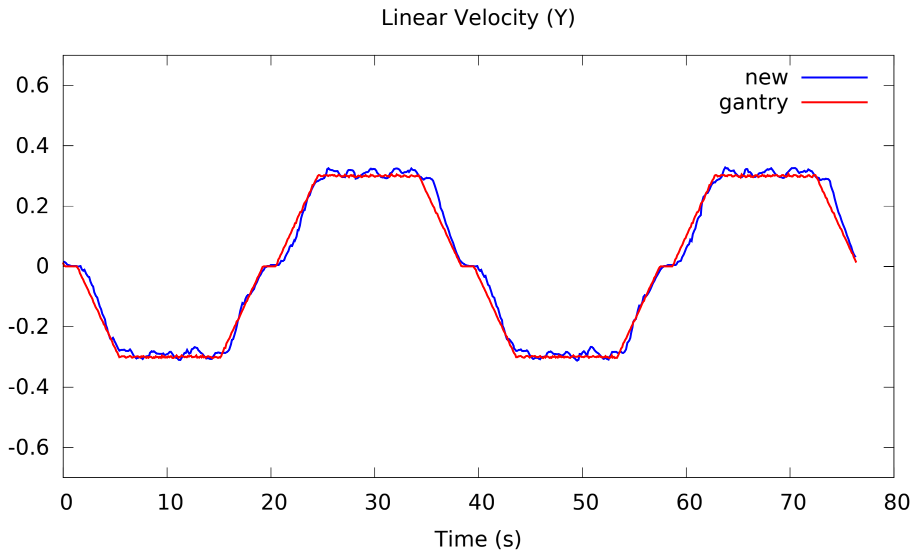

Number of Features
new
200
150
100
50
0
0
10
20
30
40
50
60
70
Time (s)

ISS is Messy

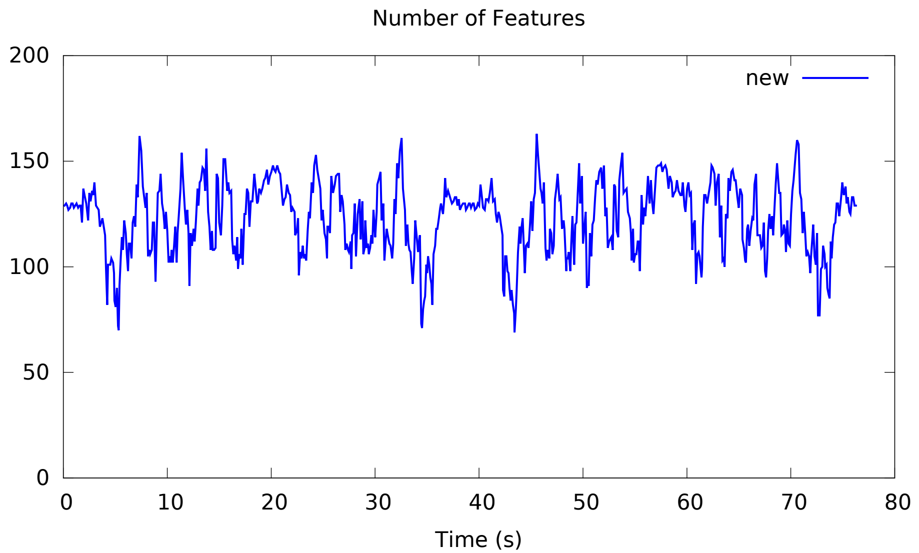
Test Setup II



Result II



Linear Velocity (Y)
new
gantry
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
10
20
30
40
50
60
70
80
Time (s)



Number of Features
new
200
150
100
50
0
0
10
20
30
40
50
60
70
80
Time (s)

Astrobee Comms Subsystem

Design Overview

Design Maturity

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

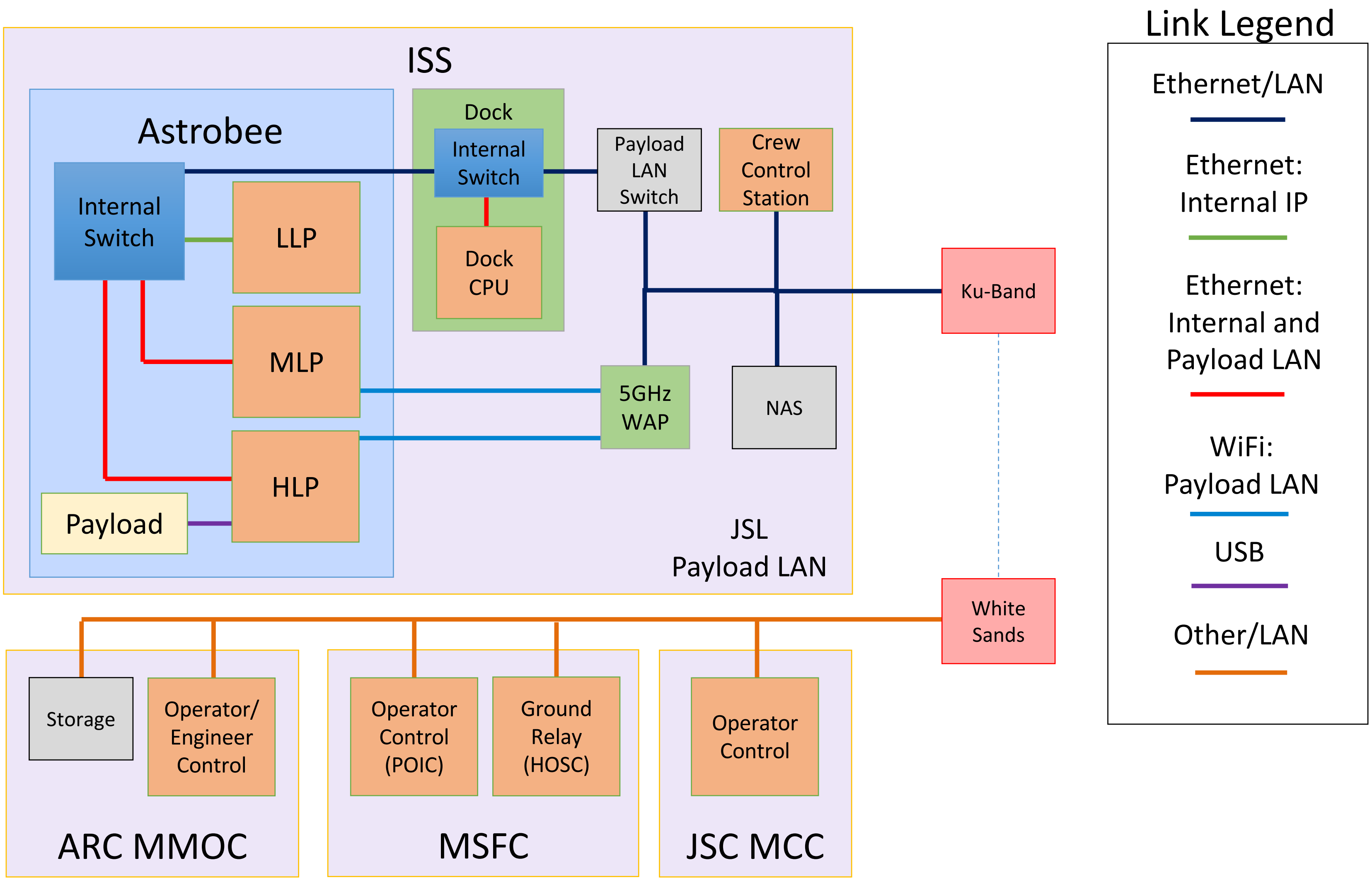
Component	Maturity / Risk	Forward Work
Antenna	High / Low	
Network Configuration	High / Med	
Data Transfer	High / Med	
DDS Routing Service	High / Med	
Video Multicasting	Med / Med	

New/Changes from PTR3

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

Component	New / Changes
Overall Design	Added Dock CPU. Add HOSC relay.
Antenna	Changed in-line connector. Changed location of antennas.
Telemetry/Video	Added data relay through the HOSC.
Engineering Tools	Updated diagram.
S/W Updates	Use Dock CPU instead of NAS for updates.

Block Diagram



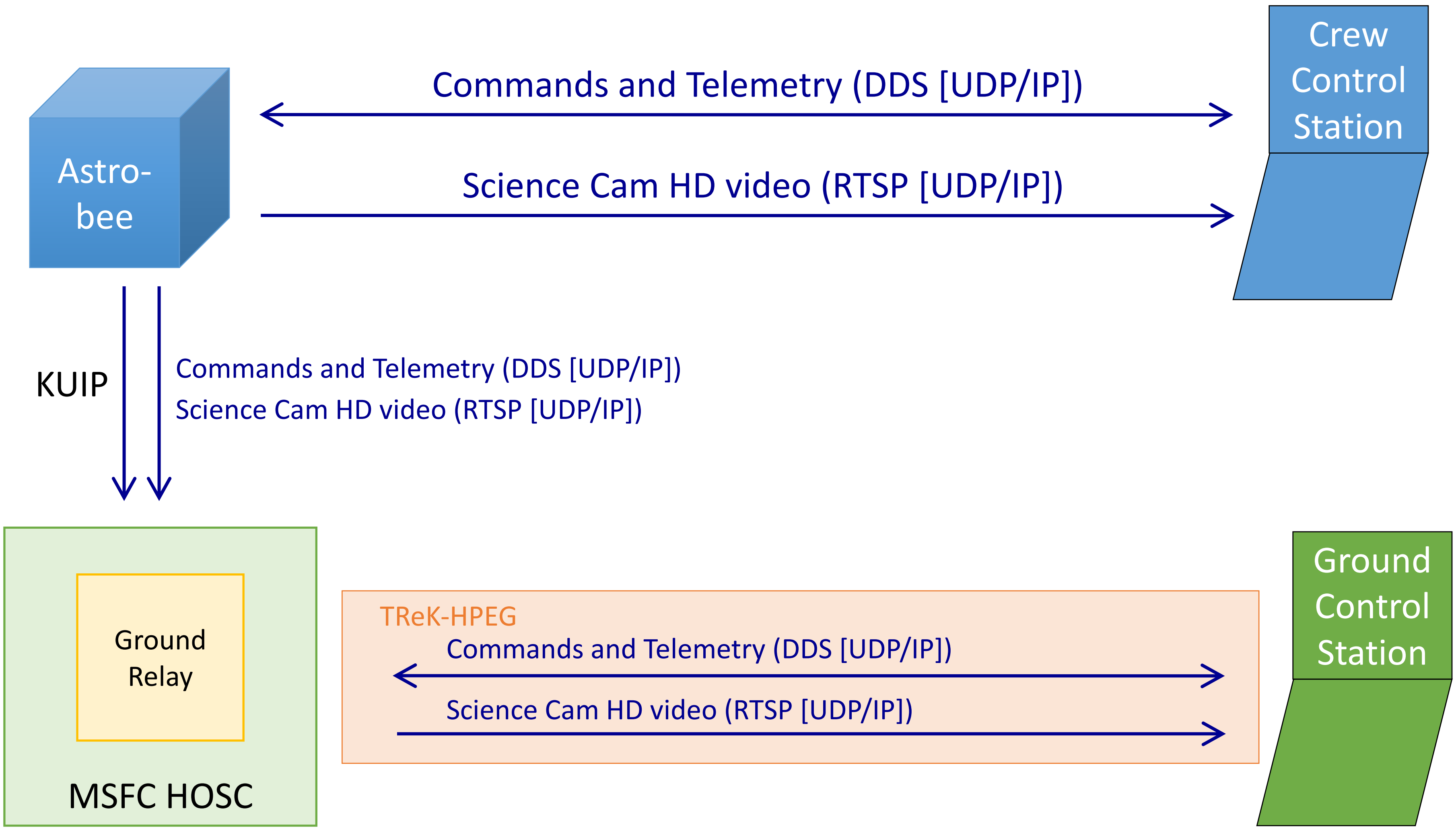
Ground Data Relay

- For conserving bandwidth, only one stream of data & video will flow to the ground per robot. Data is relayed to multiple ground stations via a "relay" at MSFC HOSC.
- A computer at the HOSC routes DDS and steaming video traffic from ISS KUIP to interested ground nodes.
  - It will use COTS software, with custom configuration files. The configuration files will be under version control at Ames.
  - The DDS data relay has been tested at Ames.

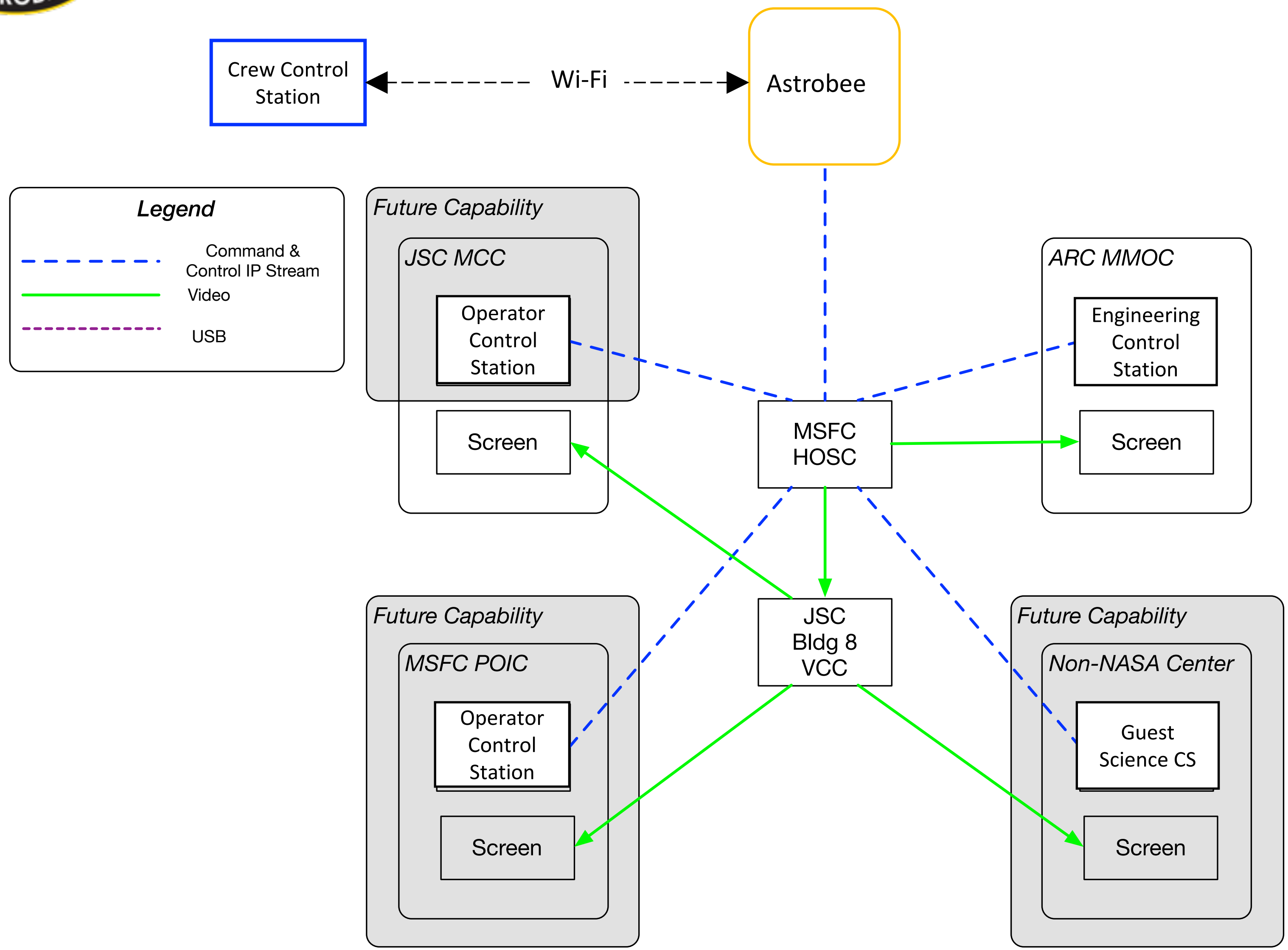
Data Paths Overview

- All data paths to the ground make use of KU-IP Services and TReK.
  - TReK HPEG: Allows us to control our payload outside of the HOSC via “proxy” IP addresses.
  - TReK CFDP: File delivery protocol based on CCSDS.

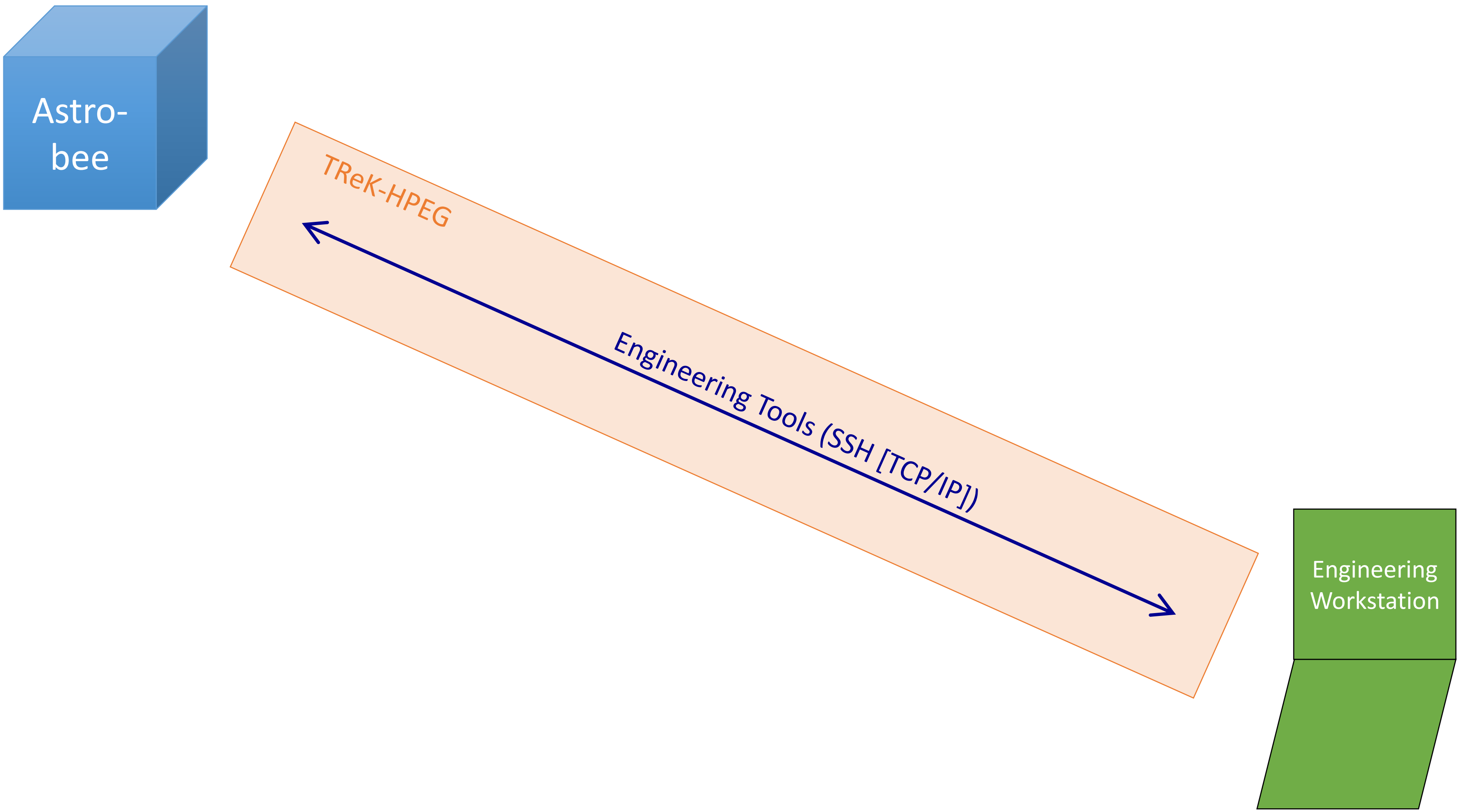
Data Path: Telemetry & Video



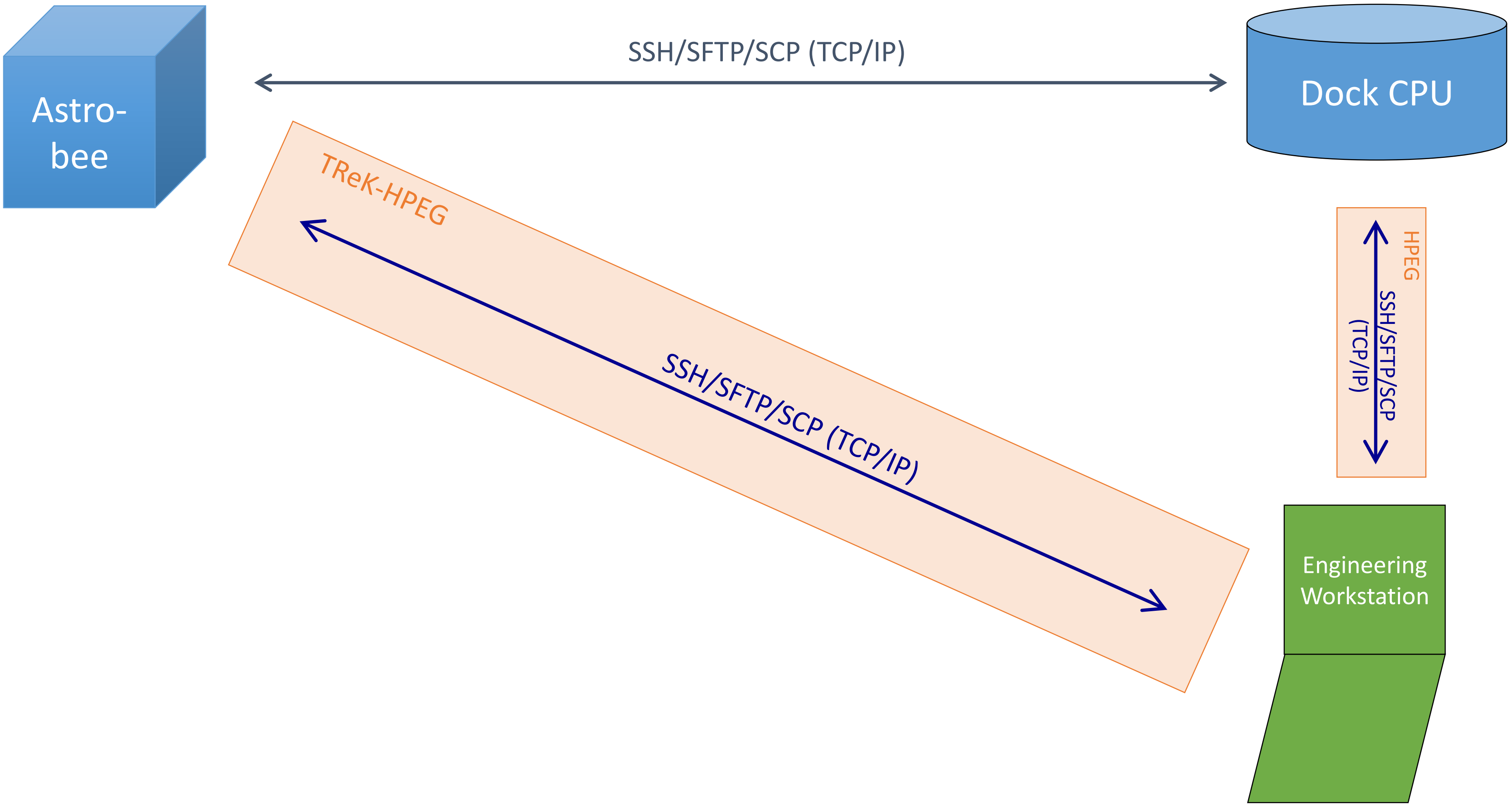
Data Path: Video/Data Distribution



Data Path: Engineering Tools



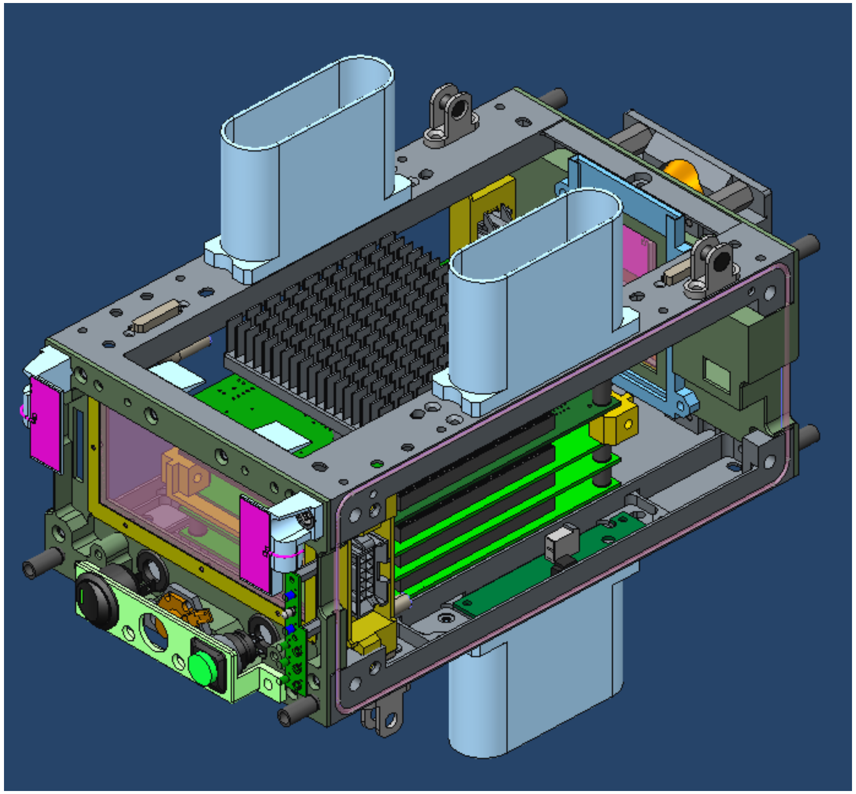
Data Flow: SW Updates, etc

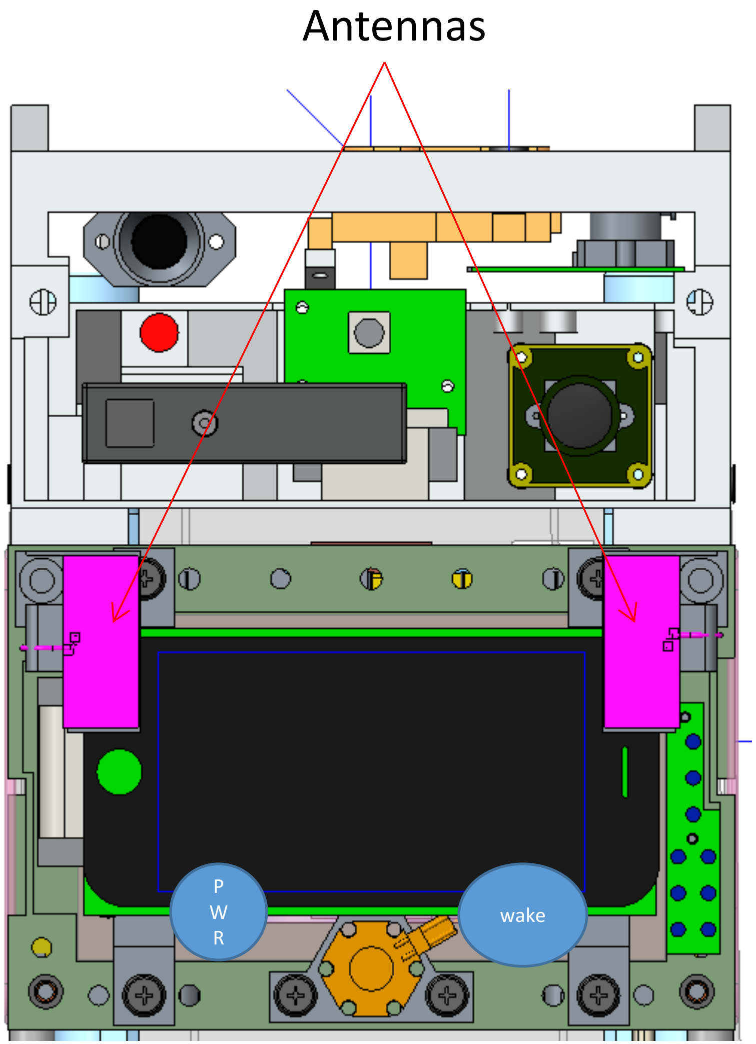


WiFi Antenna

- 2.4 GHz/5.8 GHz Wifi antenna
- ~3dBi/5dBi gain
- Omnidirectional
- Adhesive tape mounting
  - Additional tape will be applied to ensure launch survival
- Paper thin
- Mass: 0.477g

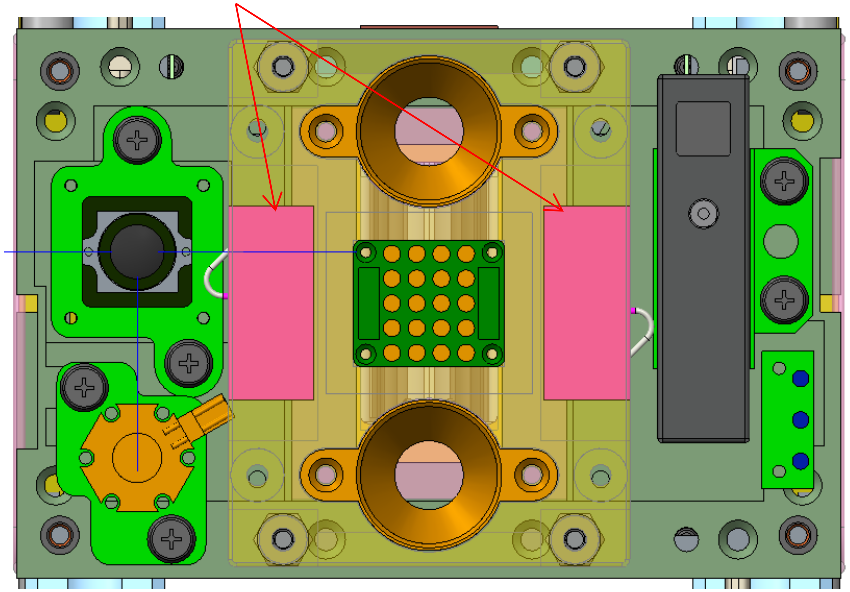
Antenna Placement - Front

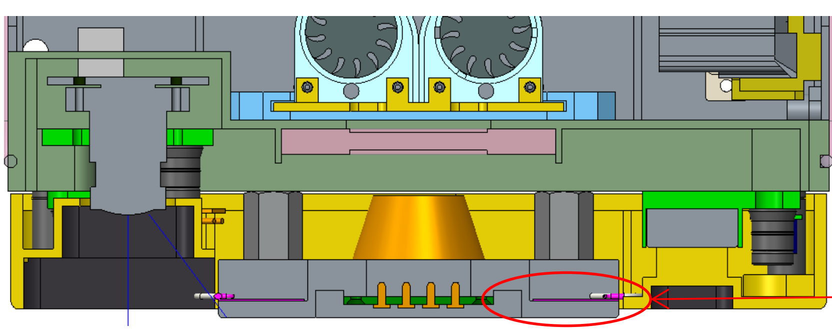


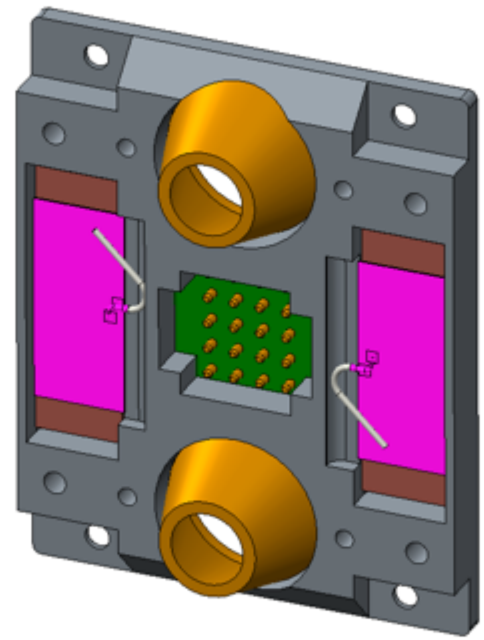


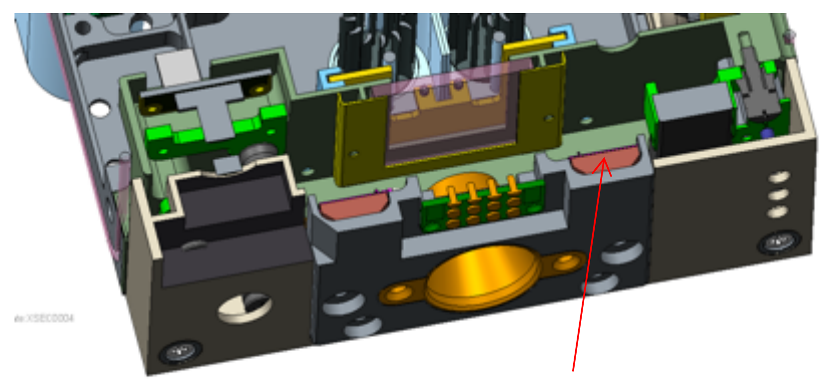
Antenna Placement - Aft

Antennas are on backside of Dock Adapter









Antenna location

Low adsorbent filler

Antenna Modularity

- An SMA/U.FL adapter has been added to ease installation and replacement.
- This adapter is in-line.

Astrobee FSW Subsystem

Design Overview

Astrobee FSW Features

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

FSW Components and Design Maturity @ PTR-3

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity. Software builds are expected to continue through on-orbit testing.

Mature

- OS (Communication Framework)
- Localization
  - Marker less Flying
  - Docking
  - Perching
- Offline mapping for localization
- *Pose Estimation + Propulsion Control (GNC)*

High Risk Components have been mitigated early

Evolving design

- Executive
  - Mode Management
  - Sequencer (Plan Execution)
- Mobility
  - Generates and validates trajectories
  - Performs collision detection
- Fault Management

Current main effort : low risk but critical components for the overall system

Draft only

- Guest Science
- User Interfaces
- Platform Management

Low Risk Components will be addressed in future Builds

FSW Components and Design Maturity @ PTR-3 delta

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity. Software builds are expected to continue through on-orbit testing.

- OS (Communication Framework)
- Localization
  - Marker less Flying
  - Docking
  - Perching
- Offline mapping for localization
- *Pose Estimation + Propulsion Control (GNC)*

Mature

High Risk Components have been mitigated early

- Executive
  - Mode Management
  - Sequencer (Plan Execution)
- Mobility
  - Generates and validates trajectories
  - Performs collision detection
- Fault Management

Mature

Low risk but critical Components for the overall system

- Guest Science
- User Interfaces
- Platform Management

Mostly designed

Low Risk Components are addressed in future build

Fault management

Fault Management Overview

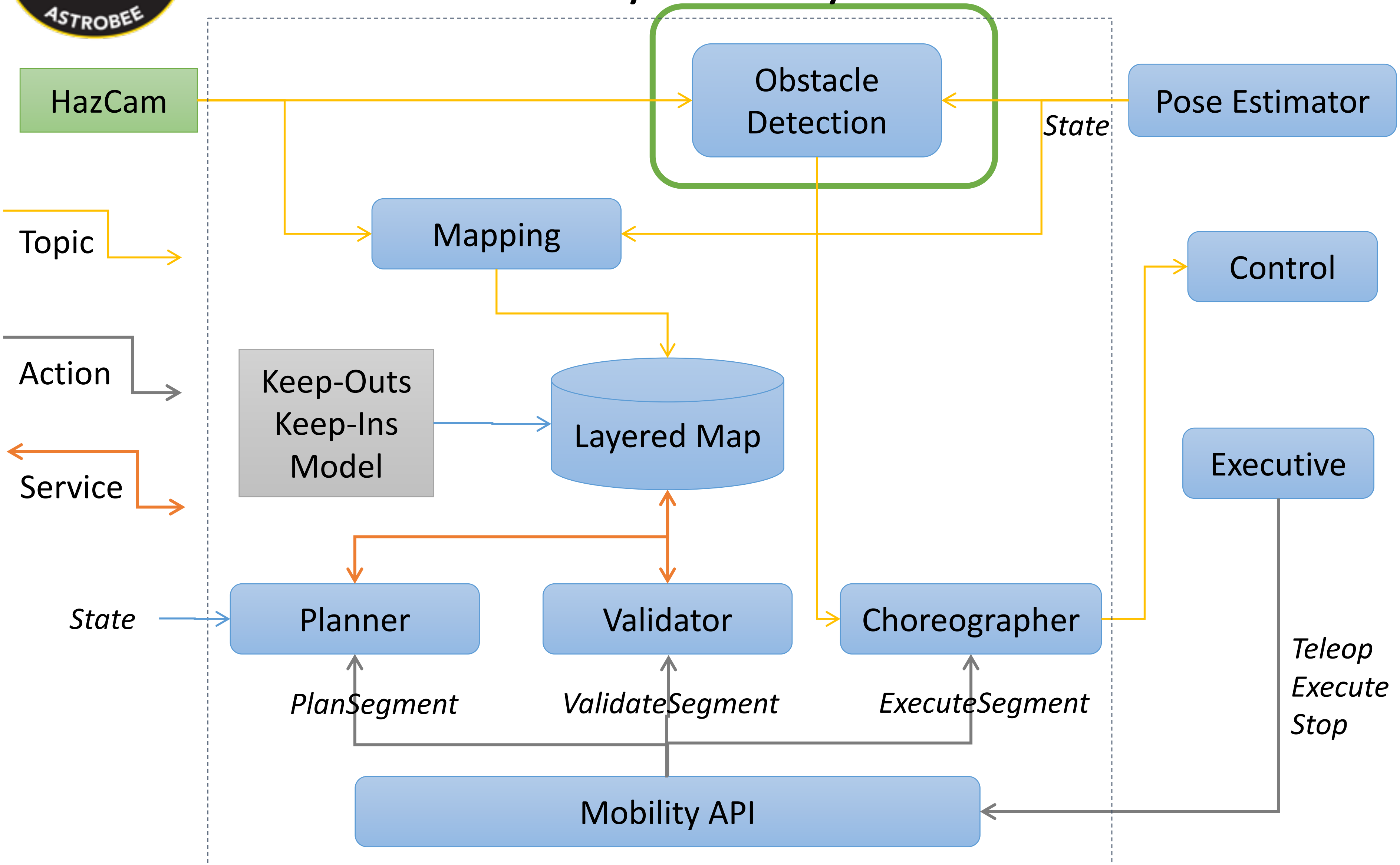
- Fault detection is performed by the subsystems
- Subsystems use configurable limits to identify faults
- Subsystems are be responsible for executing basic responses for a fault.
  - This allows for non-critical faults to be handled at a subsystem level rather than at the system level
- Subsystems communicate faults to the System Monitor
- The System Monitor can trigger system wide responses to faults and heartbeats
- ~100 faults already documented in IRG-FF042-01-Astrobee-FMECA.xlsx. Fault table automatically generated from the spreadsheet.
- Reserve for "Recovery" mechanism (not implemented)

System Manager

- System Manager module is responsible for
  - Keeping track of which faults are enabled or triggered
  - Reporting subsystem warnings and triggered faults to the ground
  - Monitoring subsystem heartbeats
- Responses type (can be extended):
  - **No-op** (advisory only, subsystem may provide response)
  - **Fault** (Mobility not affected, current command completes but system does not accept new commands)
  - **Stop** (Vehicle stops and maintain position)
  - **Idle Propulsion** (Vehicle propulsion disabled)

Mobility

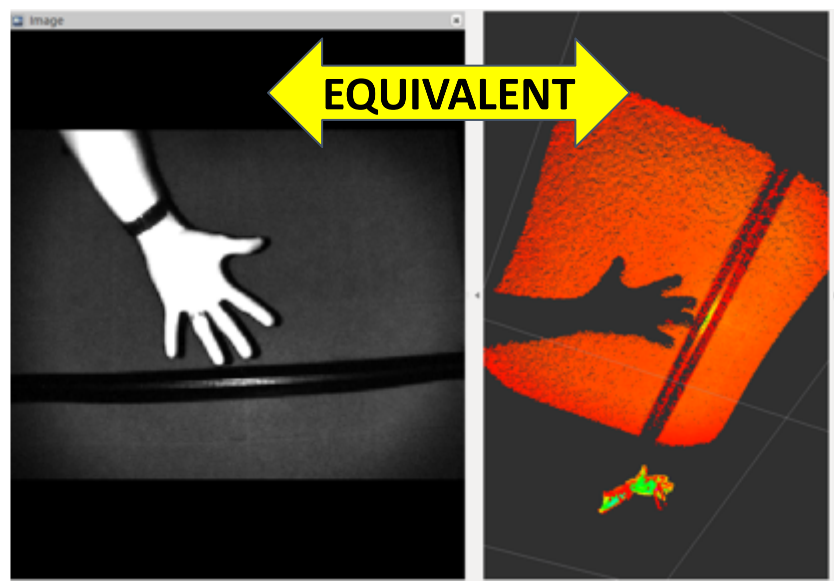
Mobility Subsystem



Collision Detection: Problem

- Use depth images / point clouds to forecast upcoming collisions
  - Assumption: not interested in classifying or modelling obstacles, only detecting collisions.
  - Assumption: each measurement is discarded after checking, and so no map is built.

Picoflexx Sensor

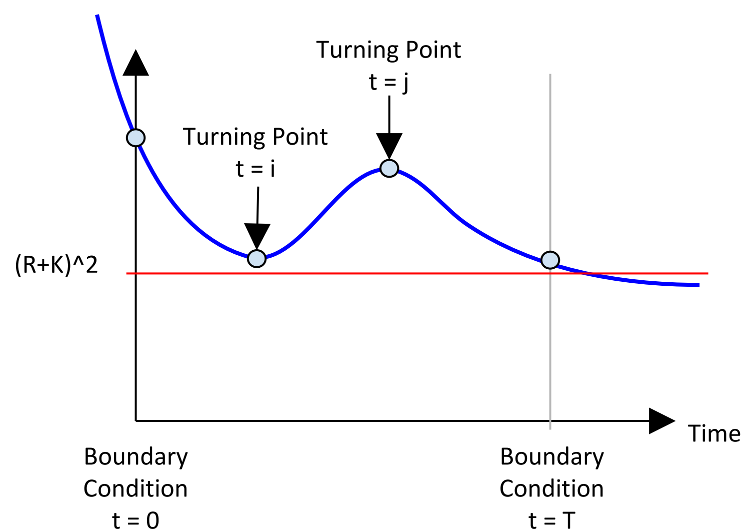


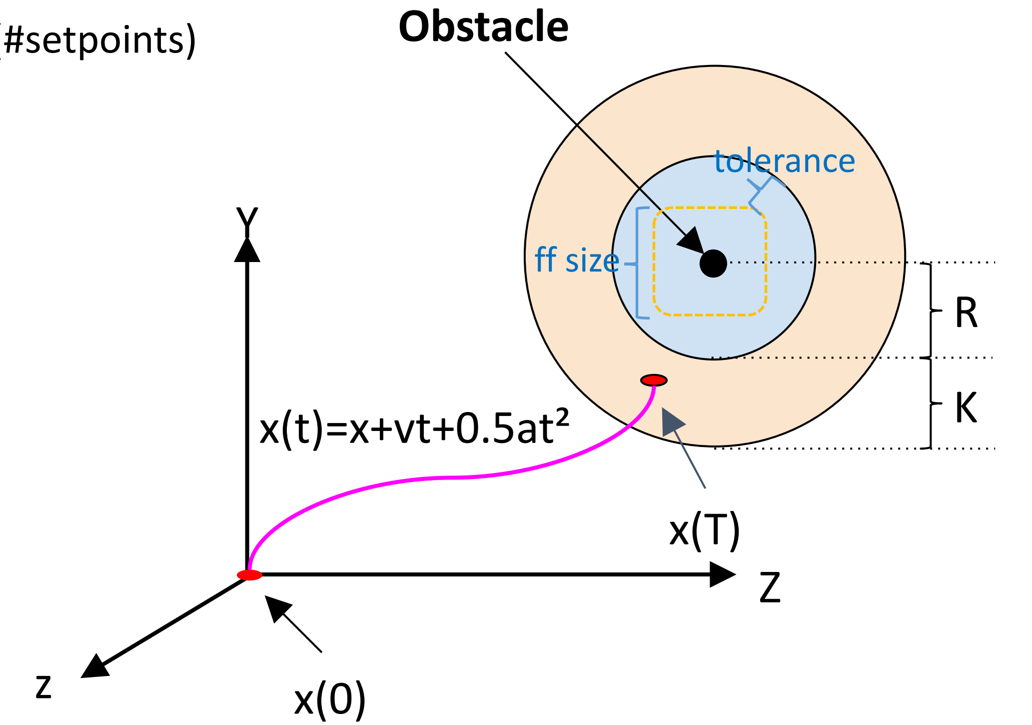
Depth image (224 x 171 px) Point cloud

Collision Detection: Algorithmic Complexity

- Reduce complexity of depth data by discretizing space into **K** x **K** x **K** regions
- Safe radius from geometric center of freeflyer given by **R** (size of FF + tolerance)
- Collision checking reduces to evaluating if the squared distance between the curve x(t) defined by the setpoint over t=[0:T] and the obstacle is <= (R+K)^2
  - Can be done by just checking boundary conditions and turning points.
  - Equivalent to solving for a cubic root: closed form.
  - Complexity linear in (#obstacles) * (#setpoints)

Squared distance between the freeflyer geometric center and the origin of the obstacle sphere



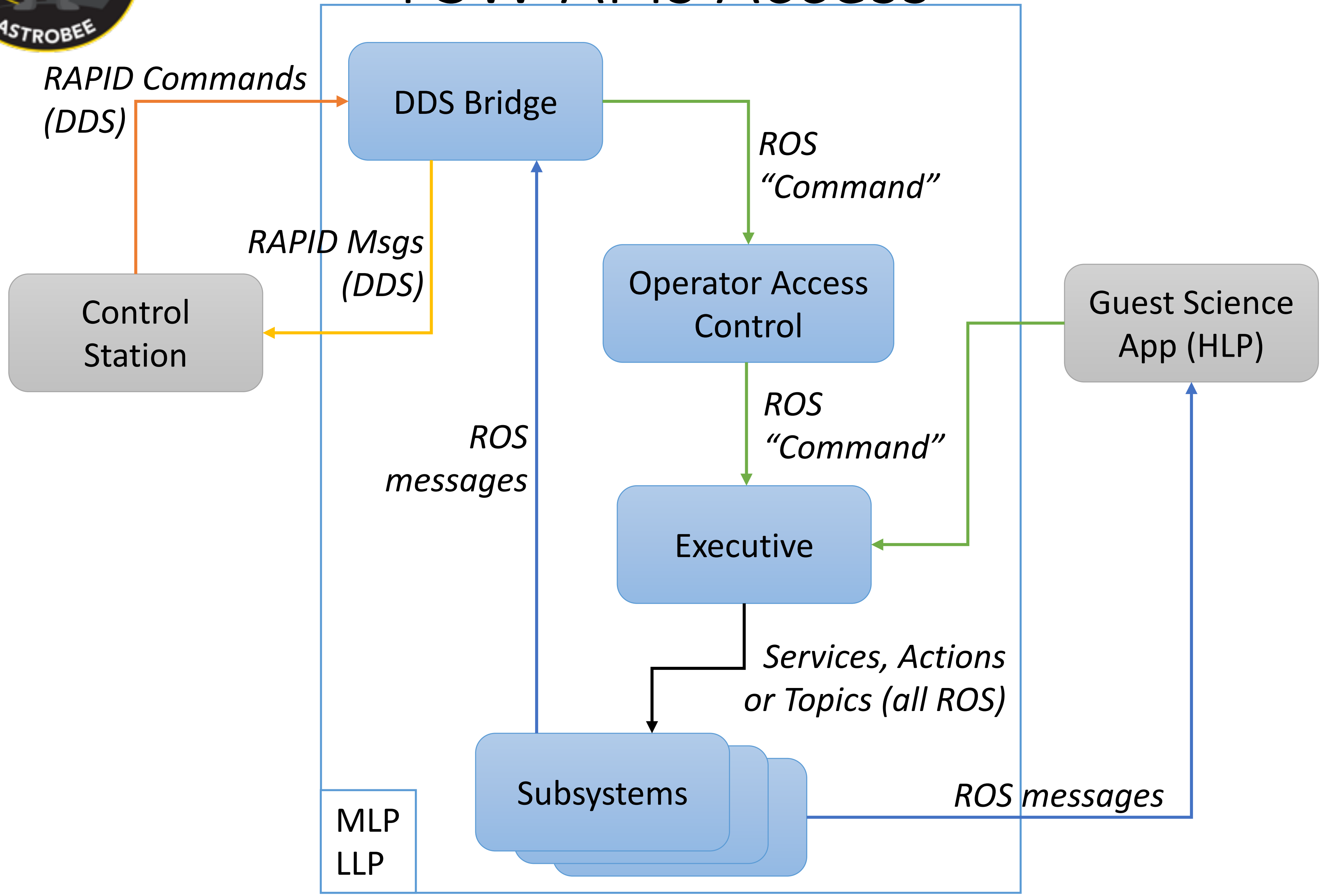


Guest Science

FSW APIs Overview

- FSW uses ROS within Astrobee: Messages, Services and Actions define the internal API
- Astrobee & Ground communication uses DDS and the RAPID framework for command and telemetry
- Commands:
  - Commands are defined using XP-JSON schema, tools auto-generates RAPID command dictionary
  - FSW defined a ”ROS Command” mirroring the DDS command structure
  - Onboard Astrobee Guest Science or Ground Applications **share** the **same command dictionary** (some commands unique to one client) with either DDS or ROS transport
- Telemetry:
  - Internal uses ROS Messages (using ROS messages when possible)
  - External uses DDS Messages (subset only, re-using RAPID messages)

FSW APIs Access



Onboard Guest Science

- Guest science benefits from a quad-core processor running Android
- Interface with guest science hardware trough USB (possible to have special USB gadgets)
- Guest science runs as an Android app on the high level processor.
- Guest science apps communicate to/from outside a Freeflyer using the DDS protocol
- Guest science API consists of the ROS telemetry topics and the generic FSW "ROS Command"

Platform Management

Software Update Overview

- FSW is deployed on 4 computers (Astrobee + Dock) running Linux and Android
- Astrobee contains 7 distinct microprocessors with custom firmware + several microprocessors with COTS firmware
- All paths for on orbit updates have been identified
- P4D provides all the physical connections to implement these updates
- Software deliverables includes:
  - Custom firmware(s)
  - Adapted Kernels
  - Linux and Android Operating Systems
  - FSW Dependencies
  - FSW code

Astrobee Custom Firmware List

Firmware	Board Type	Update Path
Dock control firmware	PIC32MX795F512H	Dock Processor via I2C
EPS firmware	PIC32MX795F512H	LLP via I2C
PMC firmware	PIC32MX795F512H	LLP via I2C
Speedcam laser firmware	unknown	ground harness only
Speedcam velocity firmware	ARM Cortex M4	LLP via USB
Signal lights firmware	PIC32MX795F512H	LLP via I2C
PerchArm firmware	dsPIC33EP512MC806	MLP via Serial over USB

Astrobee Software Categories

Software	Board Type	Update Path
Wandboard Kernel	Wandboard Dual, Dual core i.MX6	Ethernet from Dock using Recovery
Inforce Kernel	Inforce, Quad core Snapdragon 805	fastboot over USB from LLP
Linux Base OS	['Wandboard', 'Inforce']	fastboot (Inforce) or recovery (Wandboard)
Android Base OS	Inforce	fastboot using USB from LLP
FSW Linux Dependencies	['Wandboard', 'Inforce']	apt using Ethernet from Dock
FSW for Linux	['Wandboard', 'Inforce']	apt using Ethernet from Dock
FSW for Android	Inforce	adb over Ethernet from MLP
dock software repository	Wandboard	rsync over Ethernet from ground

Software Update Methods

- Base system (Kernel + OS) are flashed using:
  - Uboot (Wandboard boards, Linux)
  - fastboot (Inforce boards, Linux and Android)
- FSW dependencies are delivered as Debian packages
- FSW itself also delivered as Debian package
- Dock computer act as Debian repository
  - Only one copy from ground to ISS
  - Benefit from Debian “apt” toolset for safe upgrade
- Filesystem uses OverlayFS
  - Permanence of a valid OS and software
  - Allow temporary configuration changes while running

Localization

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
  - **Visual Odometry: velocity and maintain pose when no features are available**
  - Handrail Detector : only runs for perching
  - AR Tags : only runs for docking

Optical Flow to Visual Odometry

- EKF update is same as than with optical flow
- 16 frames are retained instead of 4
- Selected observations are used rather than last 4 frames, and always keep oldest visible feature frame
- Benefits:
  - *More stable localization in nominal conditions*
  - *Resilience to loss of map features (unmapped, obstruction, light, …)*
- Problem: covariance matrix size is (21 + 6 * augmentations)^2, increase from 4 to 16 is 576% increase, EKF had to be optimized by a factor 6

“High-precision, consistent EKF-based visual-inertial odometry.” Mingyang Li and Anastasios Mourikis. International Journal of Robotics Research, 2013.

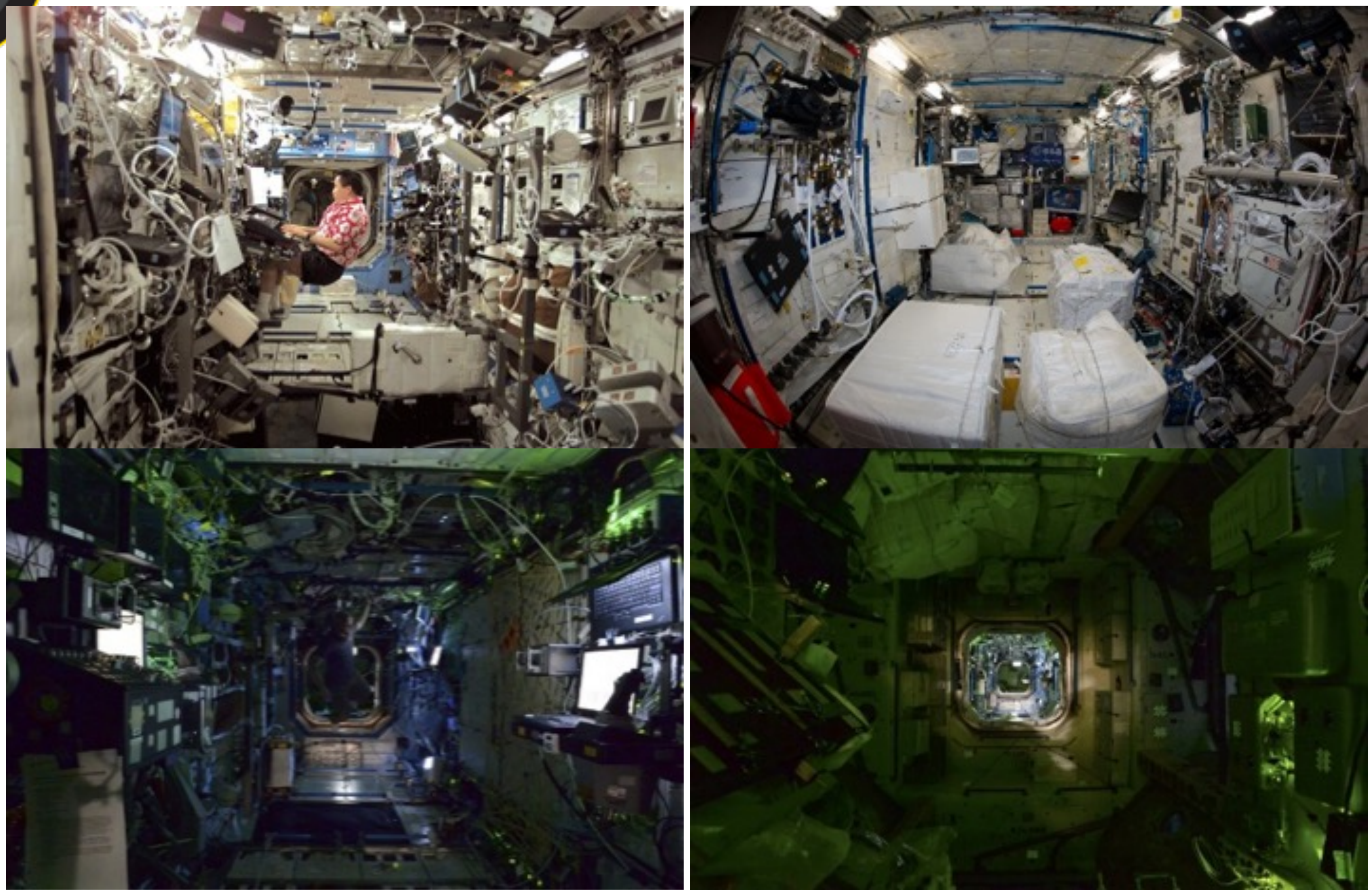
Visual Odometry Performance

- EKF is part of GNC, developed with Simulink. Despite optimizations, could not deliver the required performance.
- Computational intensive blocks have been re-written with C++ code using optimized libraries

Function	MathWorks "Optimized" Simulink-Generated C	FSW Hand Written C++ using Eigen	Improvement
of_residual_and_h	87.0 s	2.0 s	98% (43x)
delta_state_and_cov	22.5 s	3.5 s	84% (6x)
covariance_multiply	18 s	< 2 s	89% (~10x)

Video of Visual Odometry

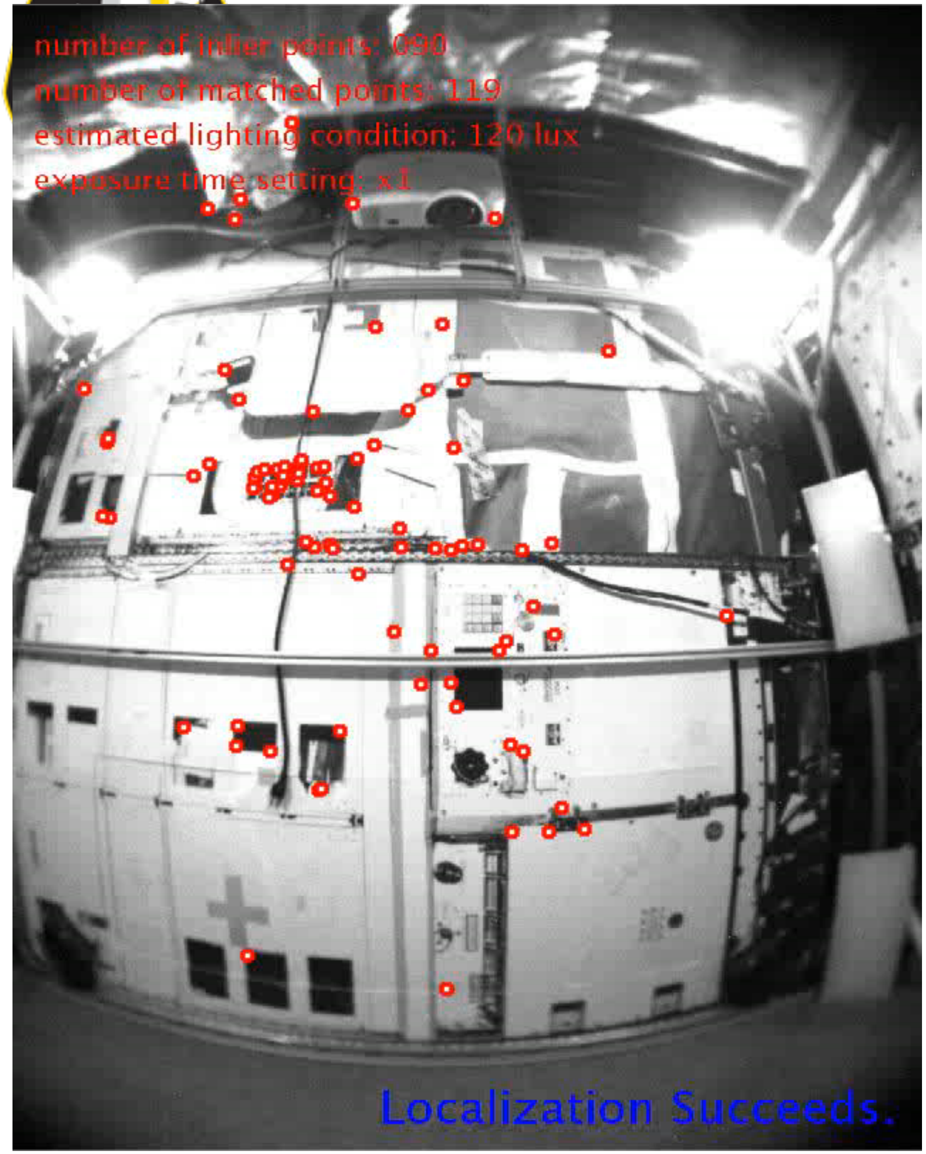
Robustness to Lighting Condition



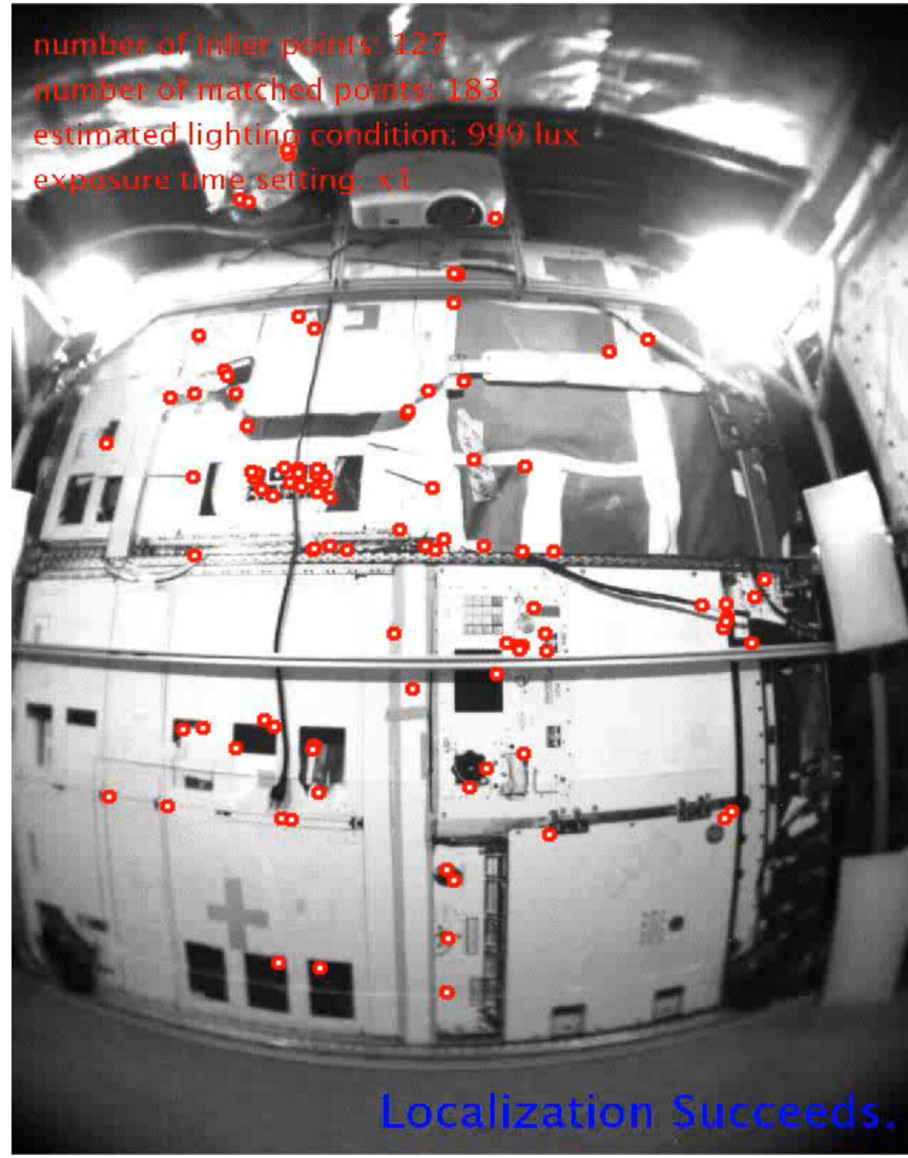
Lighting Conditions at the Day & Night Times on the ISS

“Robust Visual Localization in Changing Lighting Conditions.” Pyojin Kim, Brian Coltin, Oleg Alexandrov and H. Jin Kim. Under submission.

Pyojin's Algorithm



Original Algorithm



Forward Work

- Build 2 (CERT TR)
  - Software update (platform management)
  - Freeze DDS API for Crew Control Station
  - Refine Guest Science API
  - Mobility (obstacle detection and perching procedure)
  - Finalize all subsystems controlling hardware devices
  - Improve Infrastructure (including simulation tools)
- Build 3 (Flight TR)
  - Complete platform management (file mgt. and transfer, etc.)
  - Increase system reliability by extensive testing on Granite Lab and new Gantry (3D) facility
  - Adaptations to ISS specific environment
  - Implement UI

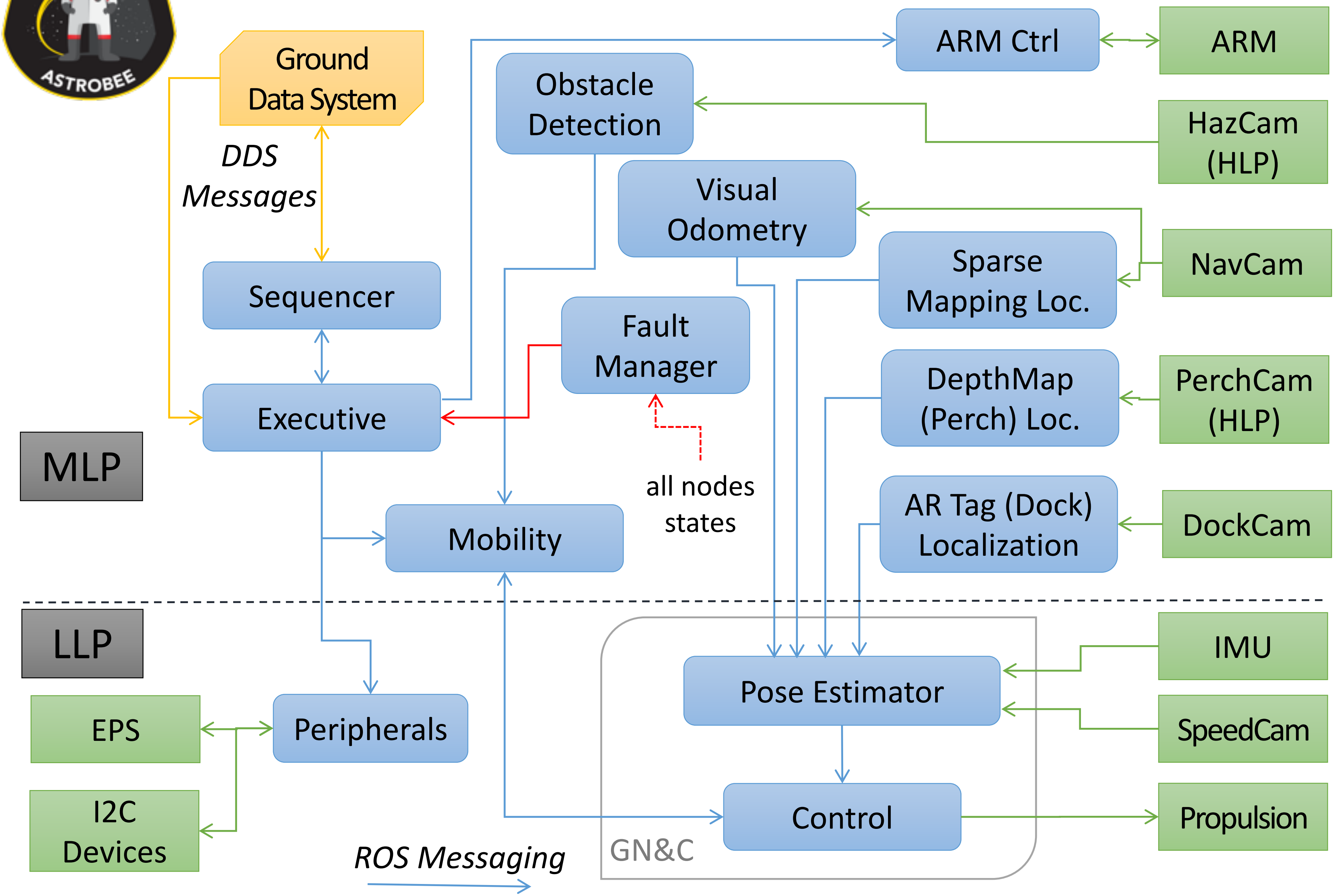
BACKUP SLIDES

Overall architecture

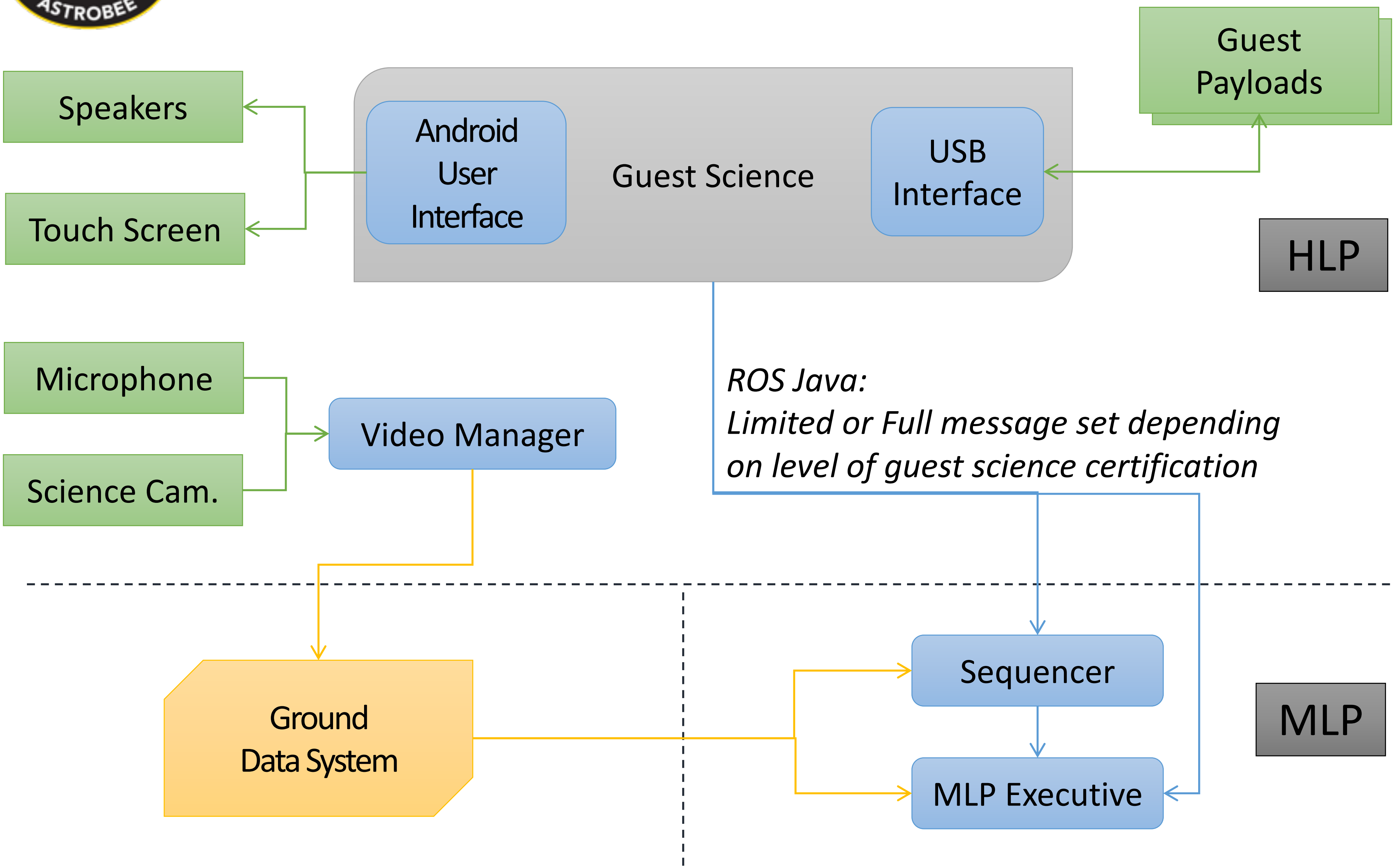
Selected HW Architecture

- *Three ARM processors to isolate guest code, vision based navigation and 100 Hz control loop*
- **Low Level Processor** (LLP) – Linux, Dual core
  - Runs high freq. EKF 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 (HLP)



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

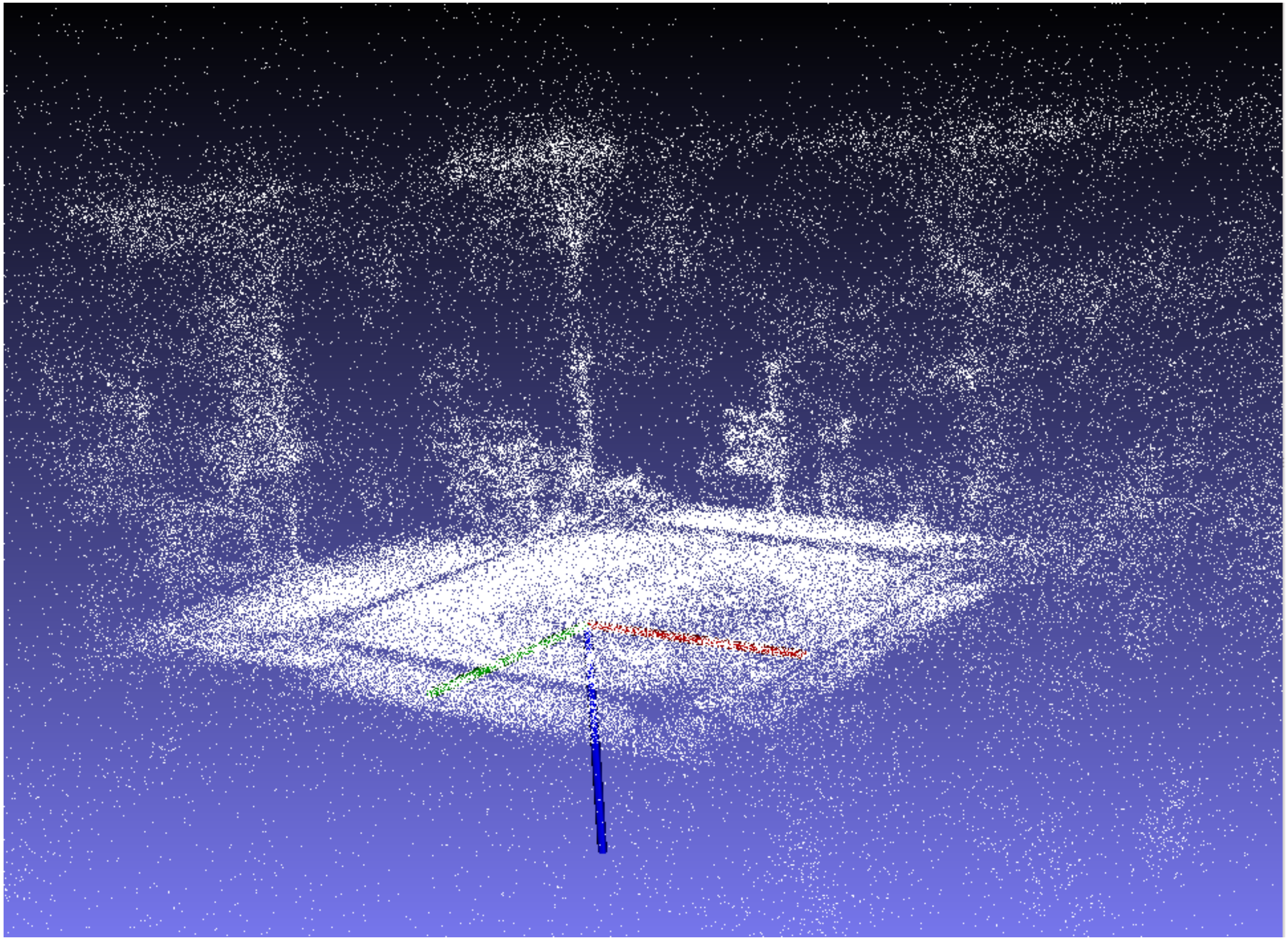
Localization Design Drivers

	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

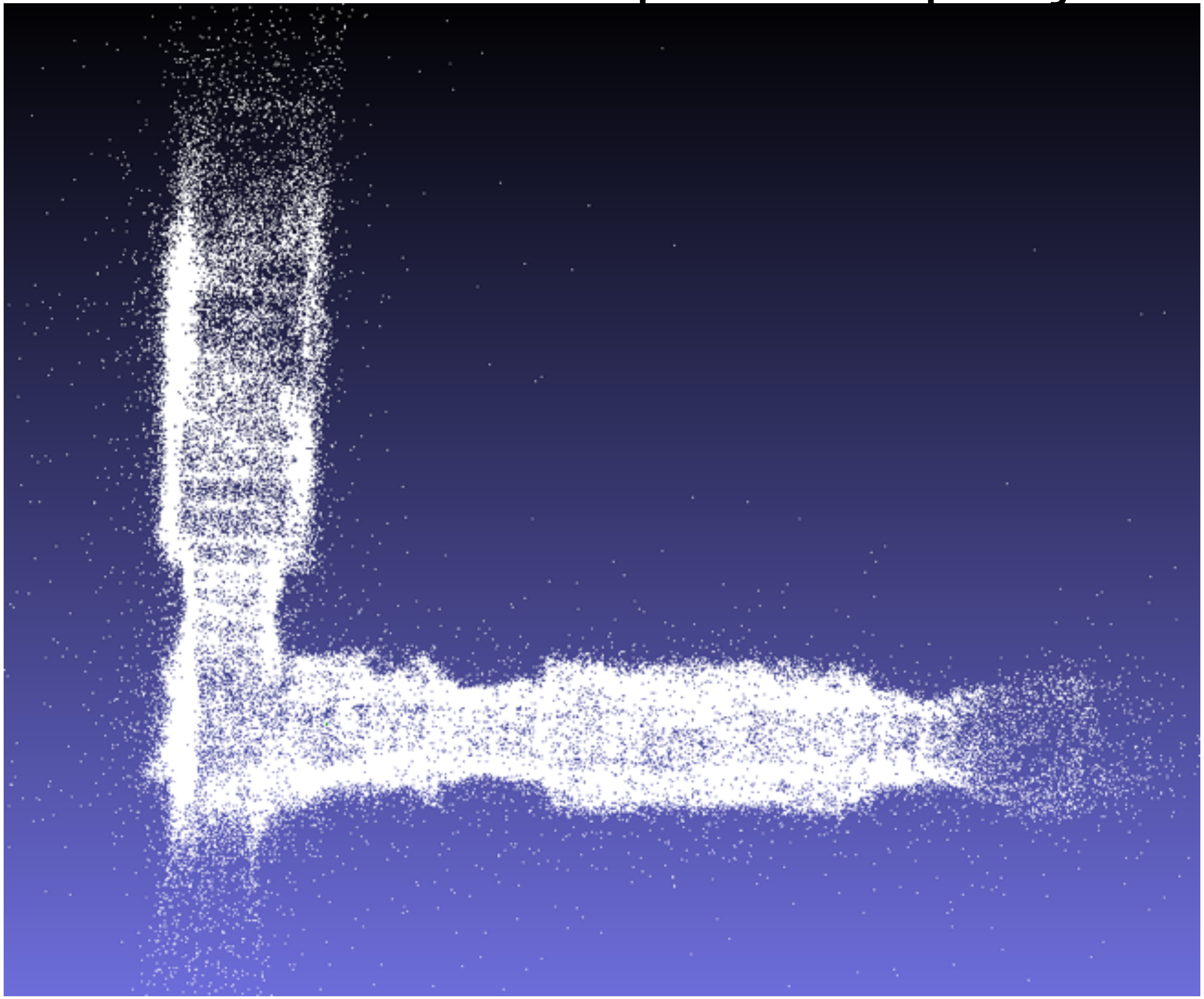
Requirements
Localize anywhere on ISS US segment
Minimize modifications to ISS
Cope with changing environment

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

Granite Lab Map



Map of connected ISS Modules (data from SmartSpheres project0



Platform architecture

Processors and communication links

Astrobee GN&C Subsystem

Delta PTR3 Design Overview

Design Maturity

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

Component	Maturity / Risk	Forward Work
IMU	High / Low	
Controller	High / Low	
Estimator	High / Low	
FAM	High / Low	
Simulator	High / Low	
Fault Management	High / Low	Implement faults from FMECA

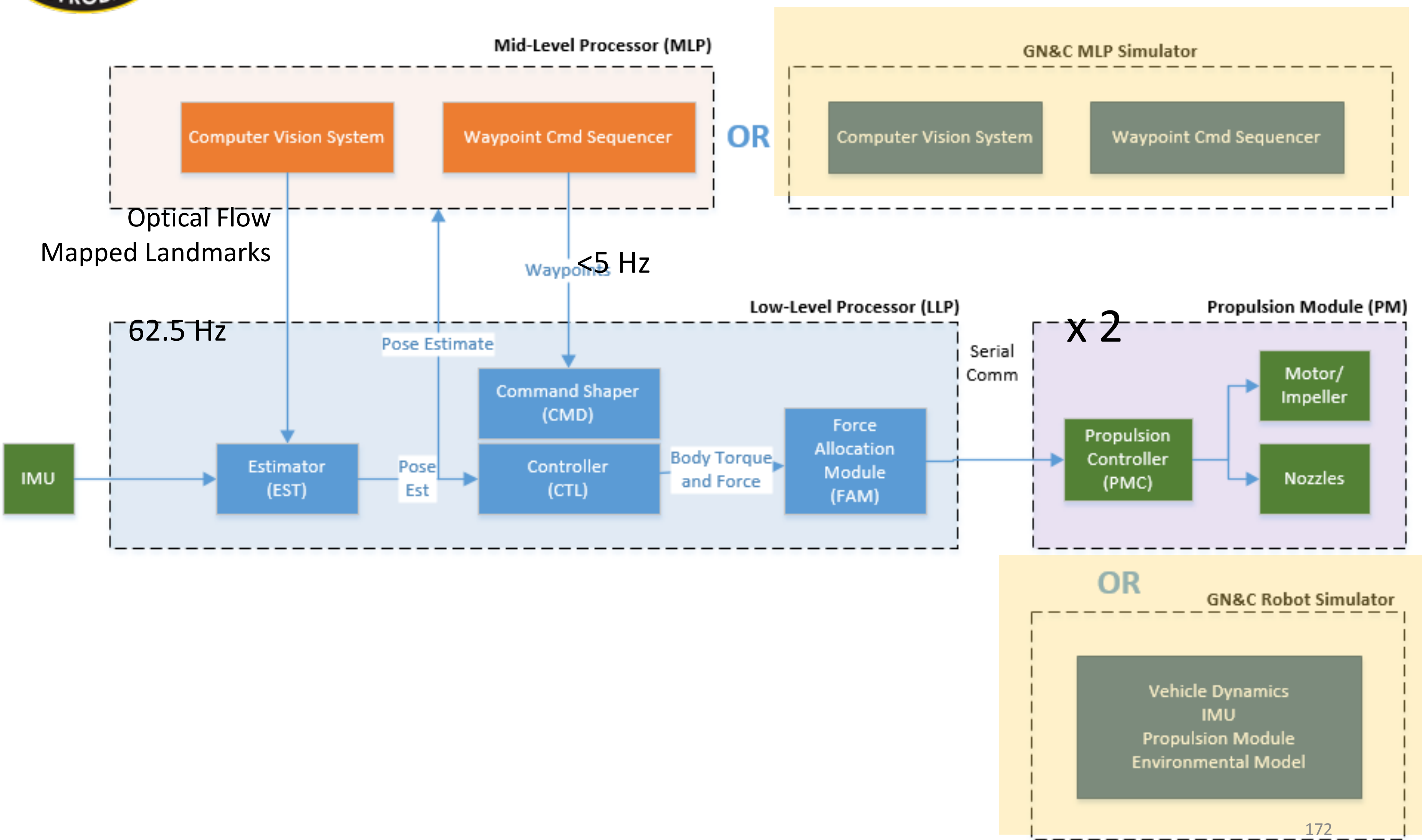
New/Changes from PTR3

Component	New / Changes
Estimator	- Re-worked optical flow augmentation process to decrease drift when operating in an area with no mapped features - Changes to allow for removing gravity from the IMU signals to allow for ground testing of 3 axis attitude control
Fault Management	- Identified baseline GN&C faults

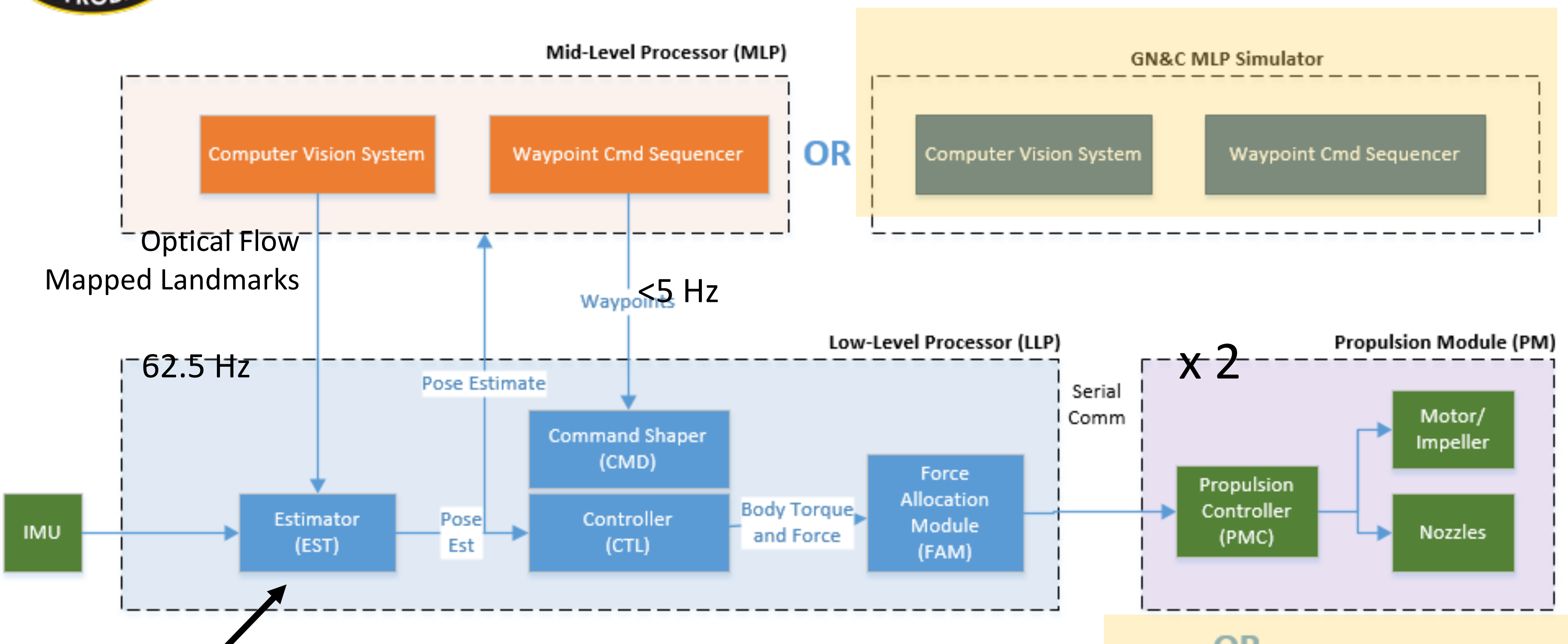
GN&C: Overview
Design Drivers

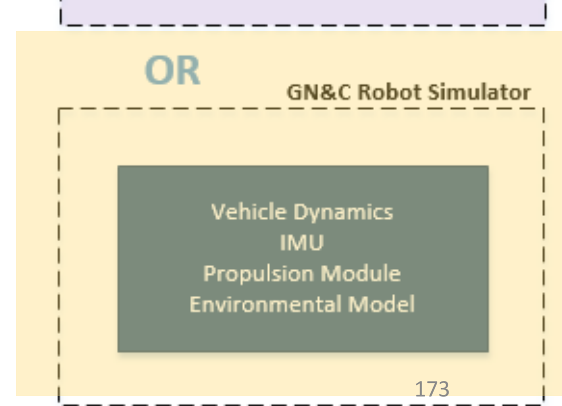
Parameter	Linear Requirement	Angular Requirement
Maintain Controllability	Up to 50 cm/s	Up to 45 deg/s
Max Acceleration	10 cm/s^2	10 deg/s^2
Pose Error (Nominal)	< 20 cm	< 20 deg
Pose Error (Assisted w/ AR tags, etc.)	< 2 cm	< 8 deg
Use Vision based navigation		

GN&C: Overview
Architecture Diagram



GN&C: Overview
Architecture Diagram

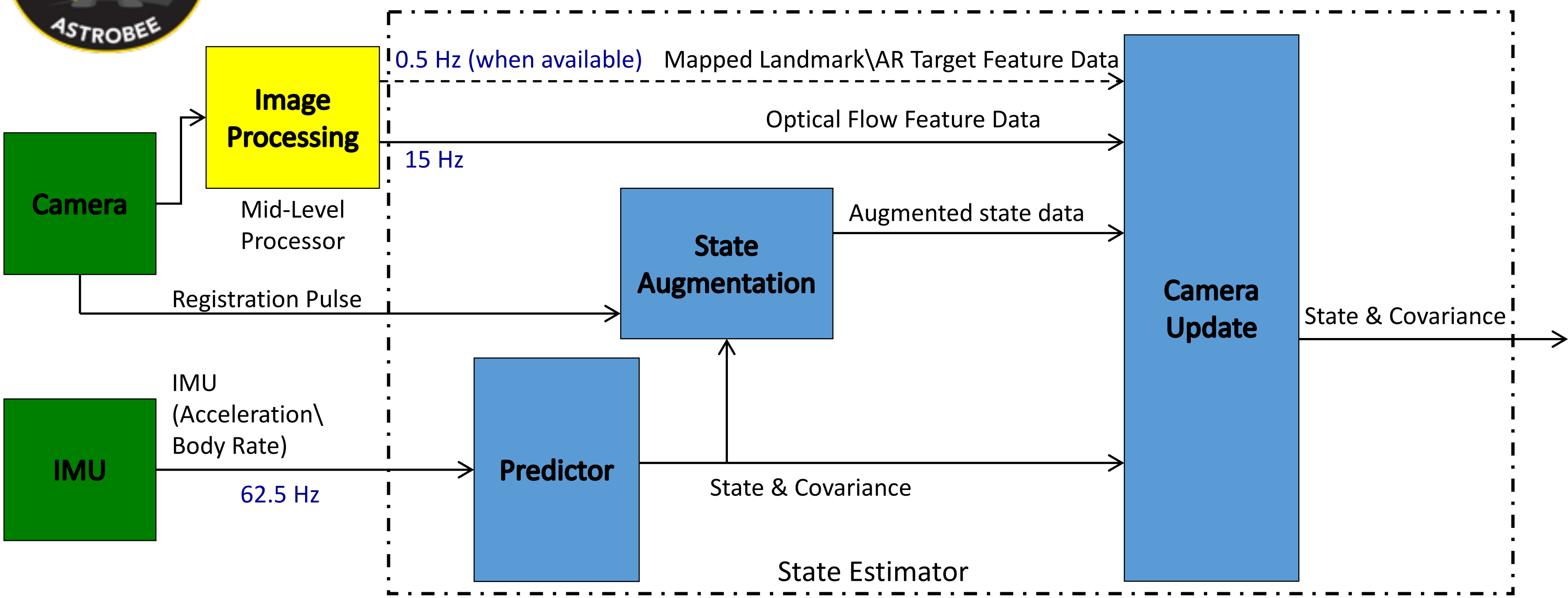




<u>Integration with FSW</u>

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

GN&C: Software Estimator (EST)

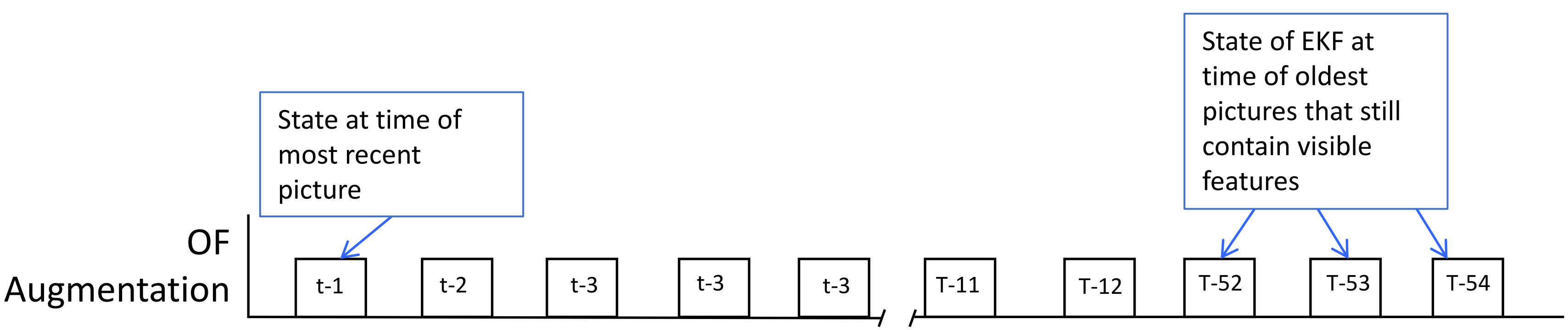


Total of 45 states: 15 core states, 6 mapped landmark, and 24 optical flow augmented states

$$x(t) = [\; q \quad b_g \quad {}^{iss}V \quad b_a \quad {}^{iss}P \quad C_{\theta,ML} \quad {}^{iss}C_{p,ML} \quad C_{\theta,OF,1} \quad {}^{iss}C_{p,OF,1} \quad \cdots \quad C_{\theta,OF,5} \quad {}^{iss}C_{p,OF,5} \;]$$

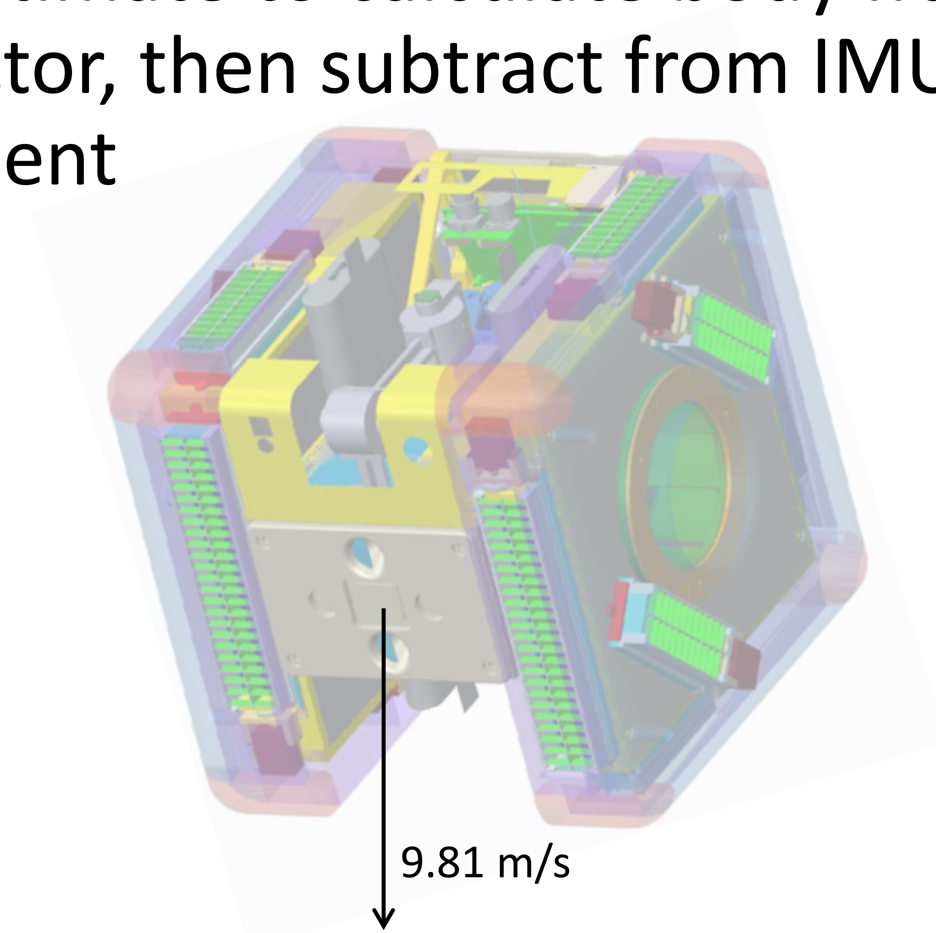
GNC: Software Estimator (EST)

- Optical flow augmentation management logic changed to retain the oldest augmentations that contain features that are still visible
  - Retaining the oldest augmentations reduces drift and improves accuracy when operating in areas with poor map coverage



GN&C: Software
Estimator (EST)

- Gravity removal done by using VisualEyez attitude estimate to calculate body frame gravity vector, then subtract from IMU measurement



GN&C: Simulation

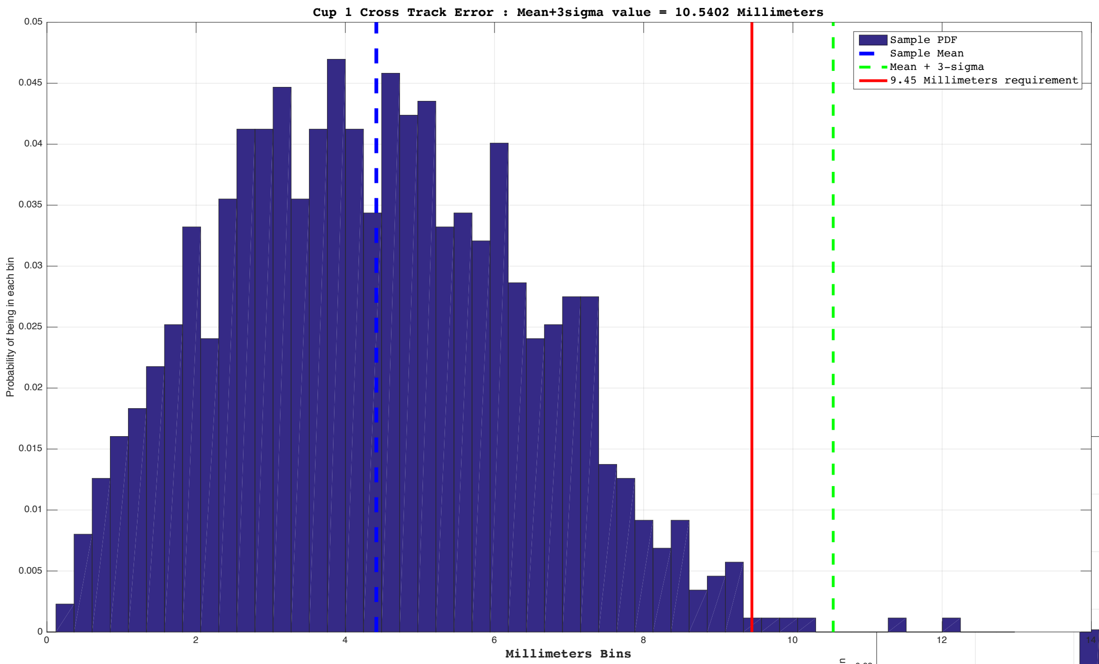
Current and Planned Uses

- 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)

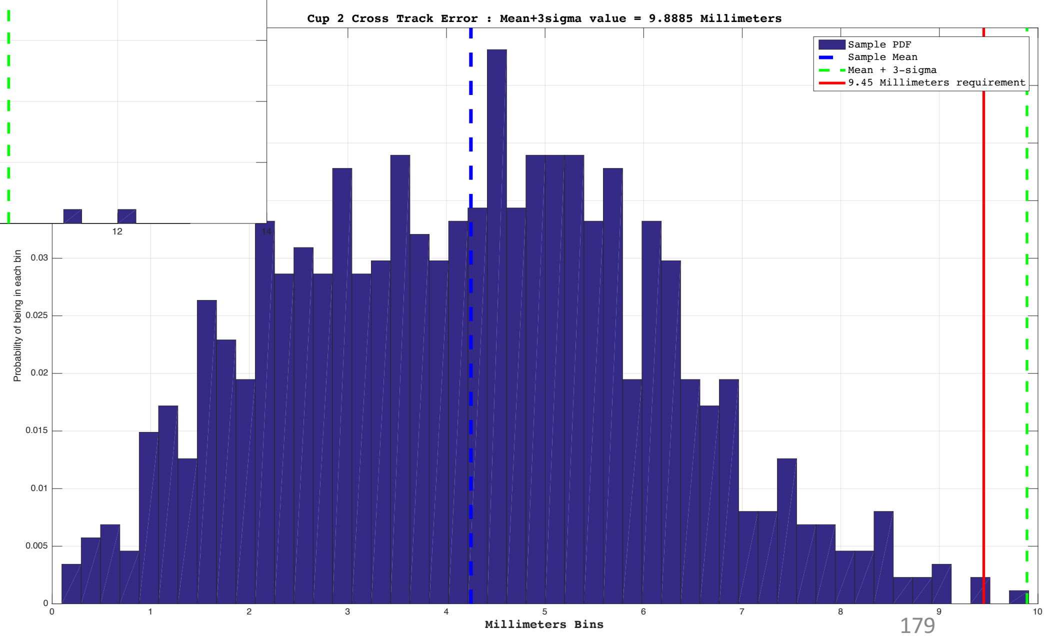
Planned Future Testing

- Granite table goniometer testing
  - Allows testing in different orientations
- Gantry testing
  - Allows testing 6-DOF system

Monte Carlo Analysis: Docking



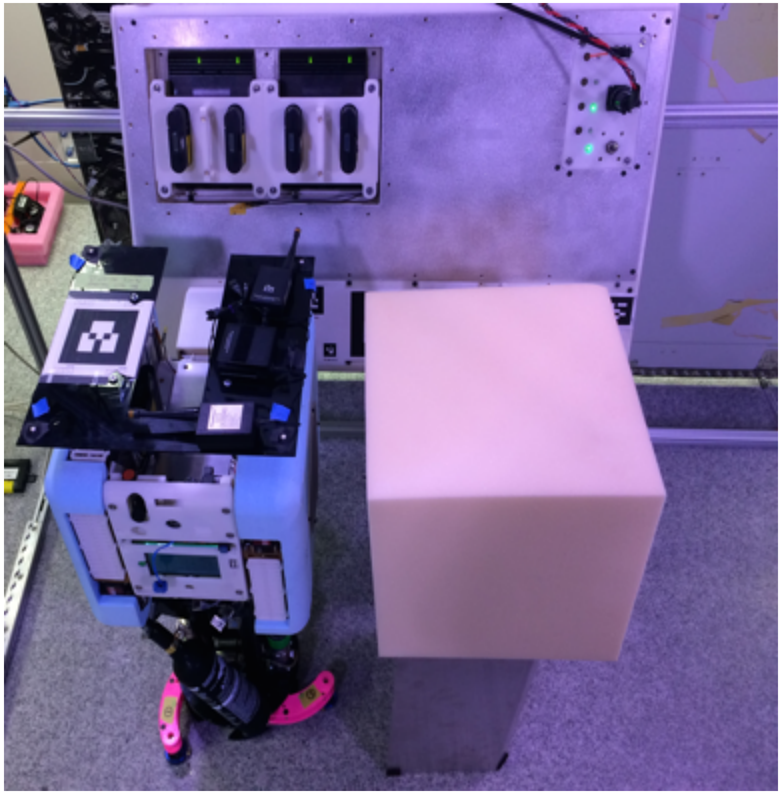
Docking Scenario repeated 873 times varying noise parameters, noise seeds, alignments, and uncertainties.



Scenario only showed errors large enough to fail docking in a handful of scenarios (mostly due to large position or alignment errors of the Dock Cam).

Testing: Ground Effect

Testing to ensure Astrobee could reject suction force from dock cooling fan and from propulsion system



Astrobee Perching Arm

Design Overview

Design Maturity

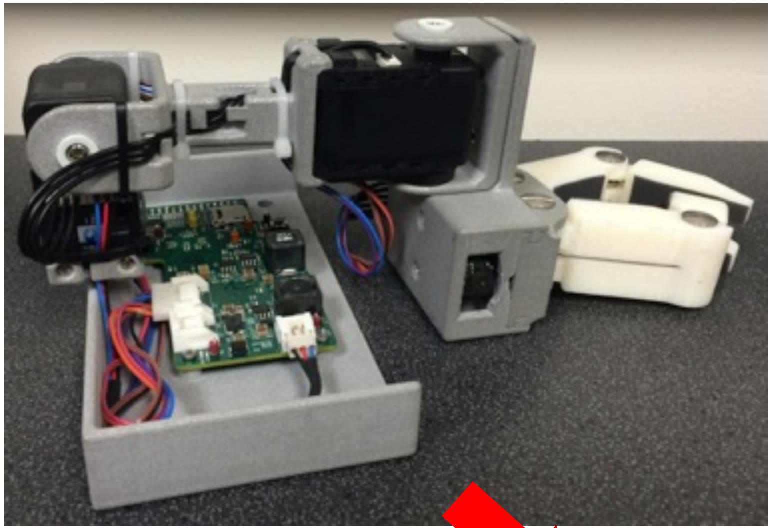
The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

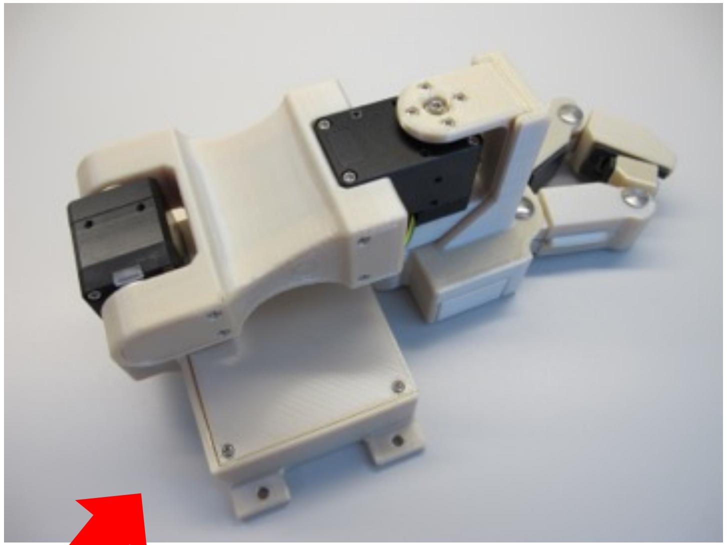
Component	Maturity / Risk	Forward Work
Arm	High / Low	
Gripper	High / Low	
Controller board	High / Low	
Software	High / Low	
Payload Attachment Mechanism	High / Low	Minor design updates

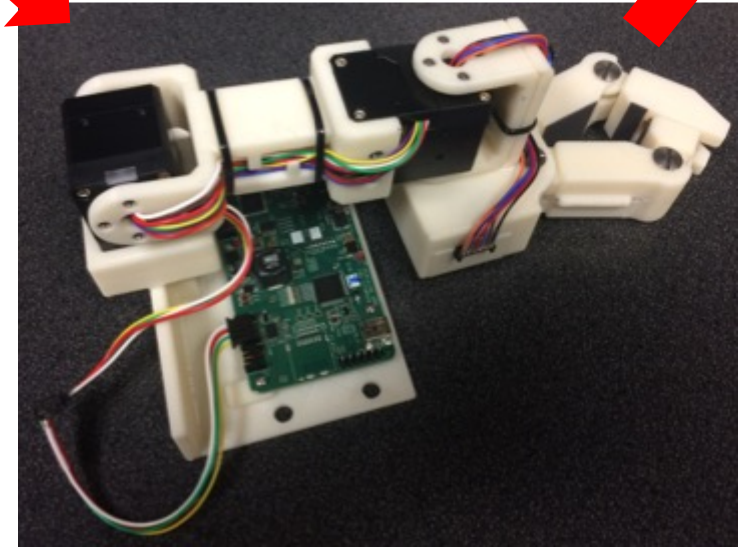
New/Changes from PTR3

Component	New / Changes
Design	- Aesthetic design updates for cable routing and appearance
Hardware	- New motors for both arm joints and gripper - New torsional springs for gripper - New silicone rubber pad for gripper
Avionics	- New load switch and current limiter for gripper motor - New level shifter to resolve impedance matching issue - New connector boards for arm distal link and gripper
Software	- New firmware for arm motors - Update MLP-Perching Arm ICD

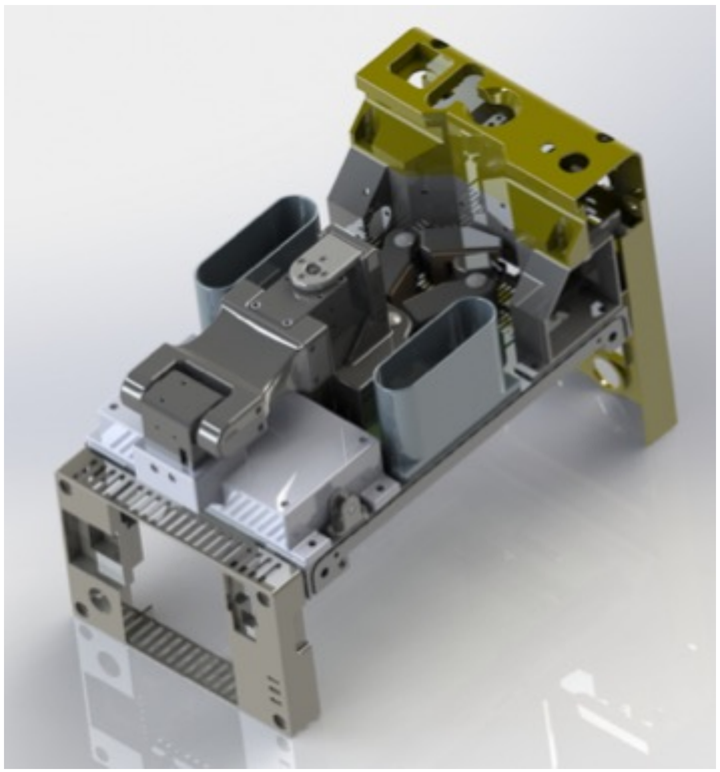
Snapshot of Hardware Progress

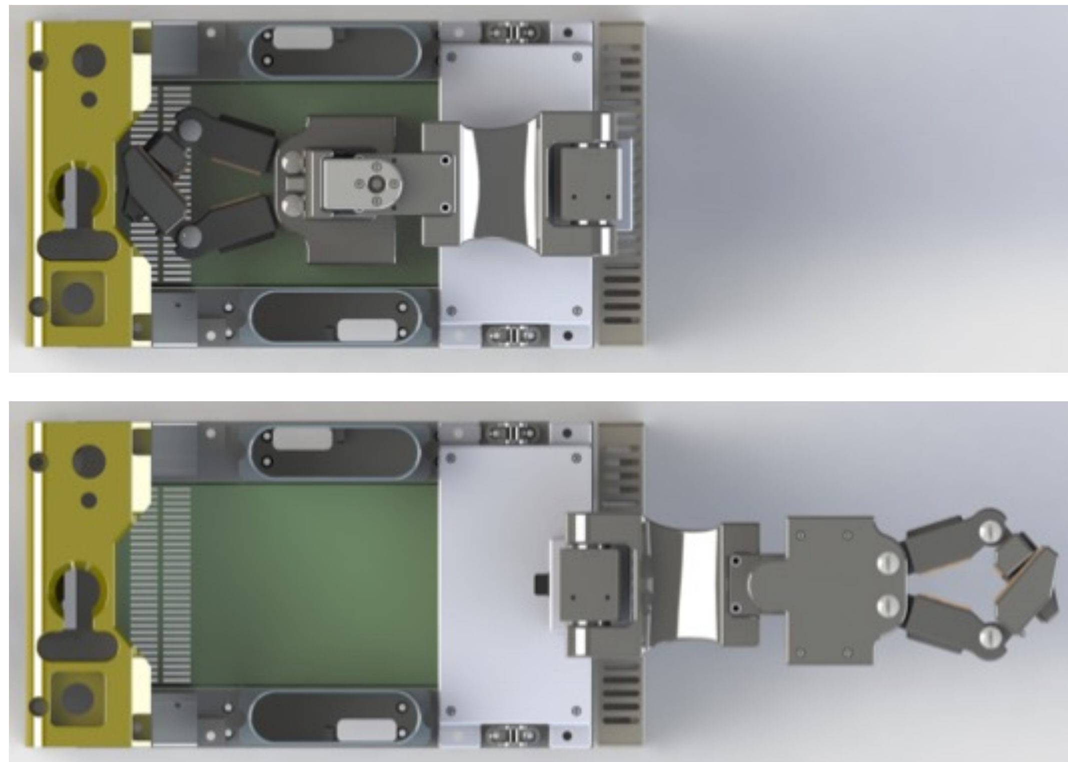






Design





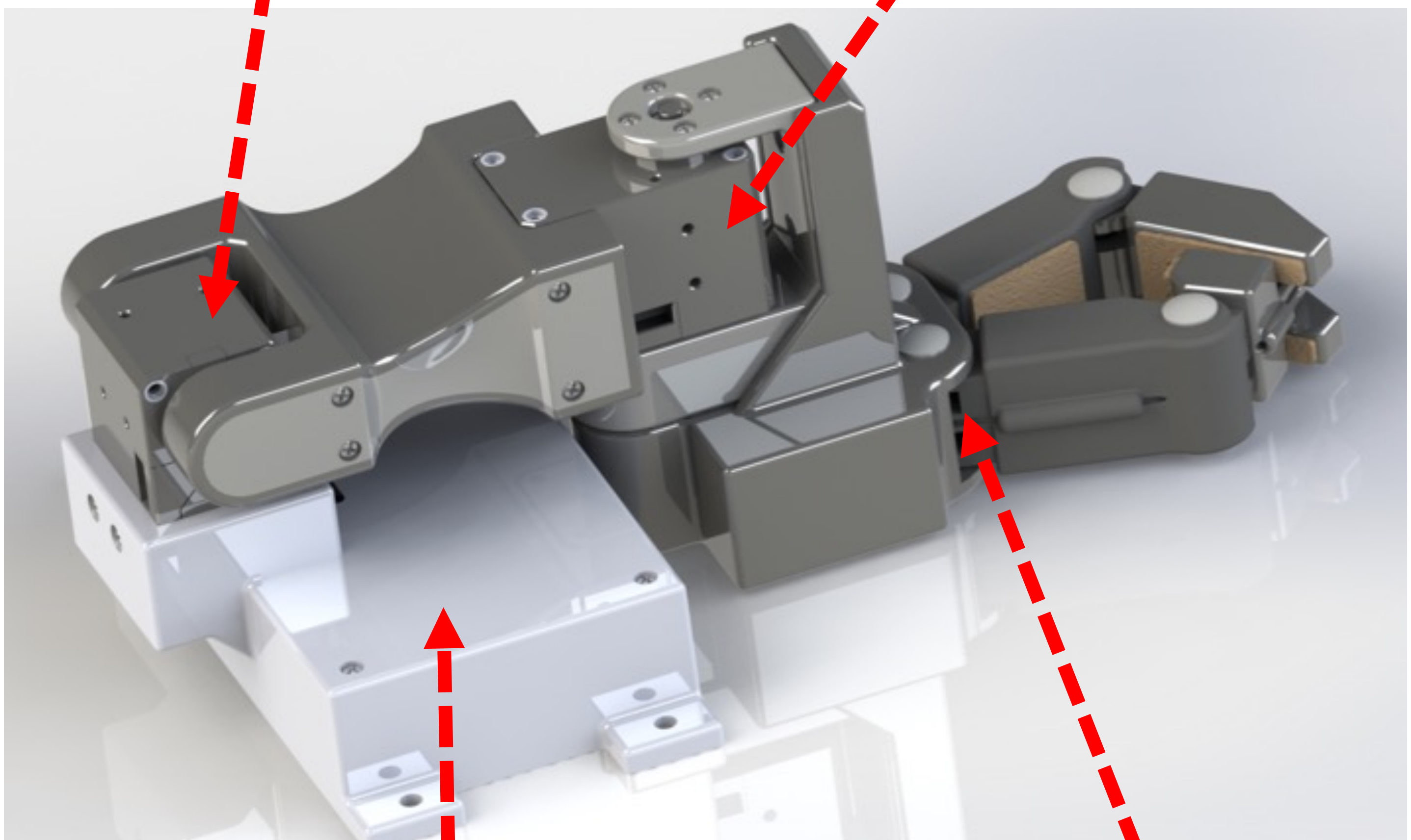
Stowed Configuration
(diagonal view)

Stowed/Deployed Configuration
(top view)

Component

Arm Proximal Assembly

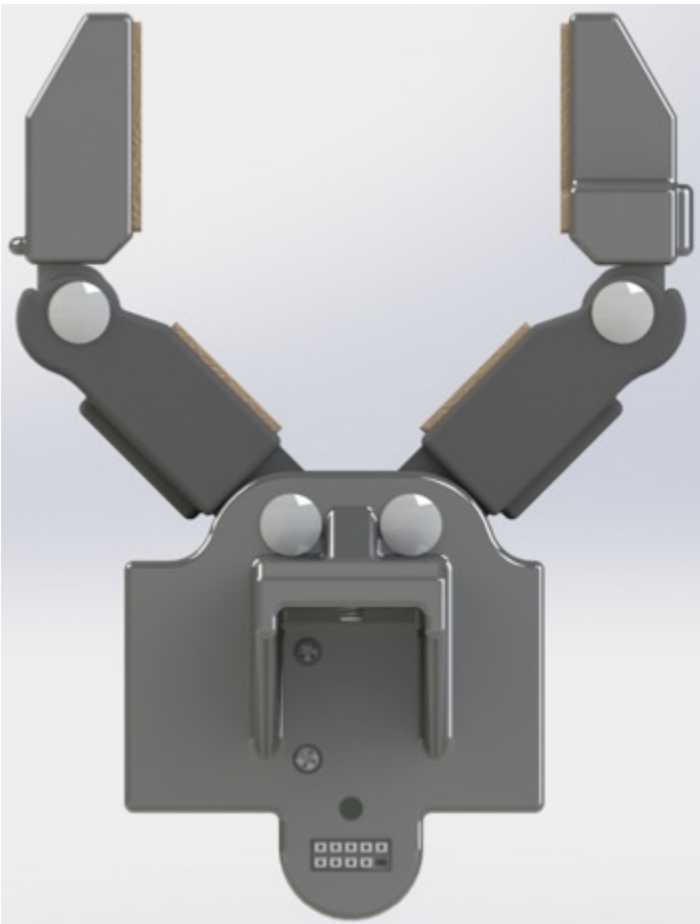
Arm Distal Assembly



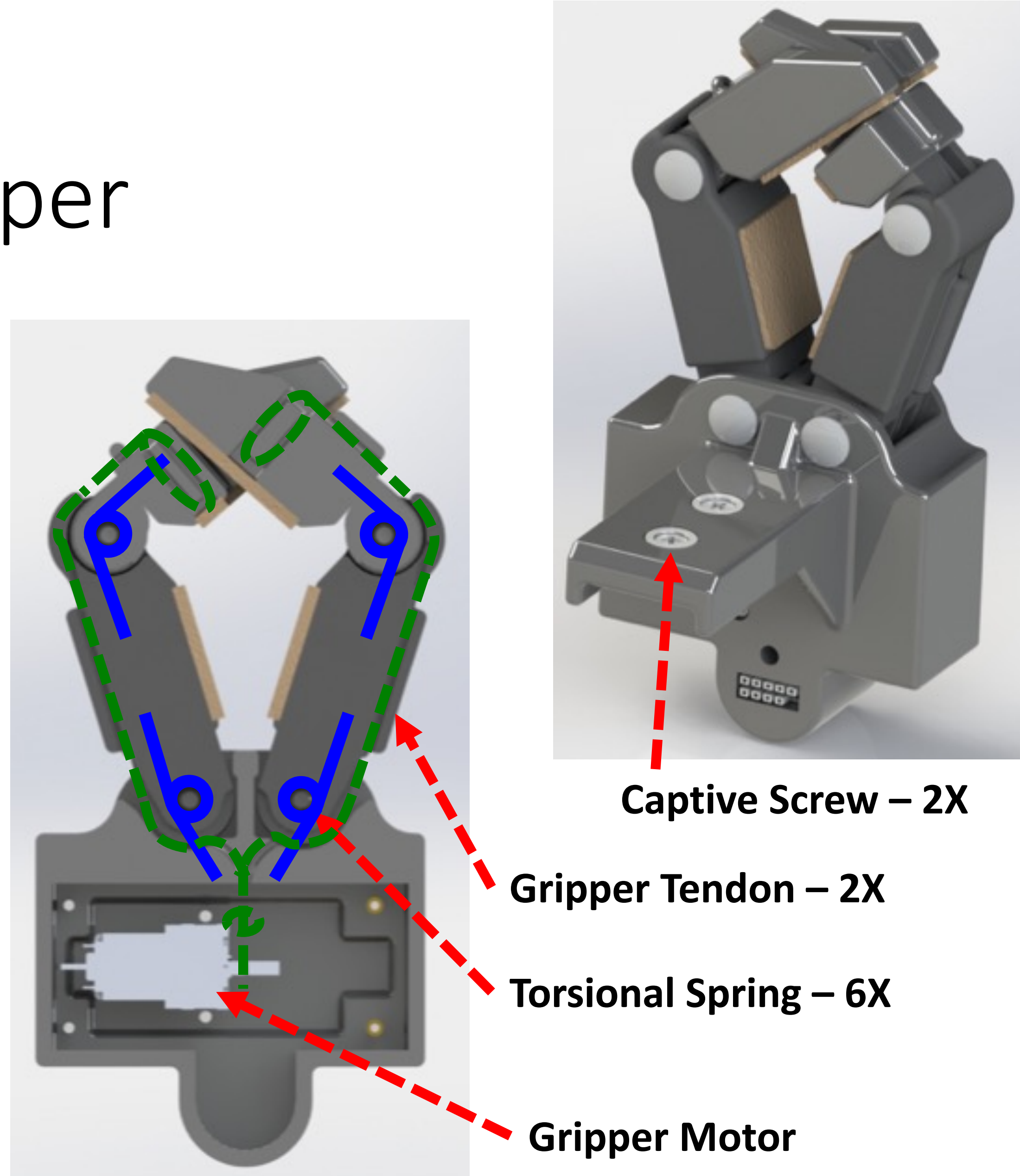
Arm Base Assembly

Gripper Assembly

Gripper



Opened Configuration



Closed Configuration

Mass

Component		Mass [g]	Comment
Arm	Motor	164.0	2 x motors for pan/tilt joint
	Bolts	4.2	16 x M2-6 bolts, 2 x M3-10 bolts
	Base Plate	181.6	Ultem 9085 density = 1.34 g/cm^3
	Proximal	80.3	
	Distal	27.0	
Gripper	Motor	11.3	
	Spring	2.4	6 x torsional springs
	Binding Post	20.8	4 x binding posts
	Bolts/Cover	1.8	2 x #2 bolts and 2 x nuts
	Palm/Proximal/Distal	165.7	
Controller Board		40.0	
Total		**733**	**1.62 lb**

- The mass of P4C perching arm is 460.7 g (1.02 lb) including wires.

Arm Motor

- Robotis Dynamixel XM430-W210-R
  - Dimension: 28.5 mm (1.12 in) x 46.5 mm (1.83 in) x 34 mm (1.34 in)
  - Weight: 82 g (0.18 lb.)
  - Input voltage: 10 V – 14.8 V
  - Gear ratio: 210:1
  - Stall torque: 3.0 Nm (at 12 V)
  - No load speed: 77 RPM (at 12 V)
  - Resolution: 0.088 °
  - Set position/velocity/acceleration, provide present current
  - Enable/disable torque, provide present temperature, limit highest operating temperature, etc.

☑ [FFREQ-934] The Perching Arm shall pan 90 degrees in 15 seconds.

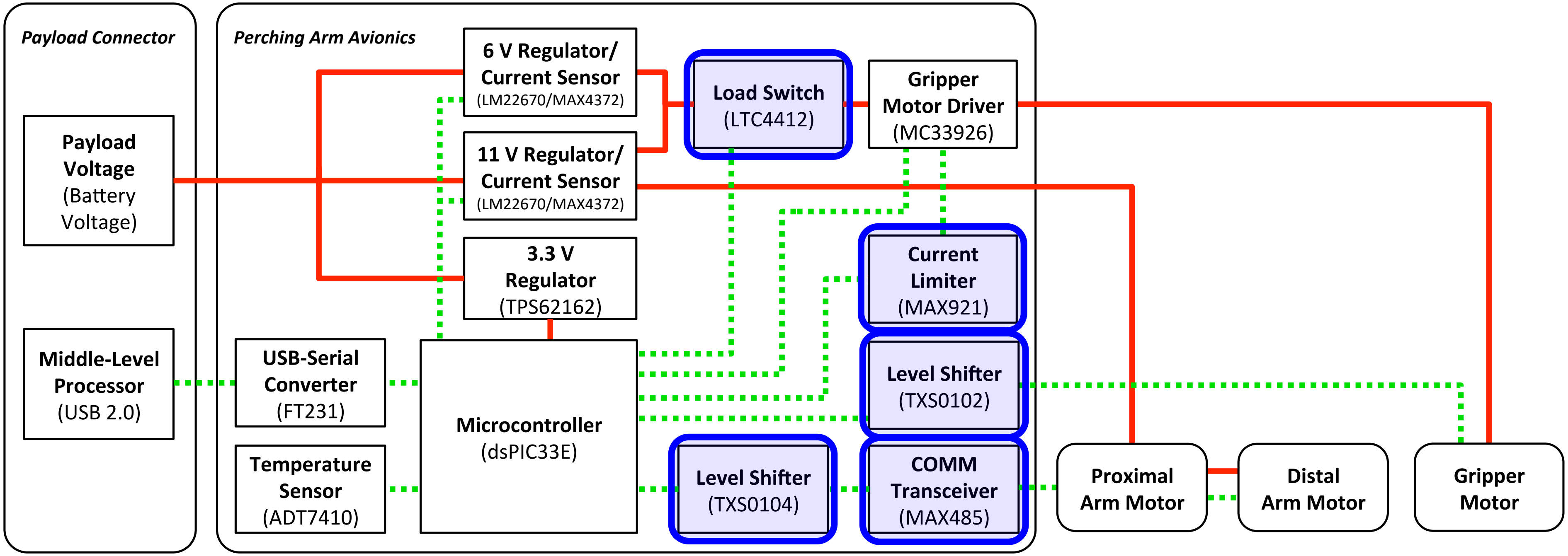
☑ [FFREQ-935] The Perching Arm shall tilt 90 degrees in 15 seconds.

☑ [FFREQ-936] The Perching Arm shall have joint angle resolution of 1 degree.

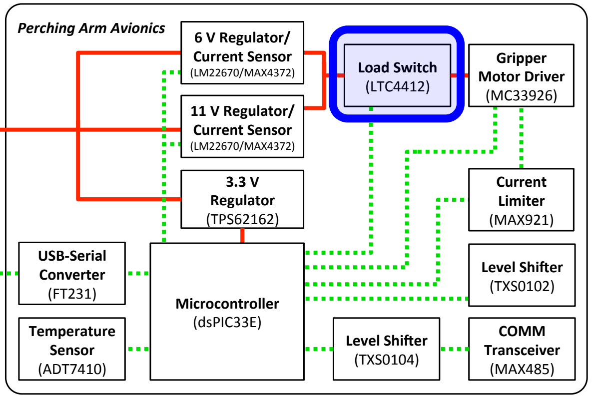
Gripper Motor

- Pololu Micro Metal Gear-motor
  - Dimension: 10 mm (0.39 in) x 12 mm (0.47 in) x 30 mm (1.18 in)
  - Weight: 9.3 g (0.02 lb.)
  - Input voltage: 12 V
  - Gear ratio: 298:1
  - Stall torque: 0.49 Nm
  - No load speed: 100 RPM
  - Resolution: 0.1 °

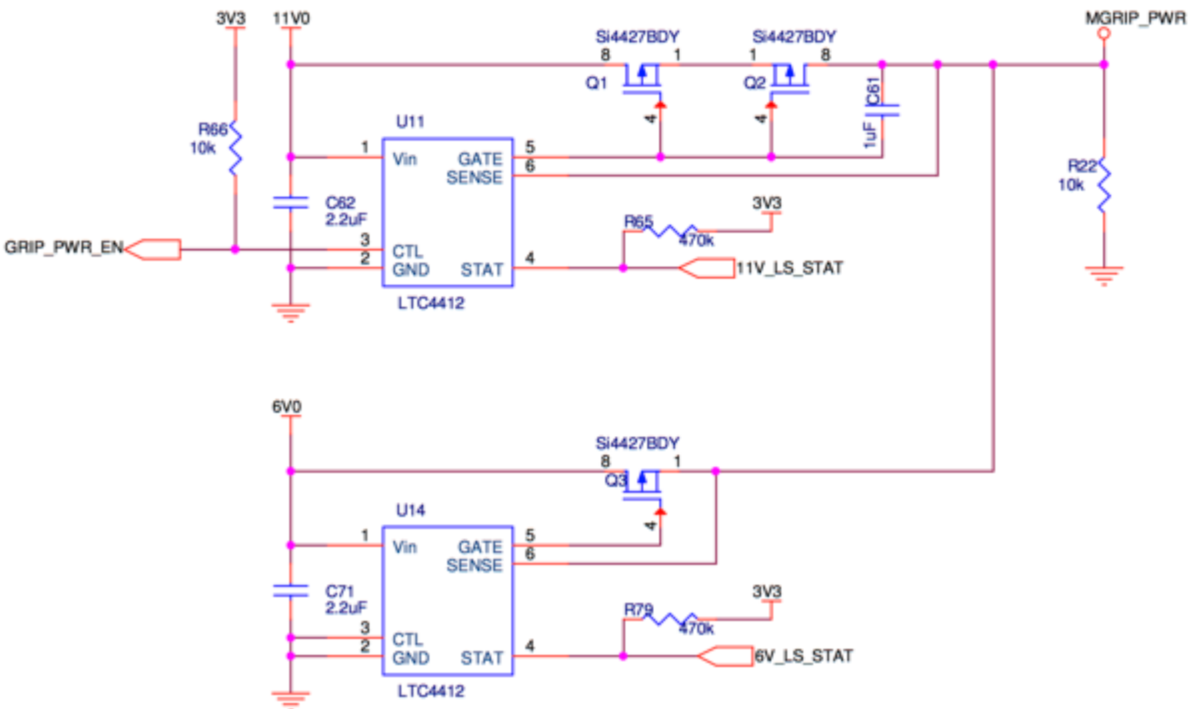
Block Diagram



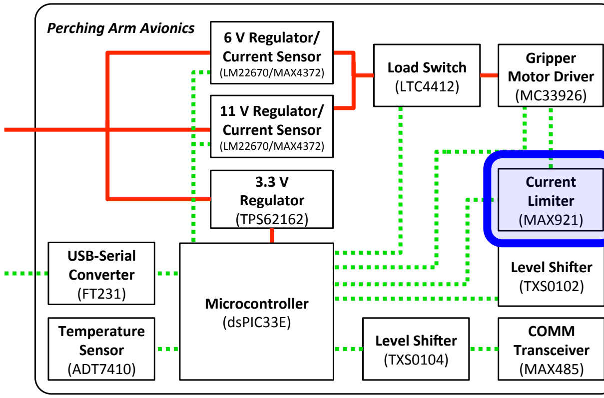
Load Switch



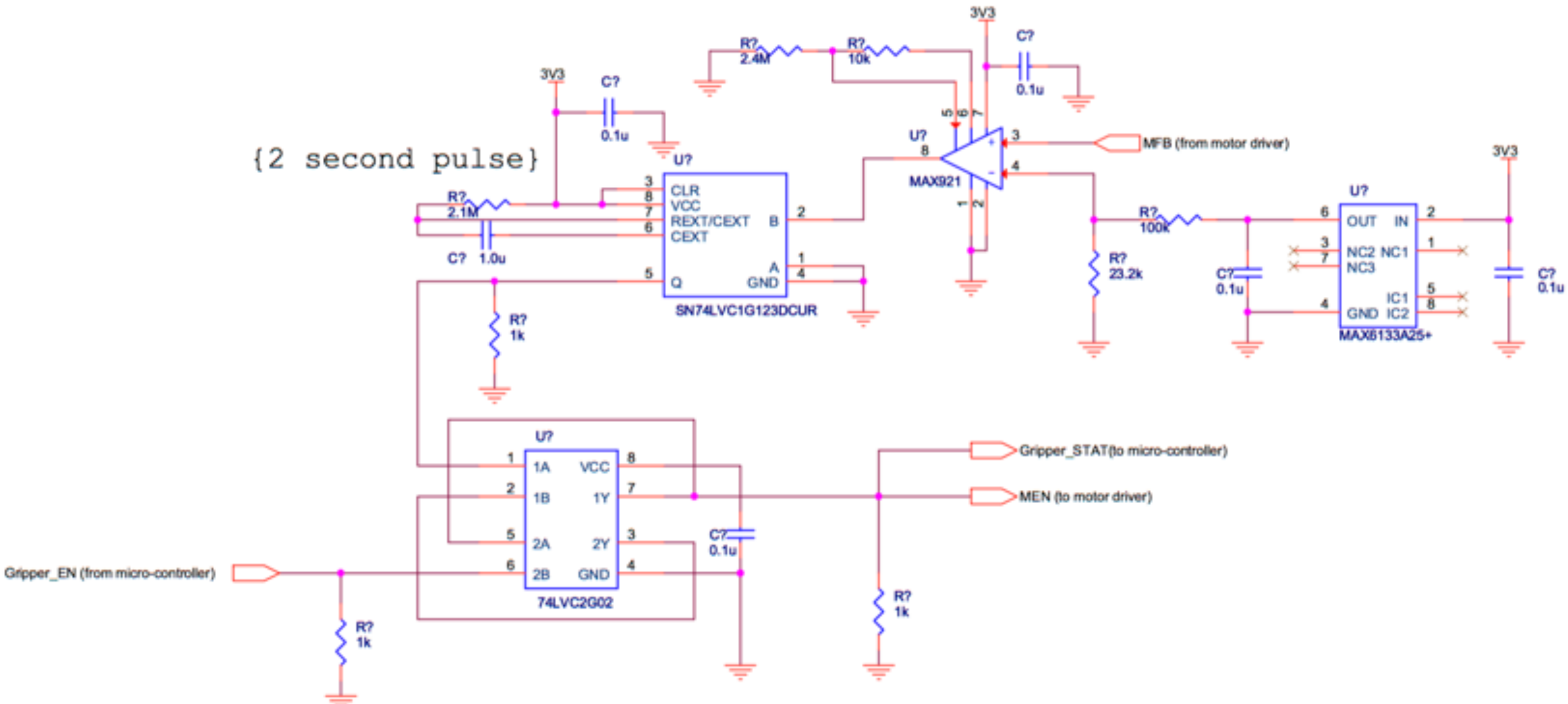
- LTC4412
  - Switch gripper motor voltage between 6V and 11V



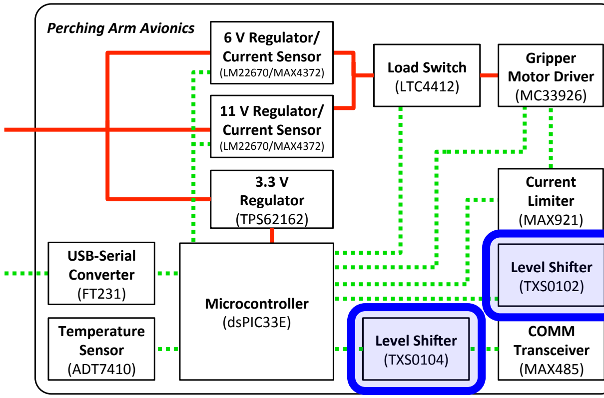
Current Limiter



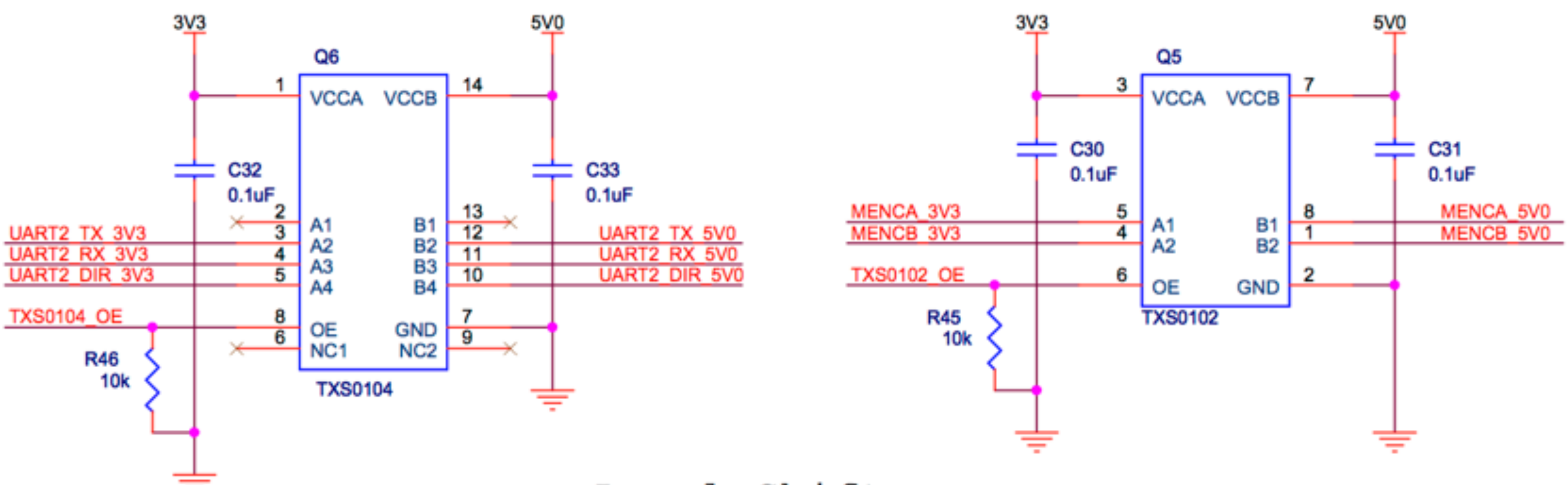
- MAX921
  - Disable gripper motor power when gripper motor reaches 80% of stall current



Level Shifter

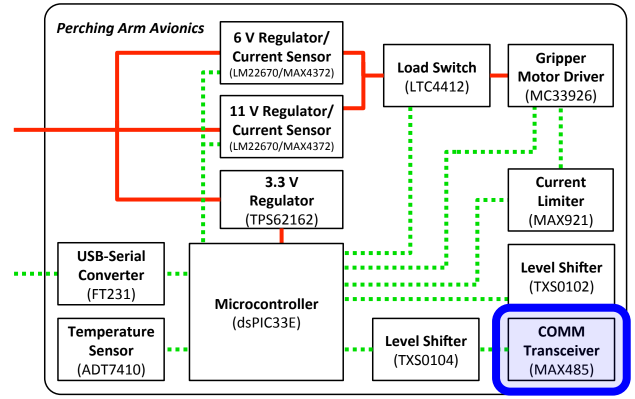


- TXS0102/TXS0104
  - Translate voltage-level of arm motor signals and gripper encoder feedback signals
  - Has an internal 10-kΩ pull-up resistor

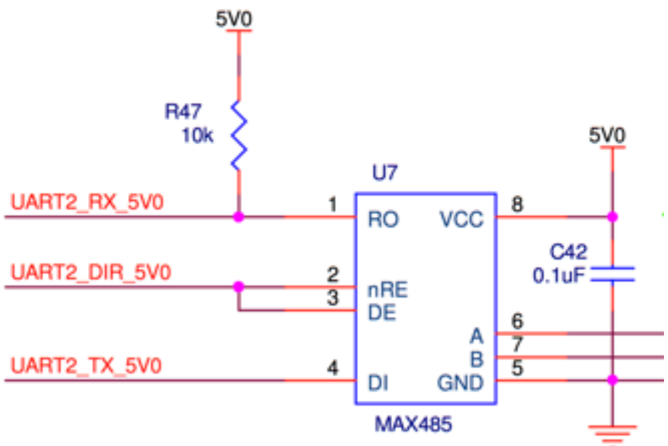


Level Shifter

Arm Motor COMM Transceiver



- MAX485
  - A low-power transceiver for RS-485 communication
  - Allow to transmit up to 2.5Mbps



Astrobee Thermal Subsystem

Delta PTR3 Design Overview

1 February 2017

Design Maturity

The Astrobee team is aiming for CDR-level of maturity for all system hardware.

Component	Maturity / Risk	Forward Work
Core Module	High / Low	None, Cert Unit Testing
Propulsion Blower Motor	High / Low	None, Cert Unit Testing
Nozzle Servos	High / Low	None, Cert Unit Testing
Perching Arm Servos	High / Low	None, Cert Unit Testing
Perching Arm Gripper Motor	High / Low	None, Cert Unit Testing
Dock Avionics	High / Low	None, Cert Unit Testing
Dock Linear Actuator	High / Low	None, Cert Unit Testing

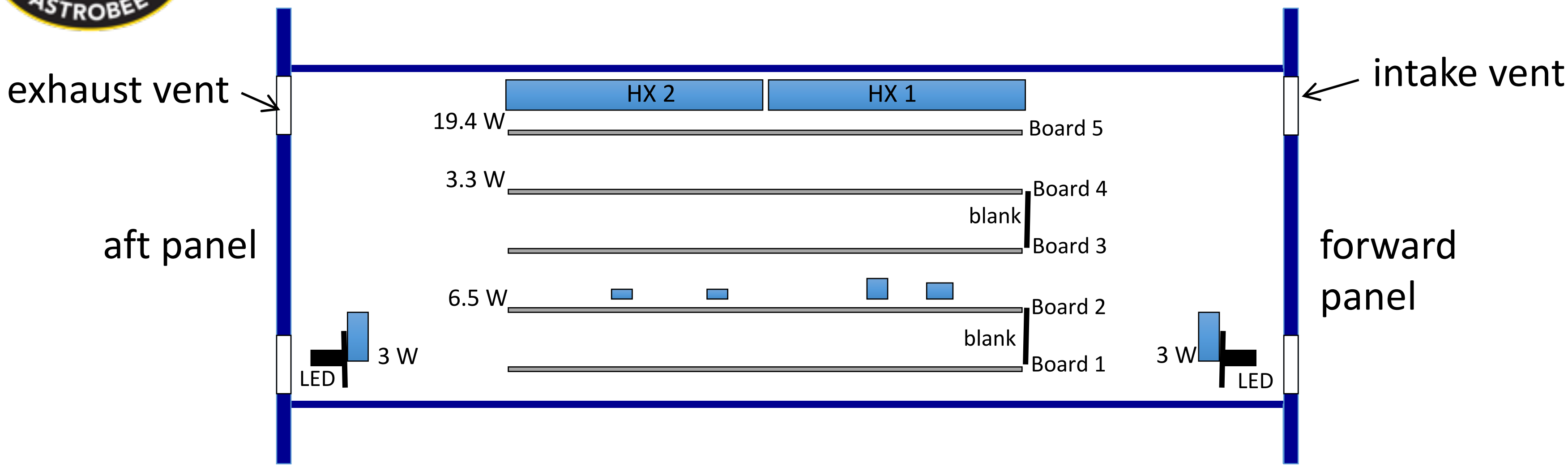
New/Changes from PTR3

Component	New / Changes
Design	- Removed LLP Heatsink, Wires bundled to minimize airflow pressure resistance in core;
Hardware	- No Thermal Fuses; Added Perching Arm gripper DC motor current limiter; Nozzle servos covered;

Thermal Management Plans

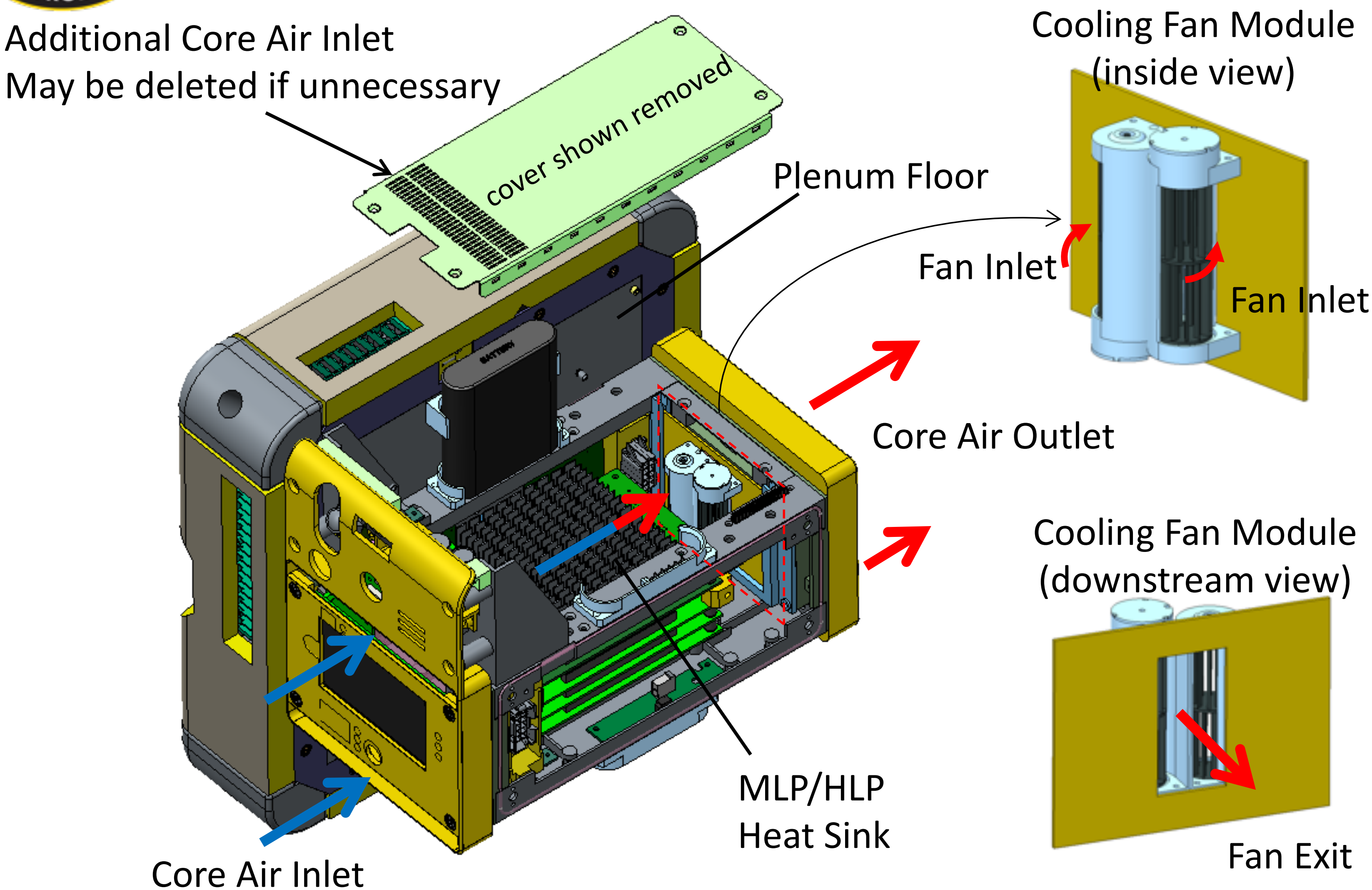
COMPONENT	THERMAL MANAGEMENT
Central Module • Avionics Boards • Fore/Aft LED Lights • Touch Screen, Status Lights, Etc.	• Forced convection (fans mounted in core). • Current Limit, Temp Sensors, Conduction to aluminum frame / forced convection. • Conduction to forward panel and frame. Heat rejection to central core (forced convection) and environment (conduction/convection/radiation).
Top Forward Module • Laser Pointer, Cameras, Etc.	• Low power and/or infrequent operation: Conduction to panel and frame. Rejection to central core and environment.
Prop Module (2) • Impeller Motor • PMC Board • Nozzle Servos	• Conduction to aluminum plenum floor; forced air rejection via nozzles. • Conduction to plenum floor. Heat rejection by forced air in central module. • Conduction to structure. Rejection via plenum air flow.
Perch Arm • Arm Controller Board • Joint Servos • Gripper DC motor	• Conduction to structure; rejection via conduction/convection/radiation. • COTS Firmware Temperature limit; Conduction to structure; rejection via conduction/convection/radiation. • Load Switch and Current Limiter
Dock • Avionics Boards and DC-DC converters • Linear Actuators	• Forced convections (fan mounted on Dock face) • COTS Firmware Current Limit; Conduction to structure; rejection via conduction/convection/radiation.
Batteries (4)	Low thermal power. Conduction to structure; rejection via core forced air. Direct rejection to environment via conduction/convection/radiation.

Central Module Heat Sources

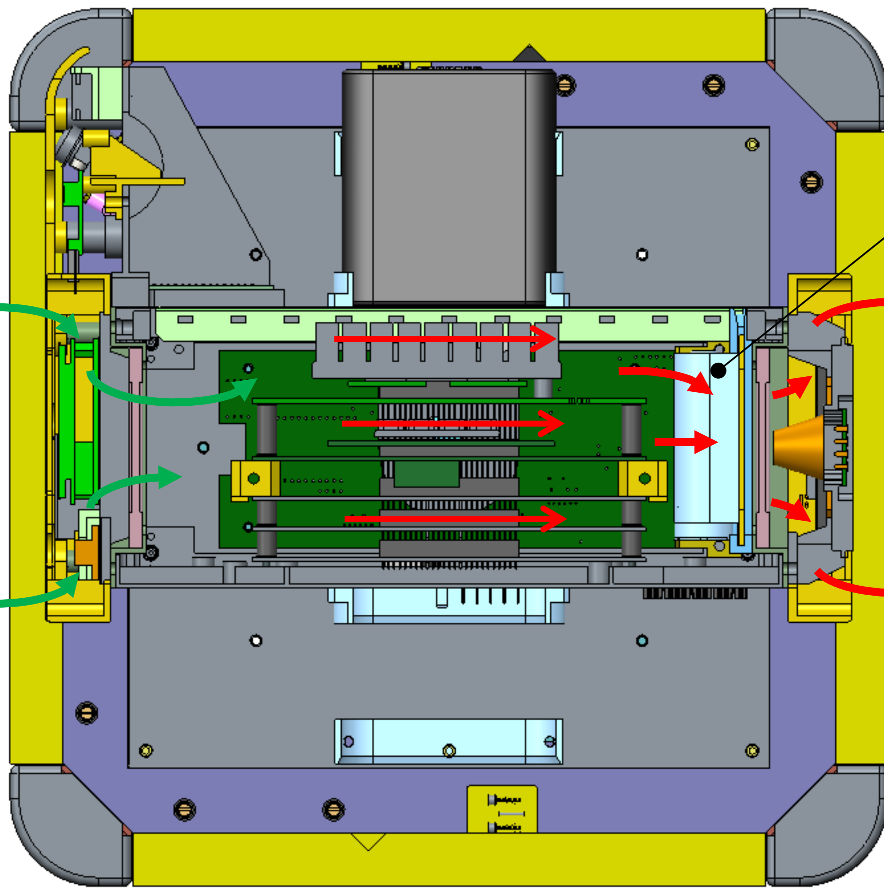


- Most of the heat is produced on Board 5 (MLP, HLP).
- Heat produced by Boards 1 and 3 is negligible. Flow to those boards can be restricted: Plastic strips attached to board stand-offs. However, this would increase the overall ΔP.
- Forward and aft LED lights: Heat sink to aluminum frame; frame cooled by air flow, thermal radiation from top/bottom/front/back panels. Finned heat sinks can be used as well.

Current Design

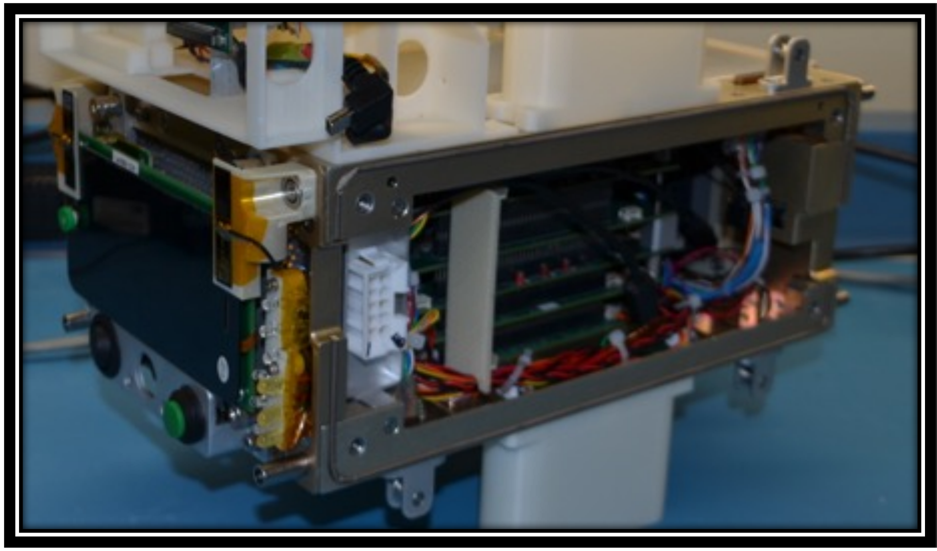


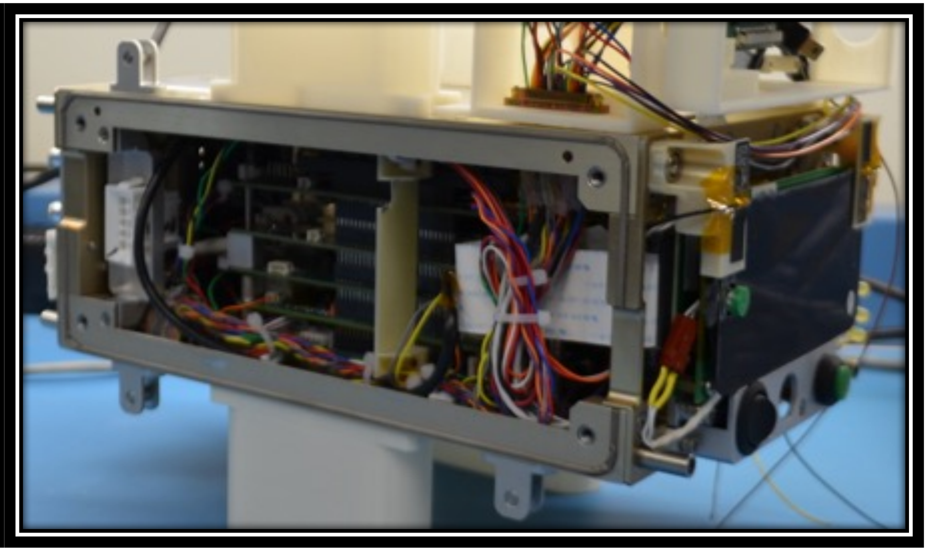
Current Design (Side View)



Core cooled by forced air convection, driven by two aft-mounted cross-flow fans.

Core Airflow Baffles

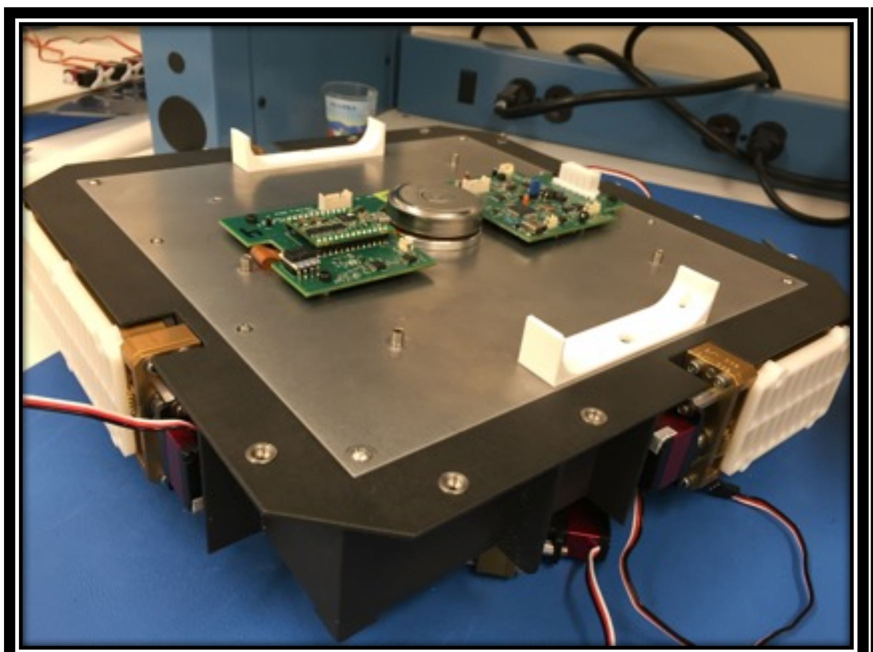

Left Side Baffle

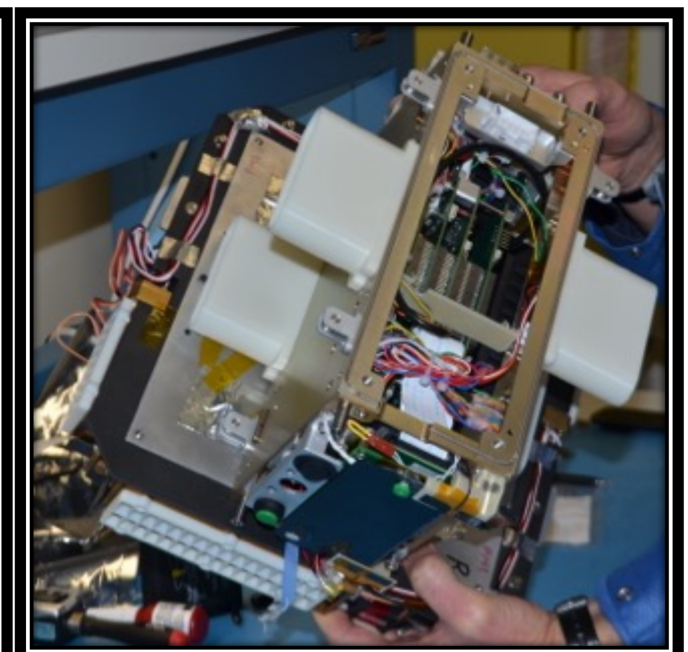

Right Side Baffle

Baffles prevent air flow circumvention of avionics boards.

Thermal Management
Propulsion Modules

- Mount prop motor to aluminum floor of plenum.
- Max air speed in plenum is ~ 31 ft/s (near fan shaft at center of plenum).
- At max motor power, must reject 3 W (based on efficiency of motor).
- This requires a turn-over of ~ 1 CFM to remove the heat from the plenum (with the exhaust temp well below the max touch temperature).





Perching Arm Servo, Gripper DC Motor, Dock Actuator

- Perching Arm Servo
  - Measured Continuous Operation Temperature less than 40^{o}C
  - Temperature Limit Set 35^{o}C in Firmware for Stall
  - Tested Temperature Limit Shutoff-Passed
- Gripper DC Motor

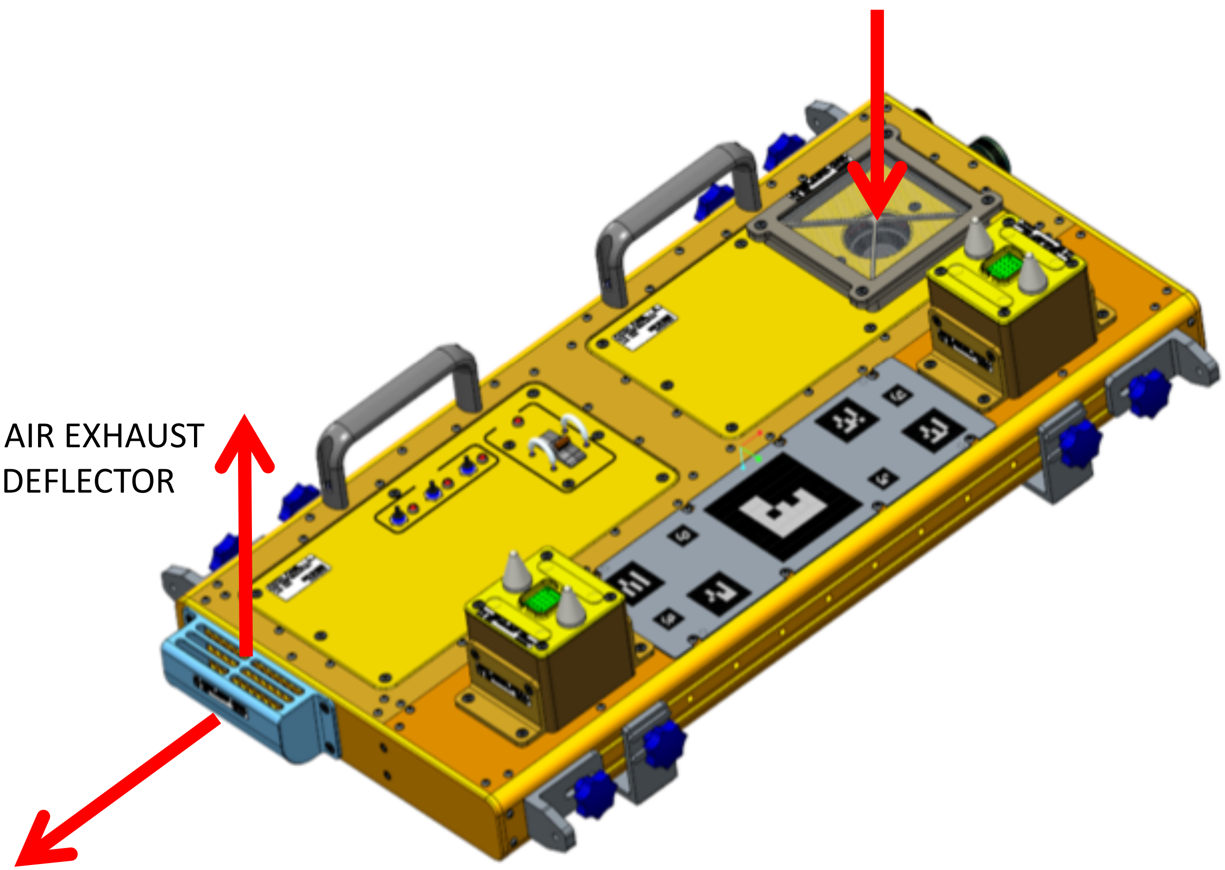
  Added 80% Current Limiter (previously discussed in Perching Arm Design Overview)
- Dock Linear Actuator

  Current Limiter for Stall Condition

Dock Air Flow

DOCK AIR INTAKE

DOCK AIR EXHAUST
WITH DEFLECTOR



DOCK AIR EXHAUST IF DEFLECTOR IS REMOVED

SANYO DENKI
rated to 12.7 CFM
3000 RPM

DC Blower
75X75X30

Safety Features

- Cooling fans always on—no software control (firmware).
- If forward/aft LED lights temperature limit exceeded, hardware over temperature power cut-off engages.
- Forward/aft LED lights recessed from panels, not touchable.
- If processor temperature limit reached, processor operating system throttles power.
- Fail-safe: If system temperature sensor limit is exceeded, hardware over temperature cut-offs entire system power.

Astrobee Dock Mechanical Subsystem

Design Overview

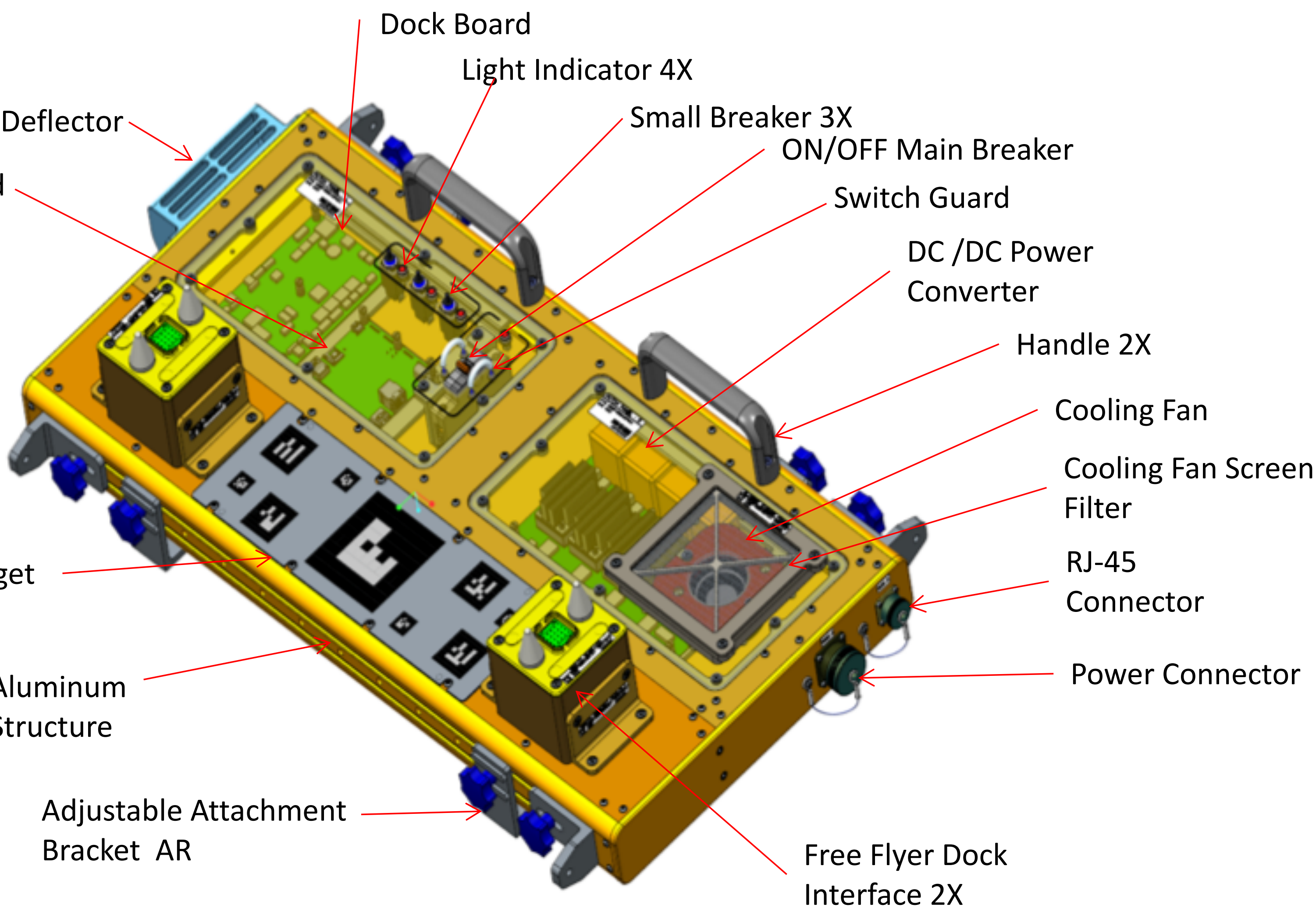
Design Maturity

Component	Maturity / Risk	Forward Work
Dock housing	High/Low	Select dock color
AR Targets	Med / Low	Change attachment mechanism and target size
Bonding Strap	Med / Low	Attachment location

New/Changes from PTR3

Component	New / Changes
Dock	- Reduced the overall width of the Dock due to removal of battery charger.
Dock	- Added an additional patch panel to accommodate more electrical components
Dock	- Added air vent deflector to direct thermal exhaust
Berth post	- New Modular attachment Bracket for Tilt and Non-Tilt Option
Berth post	- Lances change from horizontal to vertical alignment
Dock mounting	- Added additional attachment points for mounting brackets (velcro / seat track)

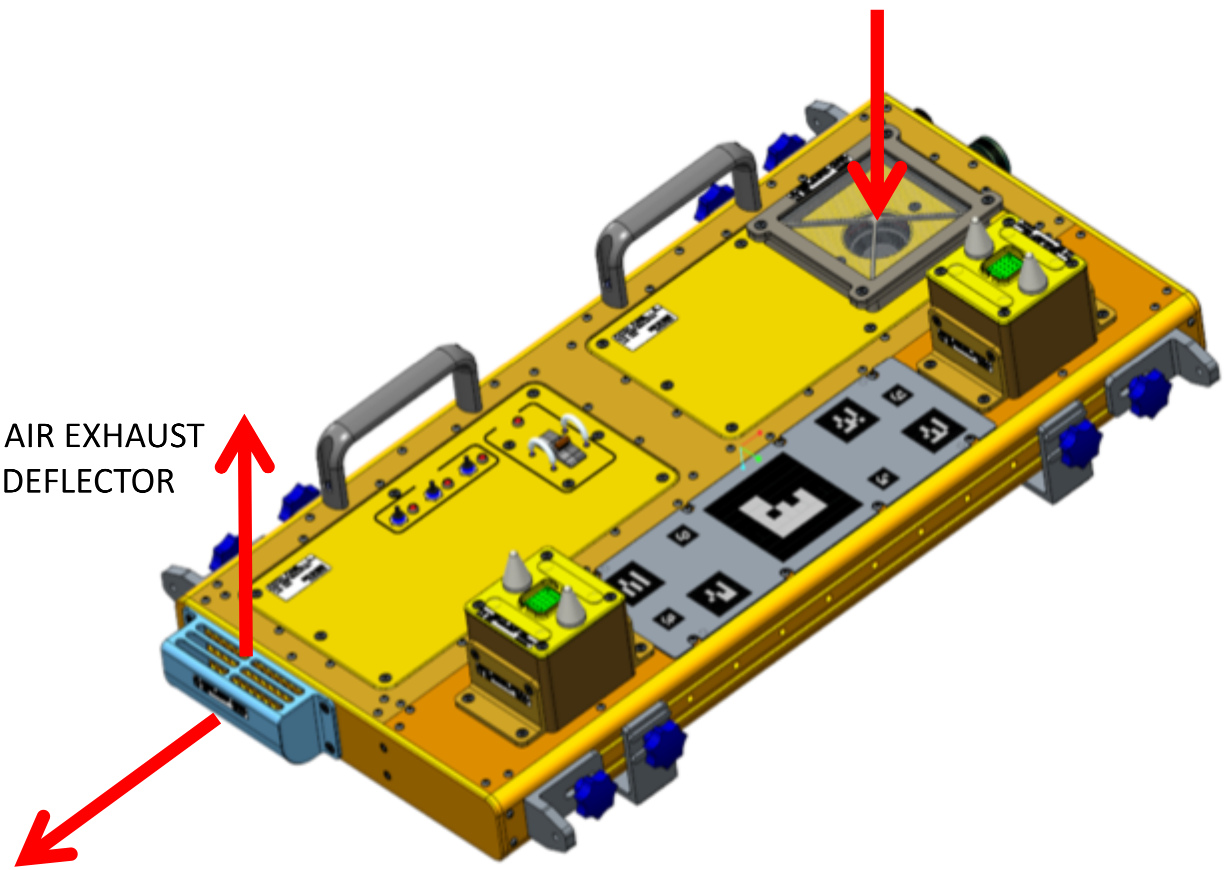
ISO View – Dock



Patch Panel Covers are Shown Transparent For Clarity

Dock Air Flow

DOCK AIR INTAKE



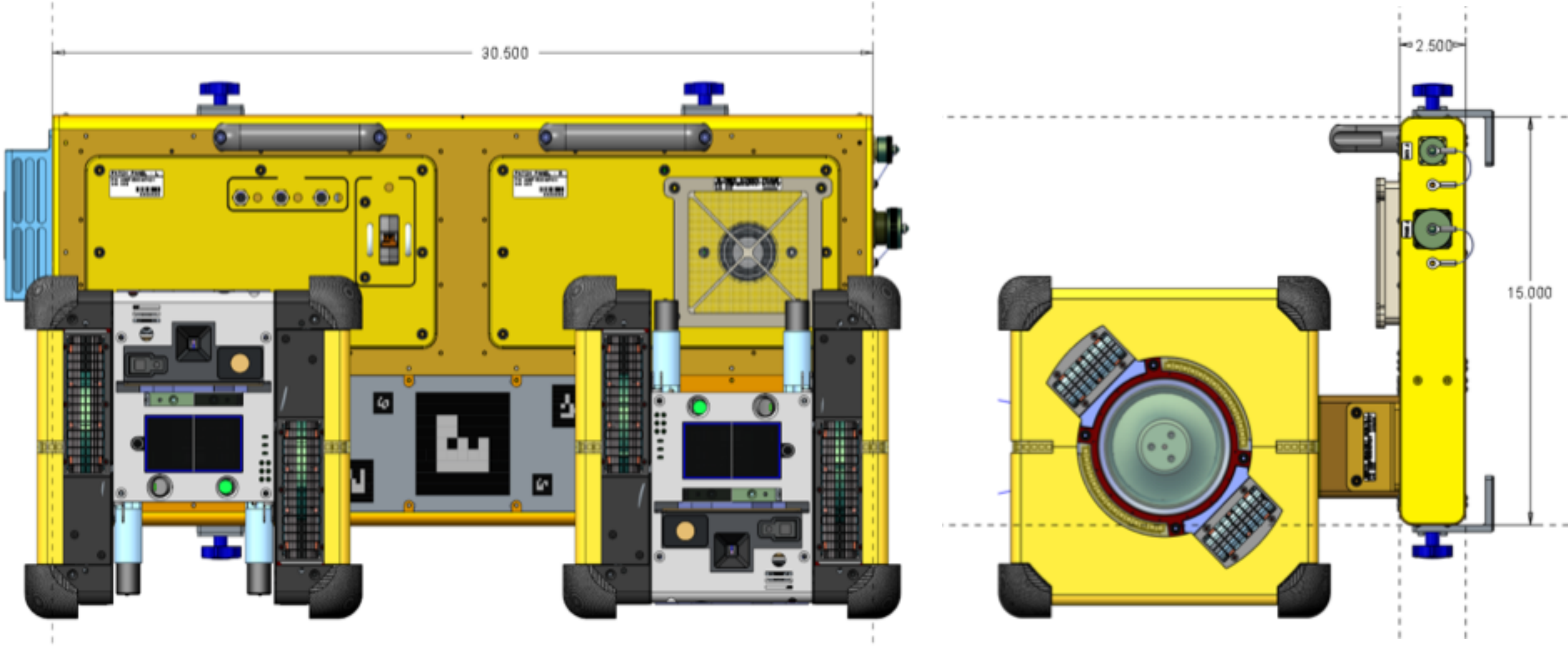
DOCK AIR EXHAUST
WITH DEFLECTOR

DOCK AIR EXHAUST IF DEFLECTOR IS REMOVED

SANYO DENKI
rated to 12.7 CFM
3000 RPM

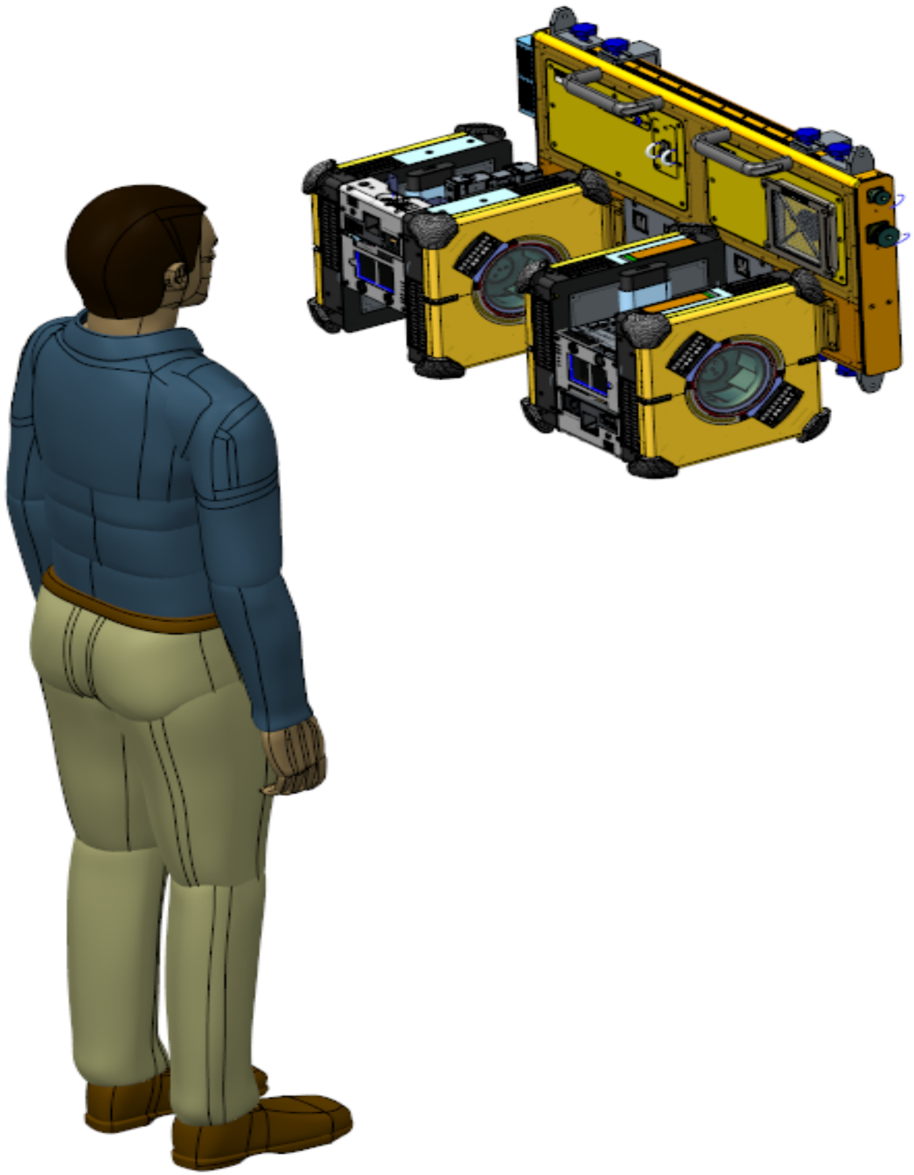
DC Blower
75X75X30

Dock
Front and Side View



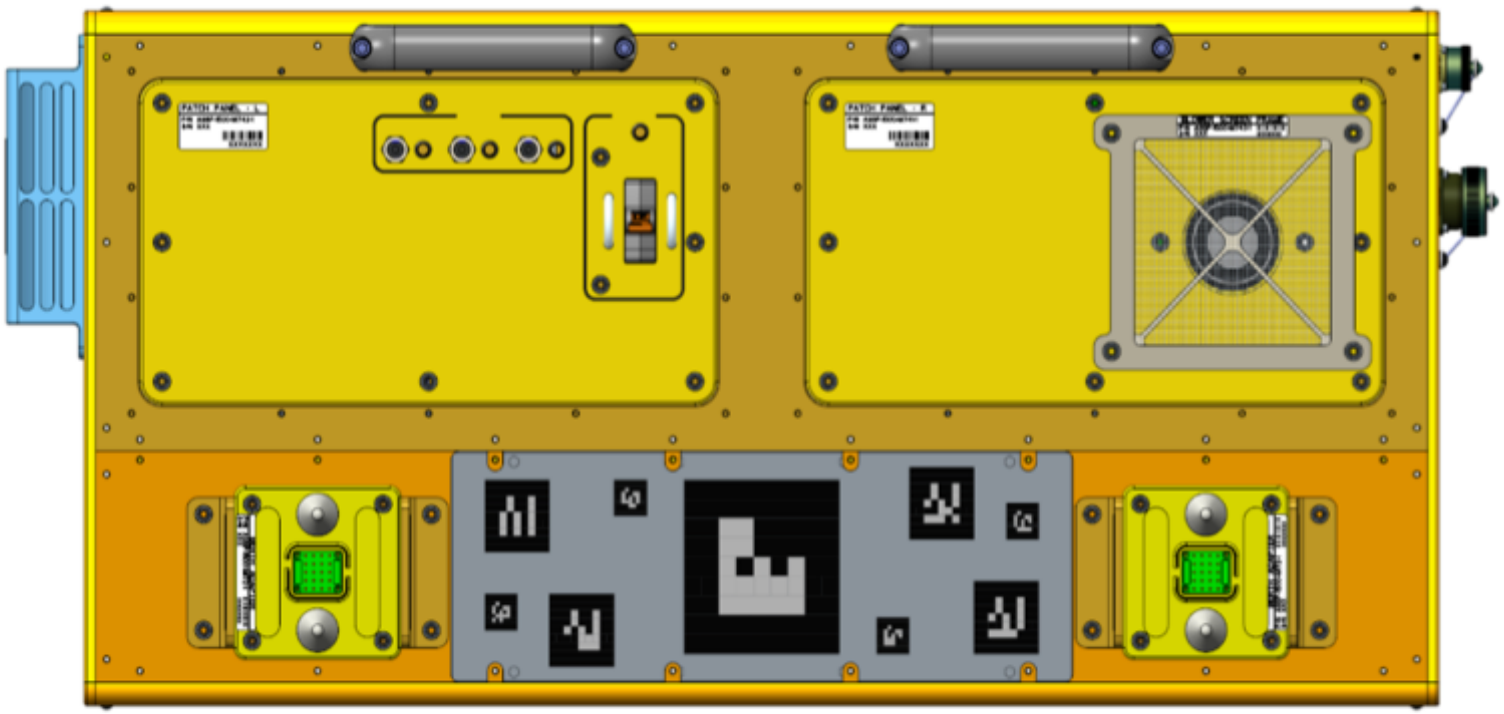
NOTE: Dimensions are in inches

ISO View
Dock –Flyer-Human

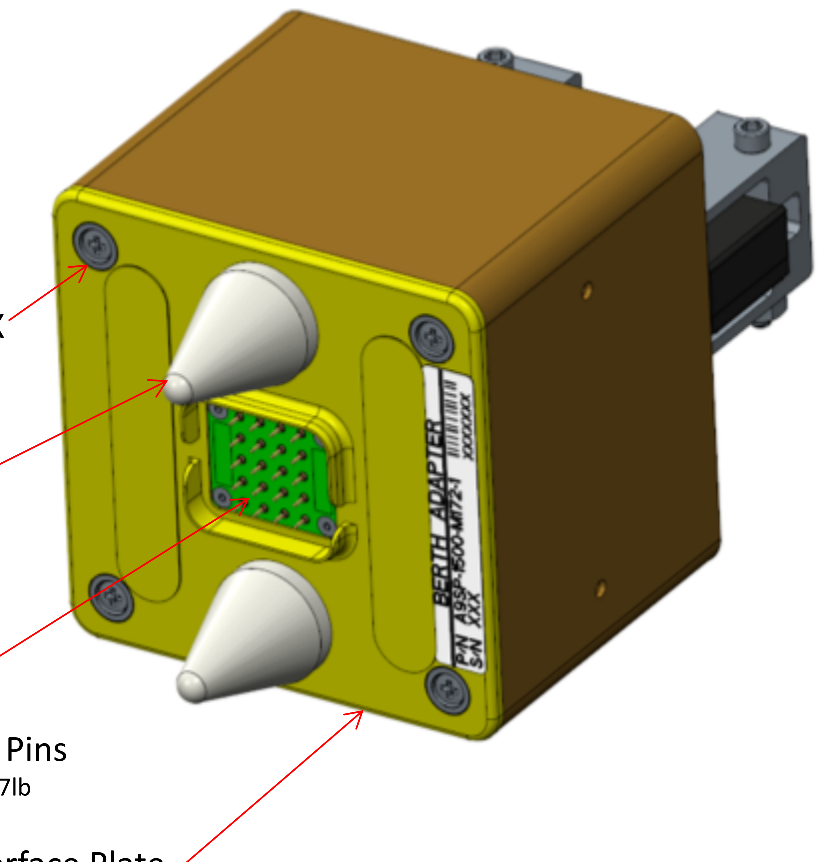


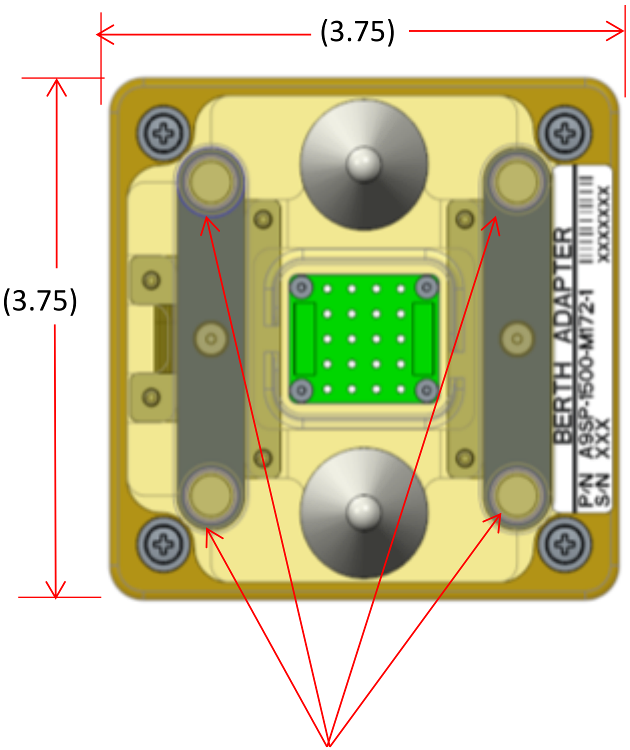
Dock

Front View With no attachment Brackets

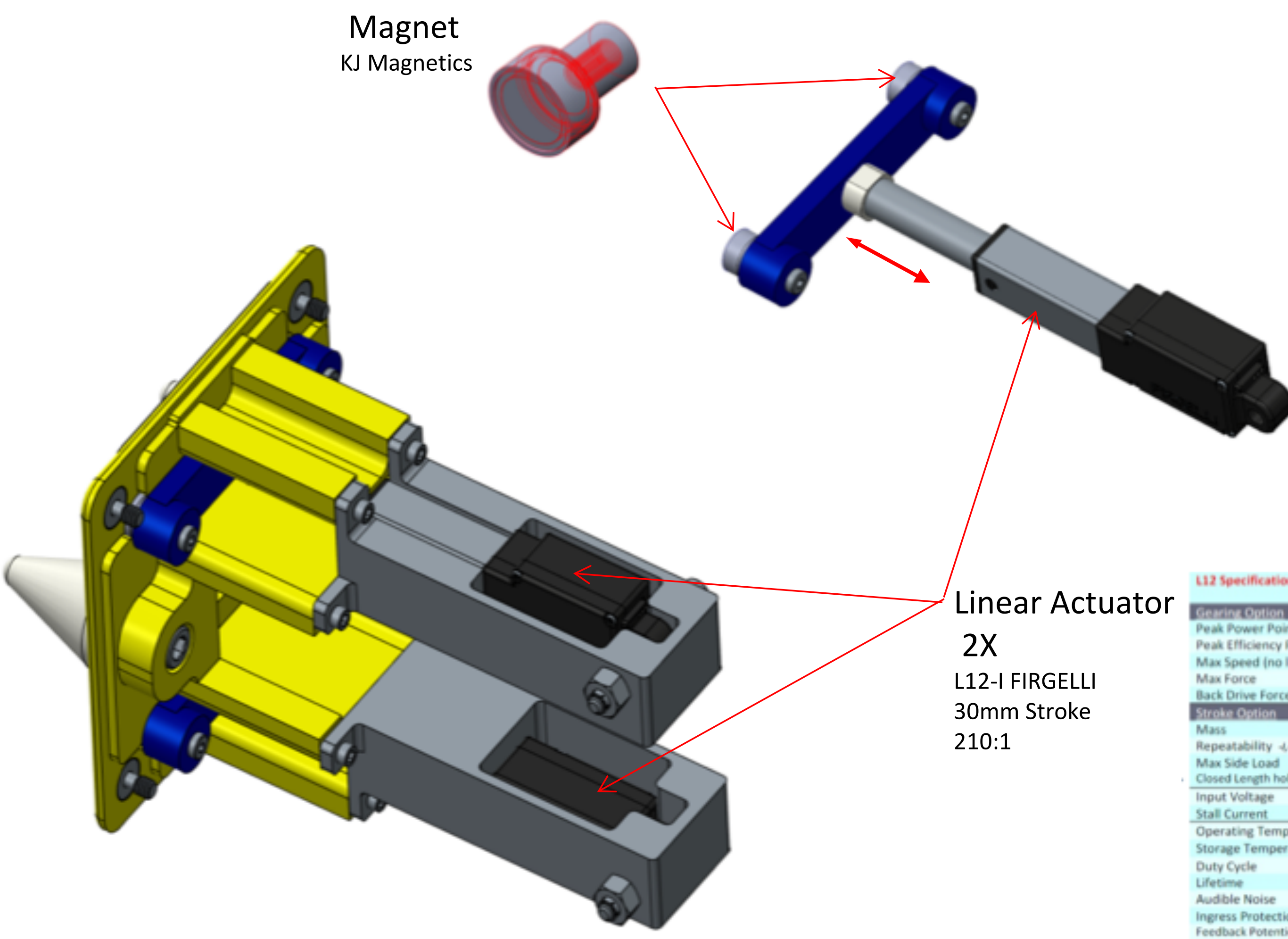


Free Flyer Dock Interface
Front Side





Free Flyer Dock Interface Plate Back Side



L12 Specifications

Gearing Option	50:1	100:1	210:1
Peak Power Point	12N @ 11mm/s	23N @ 6mm/s	45N @ 2.5mm/s
Peak Efficiency Point	6N @ 16mm/s	12N @ 8mm/s	18N @ 4mm/s
Max Speed (no load)	23mm/s	12mm/s	5mm/s
Max Force	12N	23N	45N
Back Drive Force	43N	80N	150N

Stroke Option	10 mm	30mm	50mm	100mm
Mass	28 g	34 g	40 g	56 g
Repeatability -I,-R,-P(LAC)	±0.1 mm	±0.2 mm	±0.3 mm	±0.5 mm
Max Side Load	50 N	40 N	30 N	15 N
Closed Length hole to hole	62mm	82mm	102mm	152mm
Input Voltage	0-7.5V , 6 VDC Rated		0-13.5V, 12 VDC Rated	
Stall Current	550mA @ 6V		220mA @ 12V	
Operating Temperature	-10°C to +50°C			
Storage Temperature	-30°C to +70°C			
Duty Cycle	20 %			
Lifetime	20,000 strokes			
Audible Noise	55dB @ 45cm			
Ingress Protection	IP-54			
Feedback Potentiometer -I,-R,-P	1/8W Non-Buffered 1 kΩ -20kΩ Potentiometer			
Limit Switches -S	Max. Current Leakage: 8uA			
Standby Current -I/-R	7.2mA		3.3mA	

Astrobee Dock Avionics

Design Overview

Design Maturity
Dock Avionics

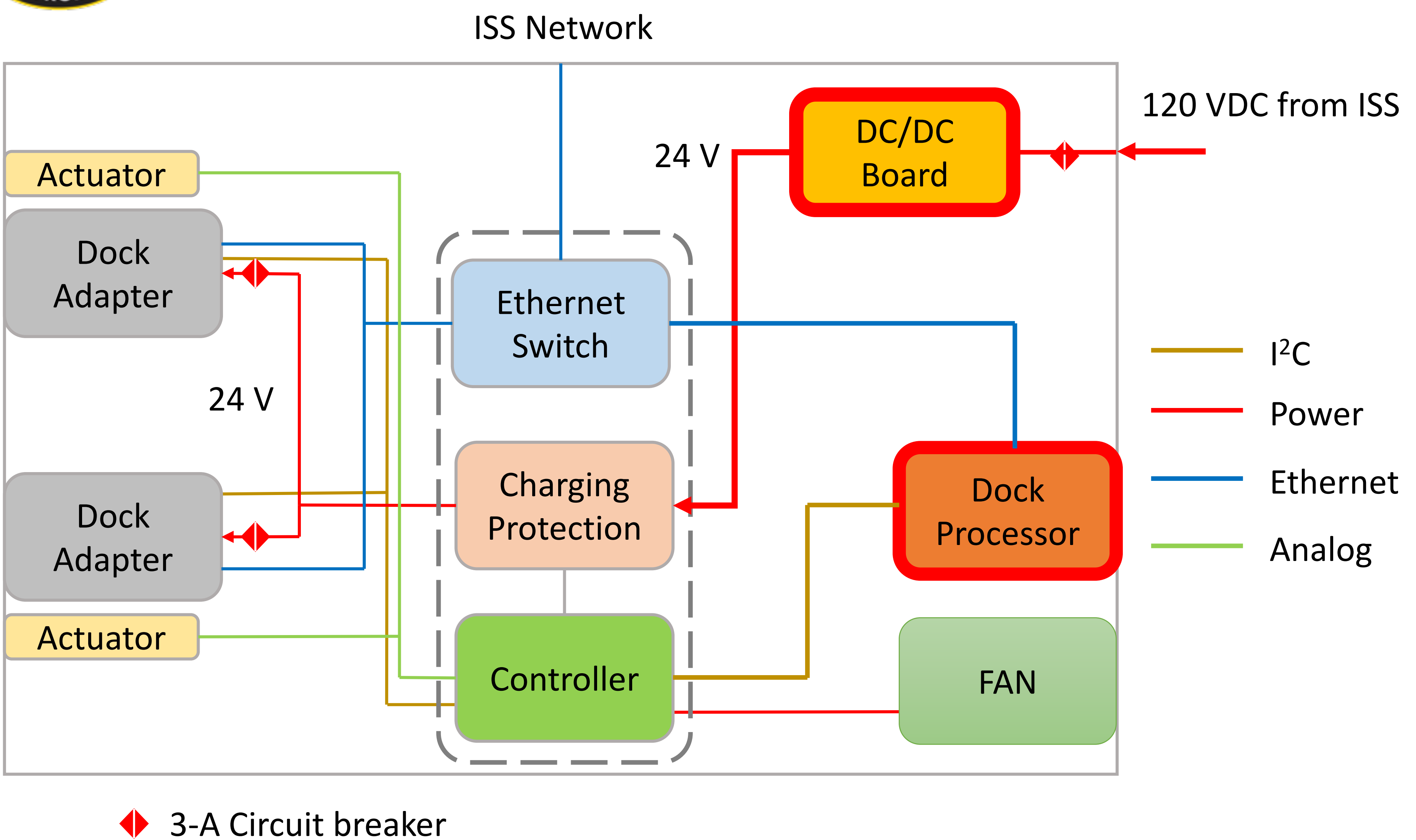
The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.

Component	Maturity / Risk	Forward Work
Controller board	High / Low	New I2C lines
DC/DC board	Low / Med	New board
Dock adapter board	High	
Dock Processor	High	New Wandboard
Actuators	High	

New/Changes from PTR3

Component	New / Changes
DC/DC	- Reverting back to our original design
Smart Dock	- New Dock Processor
COTS Charger	- Removed from dock

Dock Avionics Diagram



Dock Processor

- Same Processor as LLP
- FW updates for Dock PIC
- Remote wake up of Astrobee
- Publish Dock telemetry
- Ubuntu

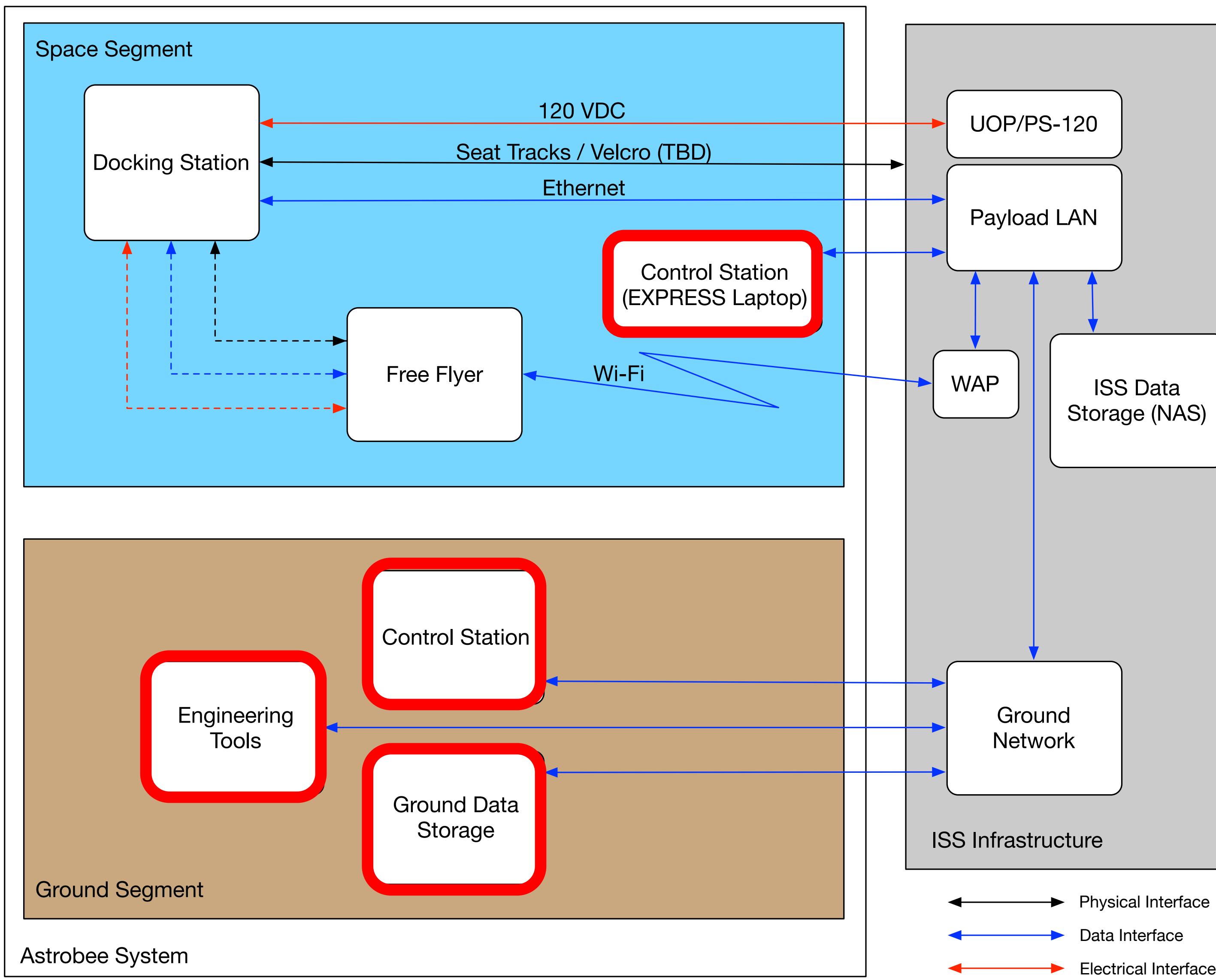
Astrobee GDS Subsystems

Design Overview

Components

- Control Station
  - Provide GUI for a remote user to command and control Astrobee during nominal operations
- Ground Server
  - Store Astrobee data and make it available to external users
- Engineering Tools
  - Provide tools for debugging and advanced engineering support

Architecture Diagram



Design Maturity

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

Component	Maturity / Risk	Forward Design Work
Plan Editor	High	
Plan Controller	High	
Teleoperation	High	
Guest Science	High	
Ground server	Med / Low	Specify server
Data Archive Interface	High	
Engineering Tools	High	

New/Changes from PTR3

The Astrobee team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.
All system software is less mature, and is not at CDR-level of maturity.
Software builds are expected to continue through on-orbit testing.

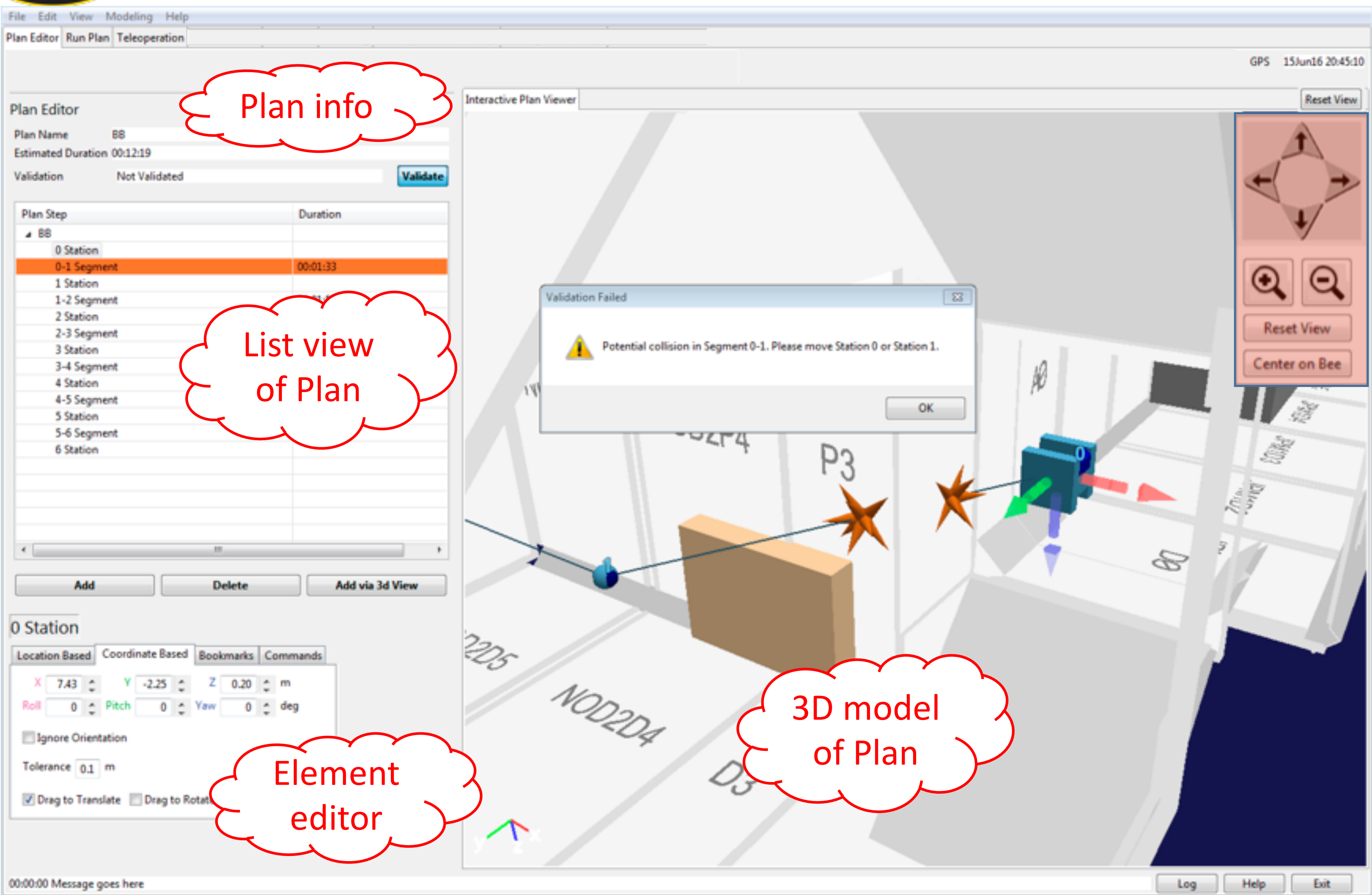
Component	New / Changes
Faults	Display name of faulty subsystem, no display for warnings
Guest Science	Split Guest Science into Crew tab and Advanced Tab
Control Station GUI	Added buttons to allow access to needed functionality
Ground Server	Verified TReK connection to Ground Server is possible
Config Files	Repository of config files
SmartDock	Support for Wake/Hibernate via SmartDock

Control Station

Control Station

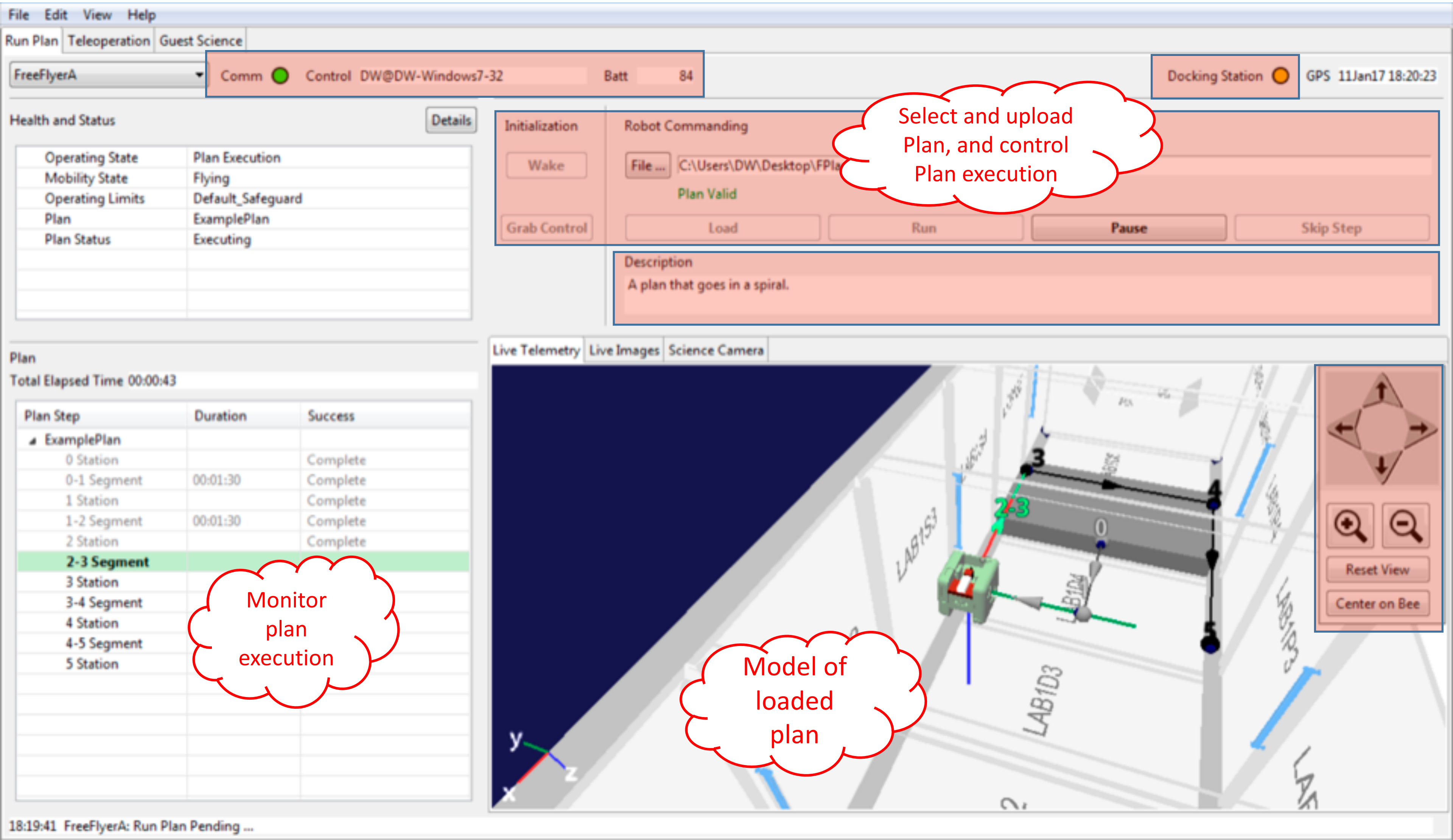
Tab	Description	Crew	Ground Controllers	Guest Scientists	Astrobee Engineers
Plan Editor	Create and edit Plans		X	X	X
Plan Controller	Run Plans and monitor execution	X	X	X	X
Teleoperation	Send individual commands	X	X	X	X
Guest Science	Run Plans on up to 3 Astrobees	X			
Advanced Guest Science	Run Plans and control APKs on up to 3 Astrobees			X	X
Advanced	Modify and monitor advanced settings			X	X

Plan Editor



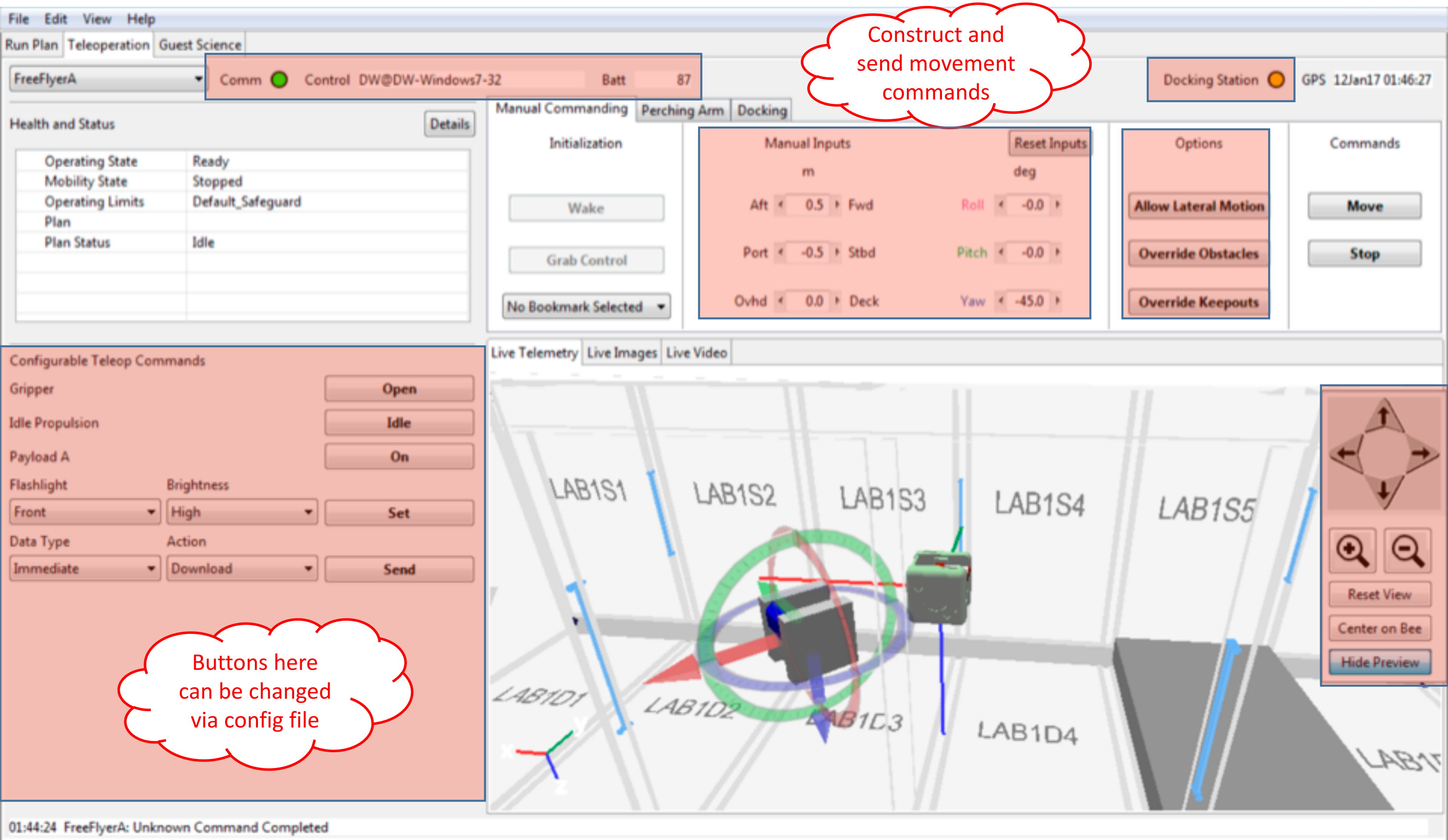
Plan info
List view of Plan
Element editor
3D model of Plan
File Edit View Modeling Help
Plan Editor Run Plan Teleoperation
GPS 15Jun16 20:45:10
Plan Editor
Plan Name BB
Estimated Duration 00:12:19
Validation Not Validated
Validate
Plan Step
Duration
BB
0 Station
0-1 Segment
00:01:33
1 Station
1-2 Segment
2 Station
2-3 Segment
3 Station
3-4 Segment
4 Station
4-5 Segment
5 Station
5-6 Segment
6 Station
Add
Delete
Add via 3d View
0 Station
Location Based
Coordinate Based
Bookmarks
Commands
Ignore Orientation
Tolerance 0.1 m
Drag to Translate
Interactive Plan Viewer
Reset View
Validation Failed
Potential collision in Segment 0-1. Please move Station 0 or Station 1.
OK
Reset View
Center on Bee
00:00:00 Message goes here
Log
Help
Exit

Run Plan Tab

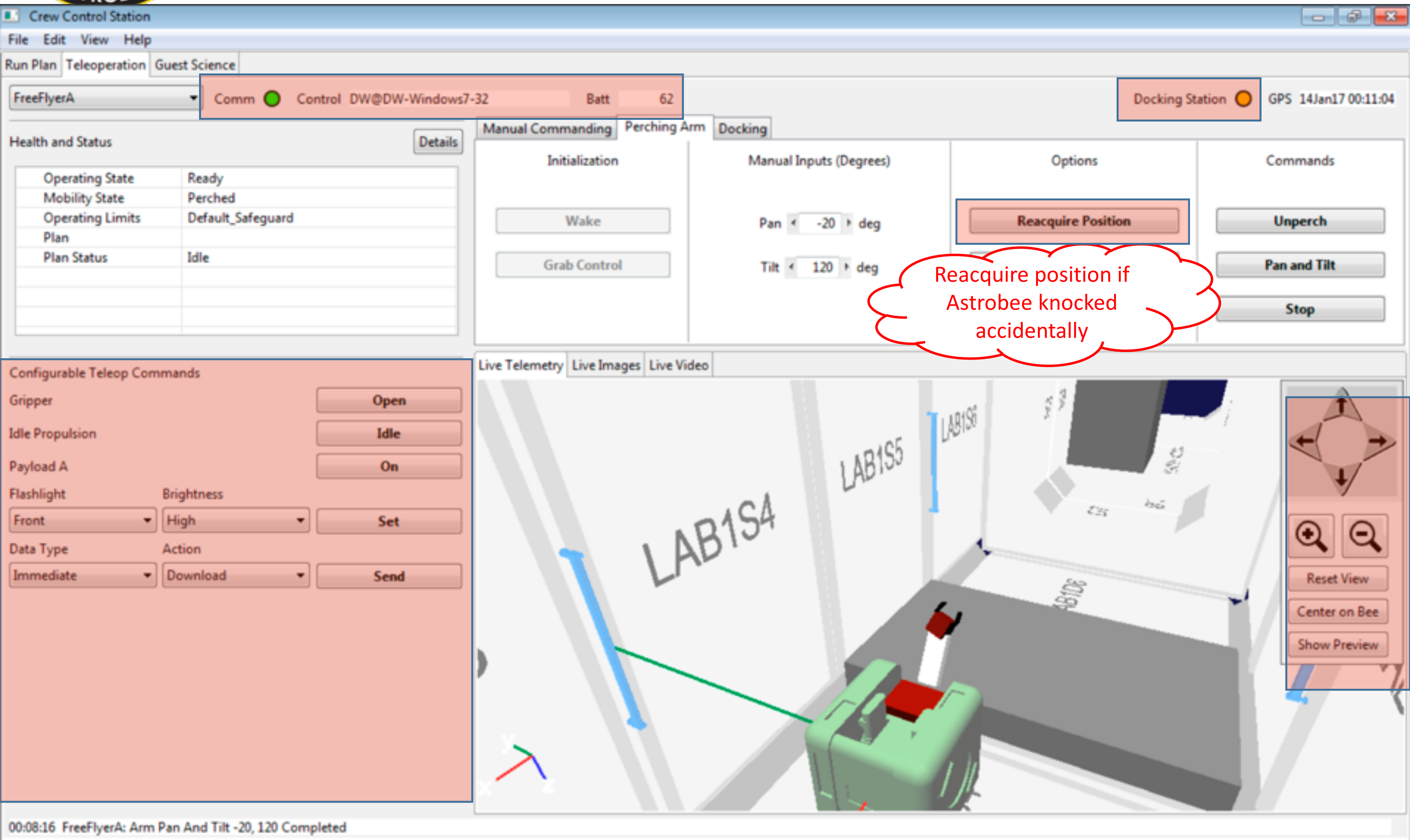


File Edit View Help
Run Plan
Teleoperation
Guest Science
FreeFlyerA
Comm
Control DW@DW-Windows7-32
Batt 84
Docking Station
GPS 11Jan17 18:20:23
Health and Status
Details
Operating State Plan Execution
Mobility State Flying
Operating Limits Default_Safeguard
Plan ExamplePlan
Plan Status Executing
Initialization
Wake
Grab Control
Robot Commanding
File ...
C:\Users\DW\Desktop\FPla
Plan Valid
Load
Run
Pause
Skip Step
Select and upload Plan, and control Plan execution
Description
A plan that goes in a spiral.
Plan
Total Elapsed Time 00:00:43
Plan Step
Duration
Success
ExamplePlan
0 Station Complete
0-1 Segment 00:01:30 Complete
1 Station Complete
1-2 Segment 00:01:30 Complete
2 Station Complete
2-3 Segment
3 Station
3-4 Segment
4 Station
4-5 Segment
5 Station
Monitor plan execution
Live Telemetry
Live Images
Science Camera
Model of loaded plan
Reset View
Center on Bee
18:19:41 FreeFlyerA: Run Plan Pending ...

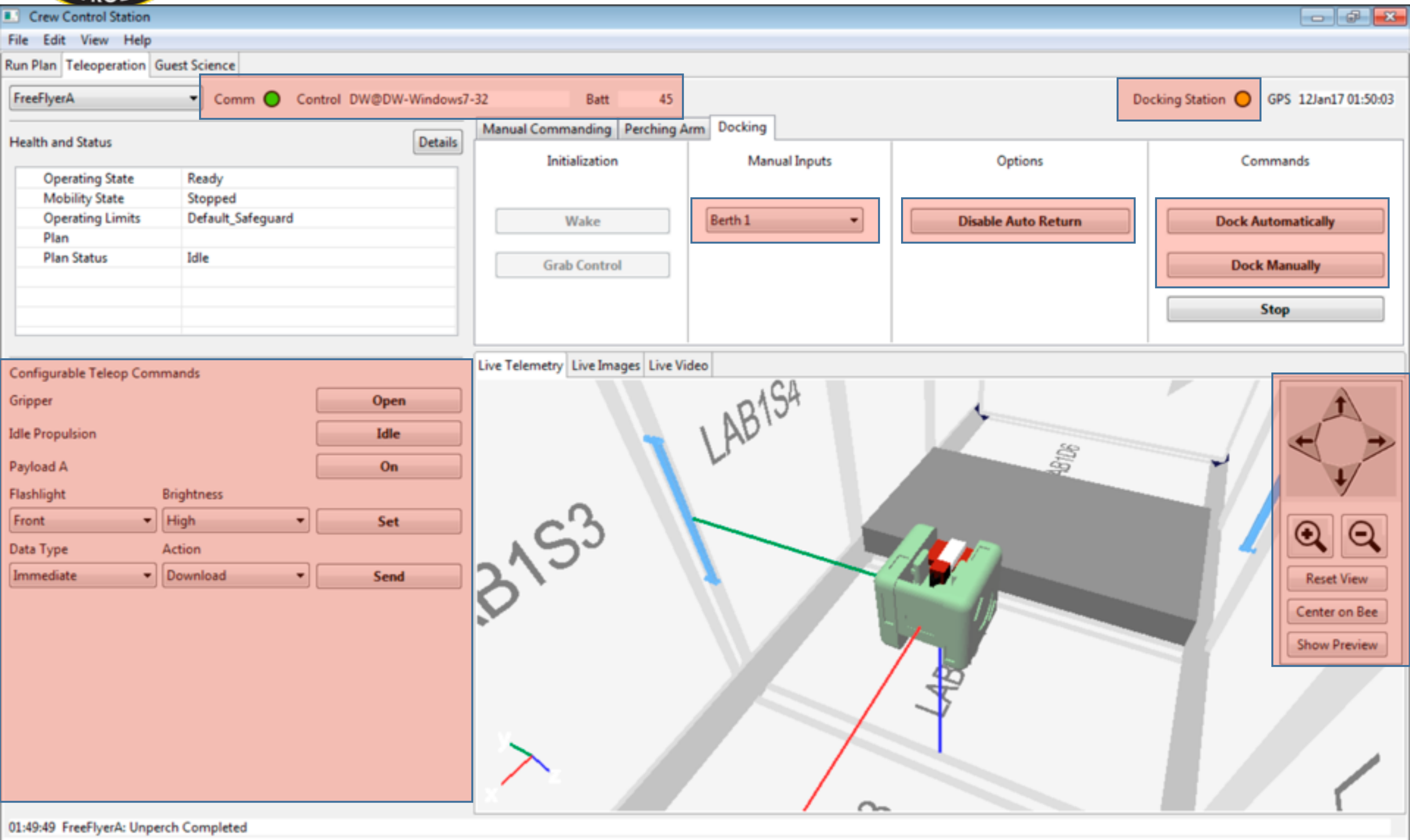
Teleoperation Tab



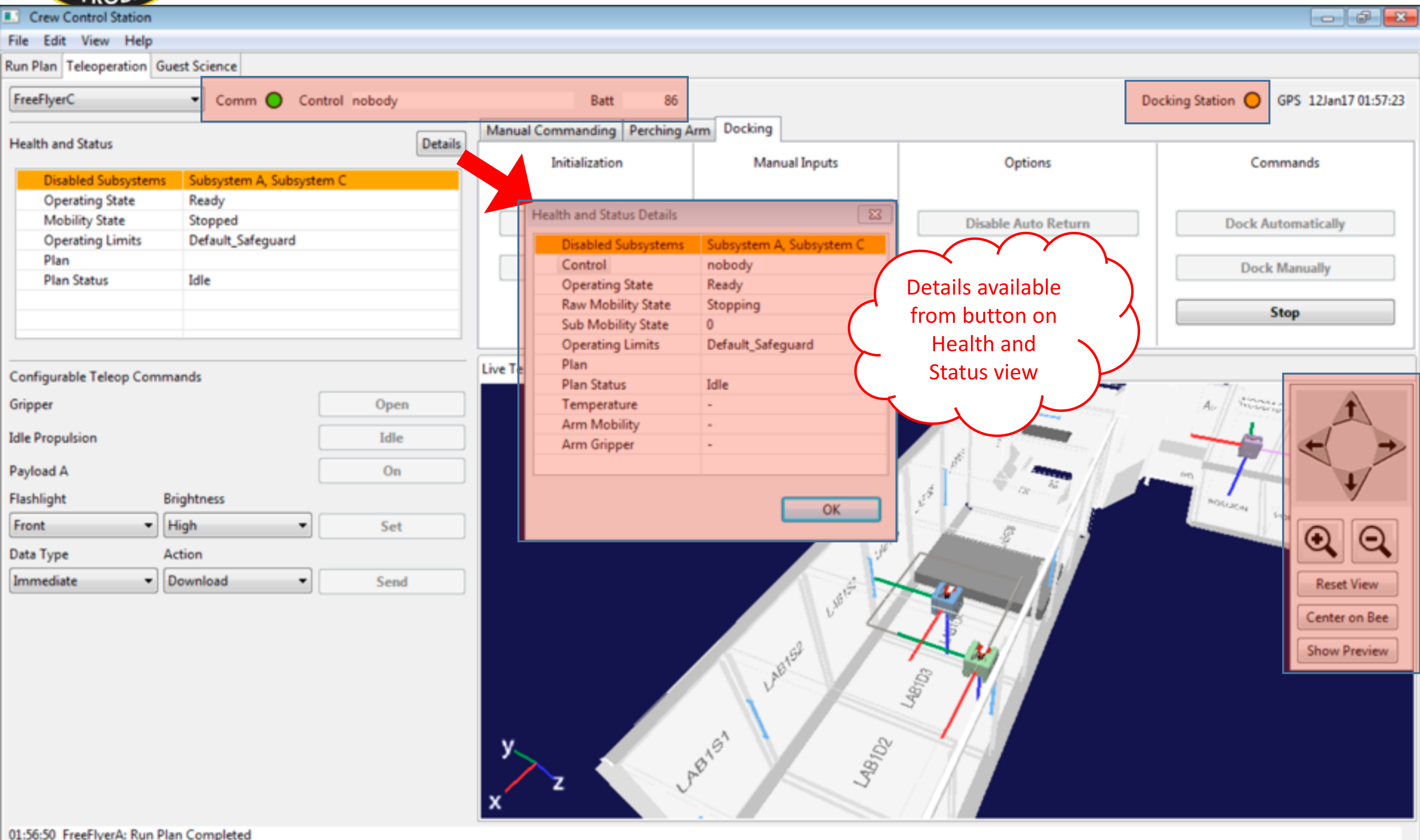
Teleoperation Tab



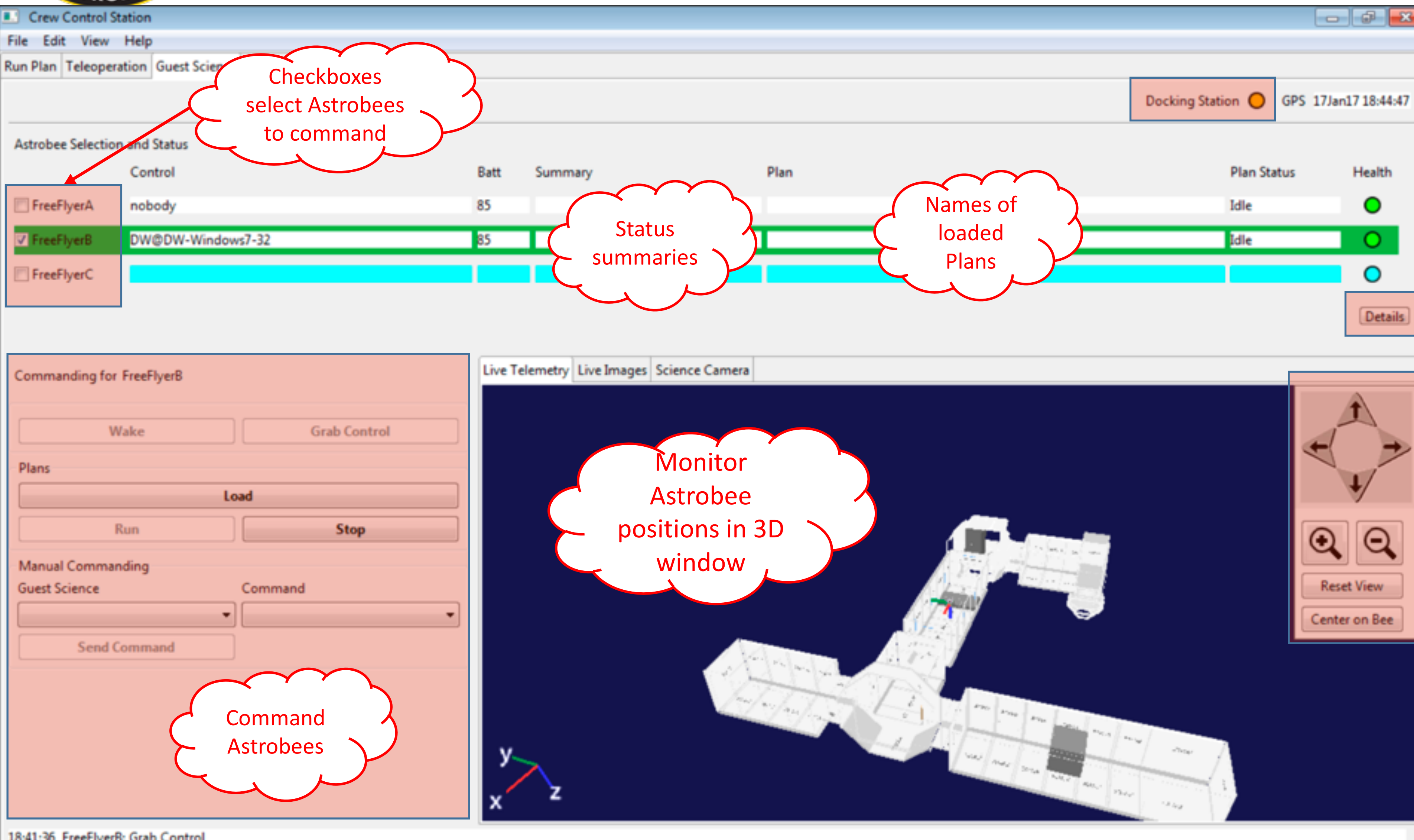
Teleoperation Tab



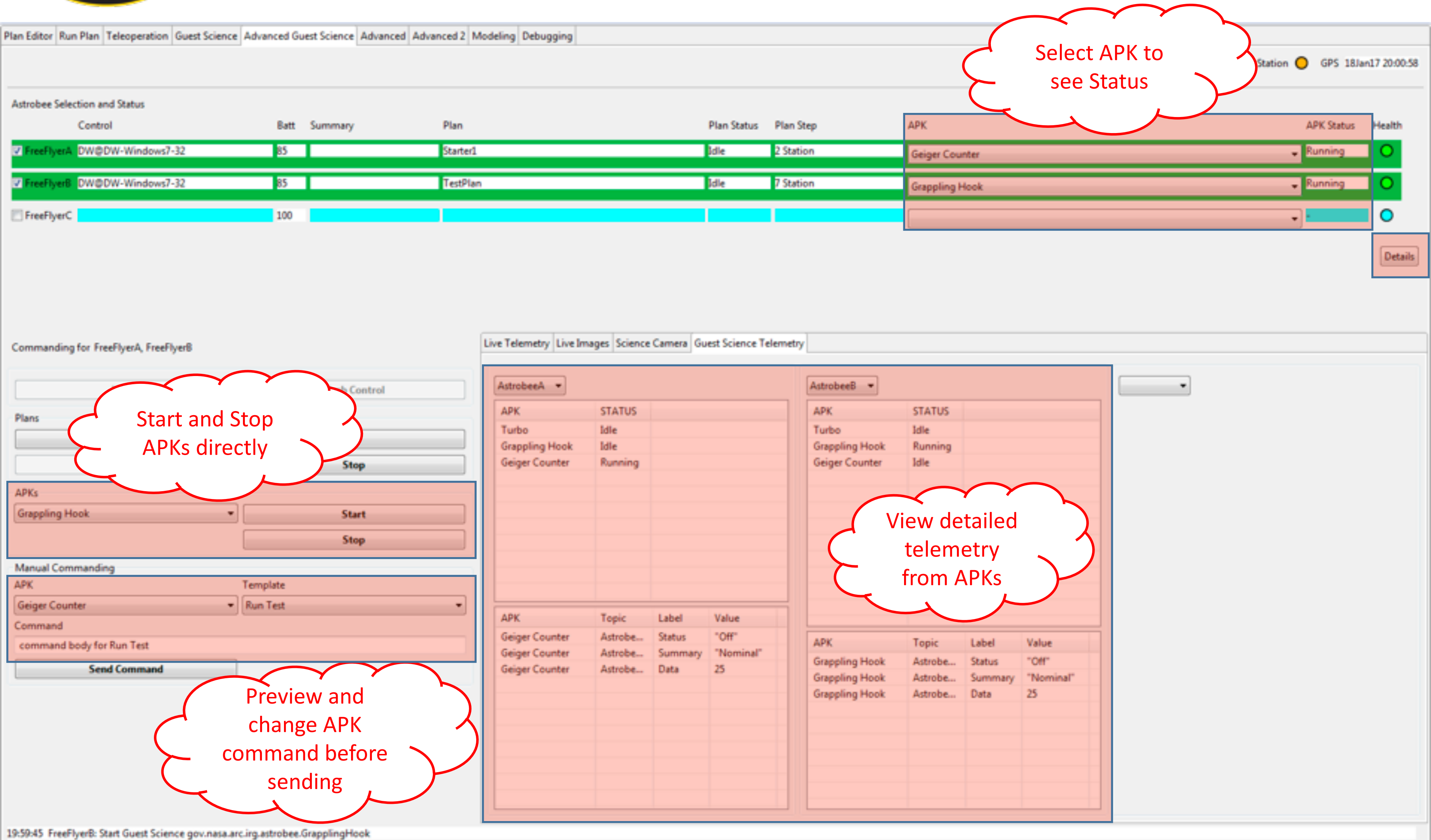
Teleoperation Tab



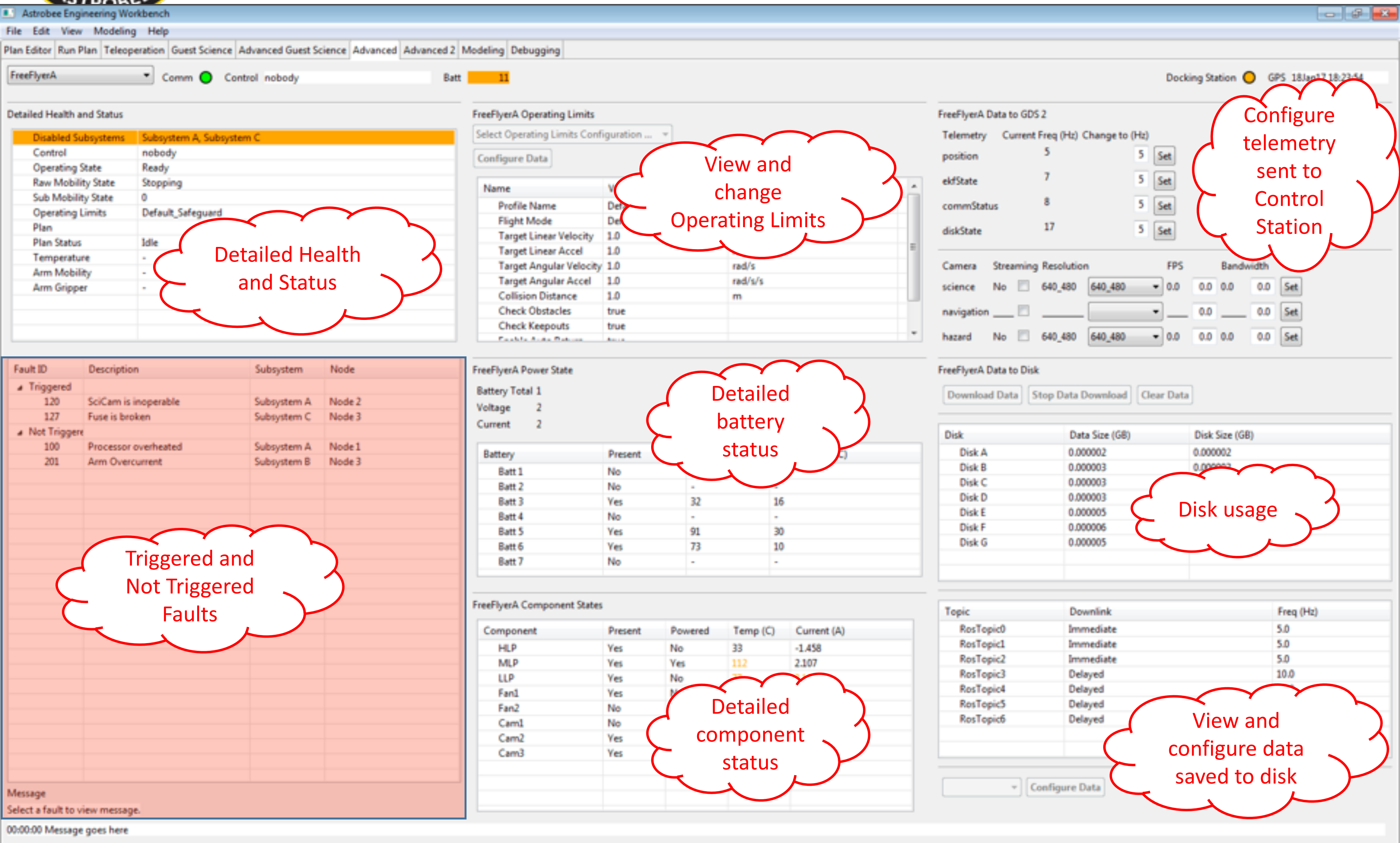
Guest Science Tab



Advanced Guest Science



Advanced Tab

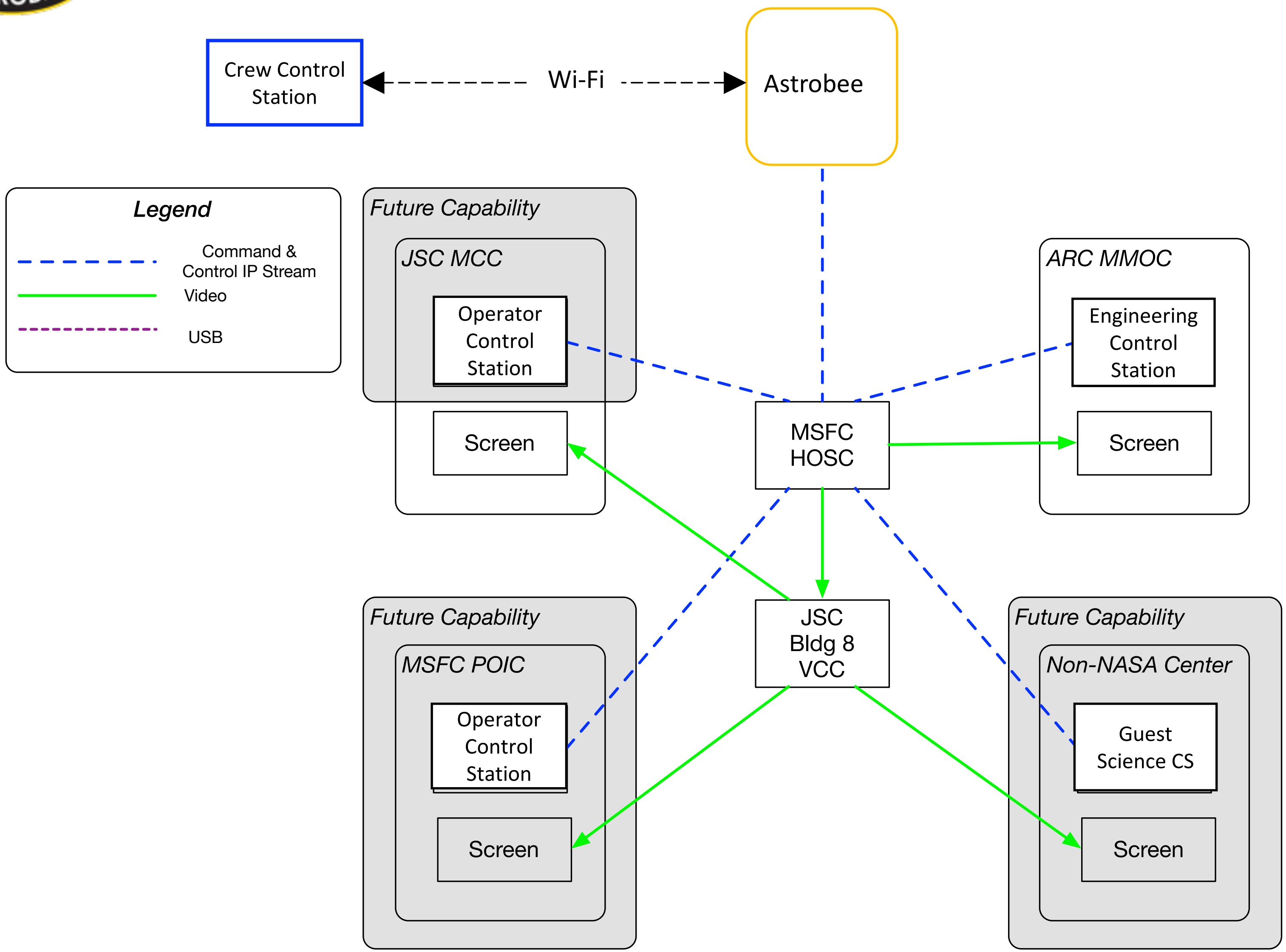


Configuration Files

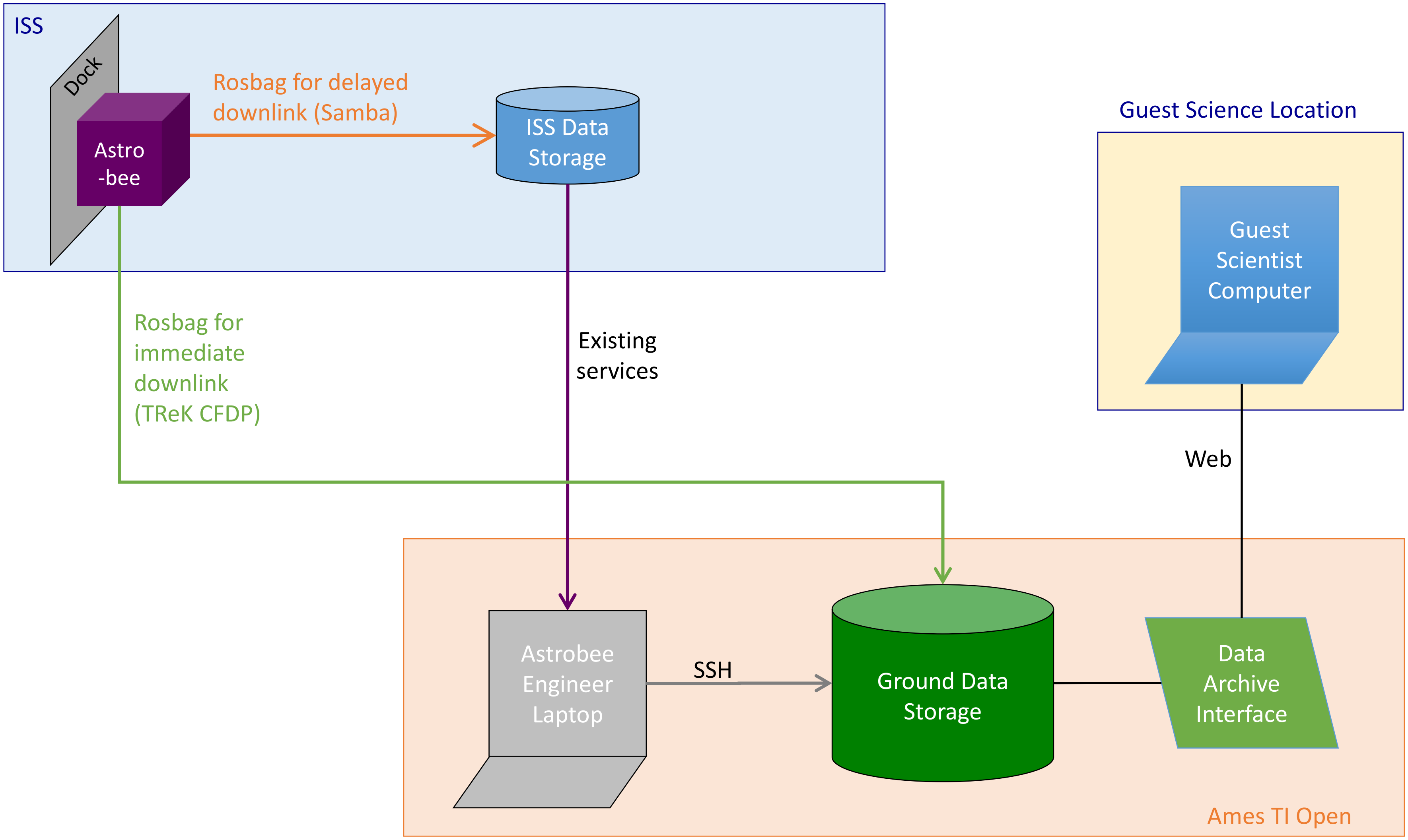
- Config files facilitate changes
- When the Control Station is run in a new location:
  - ControlStationConfig folder is created
  - Default versions of the config files are copied in
- *A config file repo exists on the ground for version control (branches for separate projects, etc)*
- *Ground users pull from repo to update configs*
- *Astrobee Engineering scps config files to ISS*

Ground Data

Data Flow During Operations



Data Flows After Operations



Data Flows After Operations

- When Astrobee is docked after a sortie:
  - Files designated for immediate downlink are transferred from Astrobee *to the Ground Server* via TReK CFDP
  - Files designated for delayed downlink are transferred to ISS data storage and downlinked via existing services at a later time

Ground Data Storage

- Ground Server
  - On TI-Open to provide access to approved external users via LaunchPad
  - Running Red Hat 6 and Apache
- Data Archive Interface
  - Web-based file listing granting read-only access to data on server.
  - Access control allows Guest Scientists to protect proprietary data

Systems Engineering

Delta Periodic Technical Review 3

February 1, 2017

Outline

- Design maturity
- Key performance parameters (KPPs) and technical performance measures (TPMs)

DESIGN MATURITY

Hardware Design Maturity Overview

Subsystem	Maturity (PTR3)	Maturity (now)	Risk	Forward work
Structure	70%	90%	2	Battery retention, camera recessing and bezels, iterate minor P4D issues. [Risk: glass safety / recessing]
Human-robot interaction	40%	100%	1	
Propulsion mechanical	60%	90%	2	Improve strength, finalize soft goods components and impeller balancing. [Risk: collision safety / bumpers; lack of integrated testing during P4D; no noise update until cert]
Propulsion avionics	80%	100%	2	[Risk: collision safety / thrust limiting]
Avionics	80%	90%	1	Over current safety, robust firmware updates, iterate based on P4D issues (e.g. wire routing)
Comm	90%	100%	1	
GN&C	90%	100%	0	
Perching Arm	70%	90%	1	Add retention levers
Thermal	70%	100%	1	
Dock mechanical	80%	90%	1	AR target panel improvements; finalize surface finish
Dock avionics	70%	100%	1	

Software Maturity Overview

Processor	Software maturity (PTR3)	Software maturity (now)	Forward work
HLP/MLP/LLP	40%	60%	Many areas
EPS	80%	90%	Remote wake, crew control details
Propulsion module controller	60%	100%	
Perching arm controller	70%	100%	
SpeedCam [PX4FLOW] *	40%	80%	Fault behavior
Signal light controller *	0%	10%	Detailed design and implementation
Dock controller	70%	90%	Thermal, interface with dock processor
Dock processor *	0%	10%	Detailed design and implementation
Crew control station	70%	90%	Minor bugs, command coverage
Misc. GDS / Enabling products	30%	60%	Identify full suite of support tools needed as conops maturity improves

* Marked rows indicate new items since PTR3 – either new processors, or significant scope increase

KPPS AND TPMS

Key Performance Parameters

Parameter	SPHERES	Threshold Value (Minimum success)	Project Goal (Full success)	Corresponding Technical Performance Measure
Max velocity	4 cm/sec	10 cm/sec	50 cm/sec	N/A – Design will achieve **threshold**; challenge is ensuring reliability at high speeds.
Max acceleration	10 cm/sec^2	5 cm/sec^2	10 cm/sec^2	N/A – Design will achieve **threshold**. Propulsion thrust is on target; acceleration performance now depends on mass.
Localize & position	+/- 3 cm	+/- 20 cm	+/- 2 cm	**TPMs 4, 6**
Measure angle & point	+/- 2 deg	+/- 20 deg	+/- 8 deg	**TPMs 5, 7**
Flight time	0.5 hr	2 hr	5 hr	**TPM 1**
Dock & resupply	Crew tended	Crew tended	Autonomous	N/A – Design will achieve goal
# peripheral ports	1	2	3	N/A – Design will achieve threshold
Sorties supported with peripheral ports	1	1	3	N/A – Design will achieve goal
Consumables used per test session	6	0	0	N/A – Design will achieve goal
ISS operational space	2m x 2m x 2m	JEM, US Lab, and Node 2	All USOS	N/A – Design will achieve goal (modulo safety keepout zones that might include Cupola, Airlock)

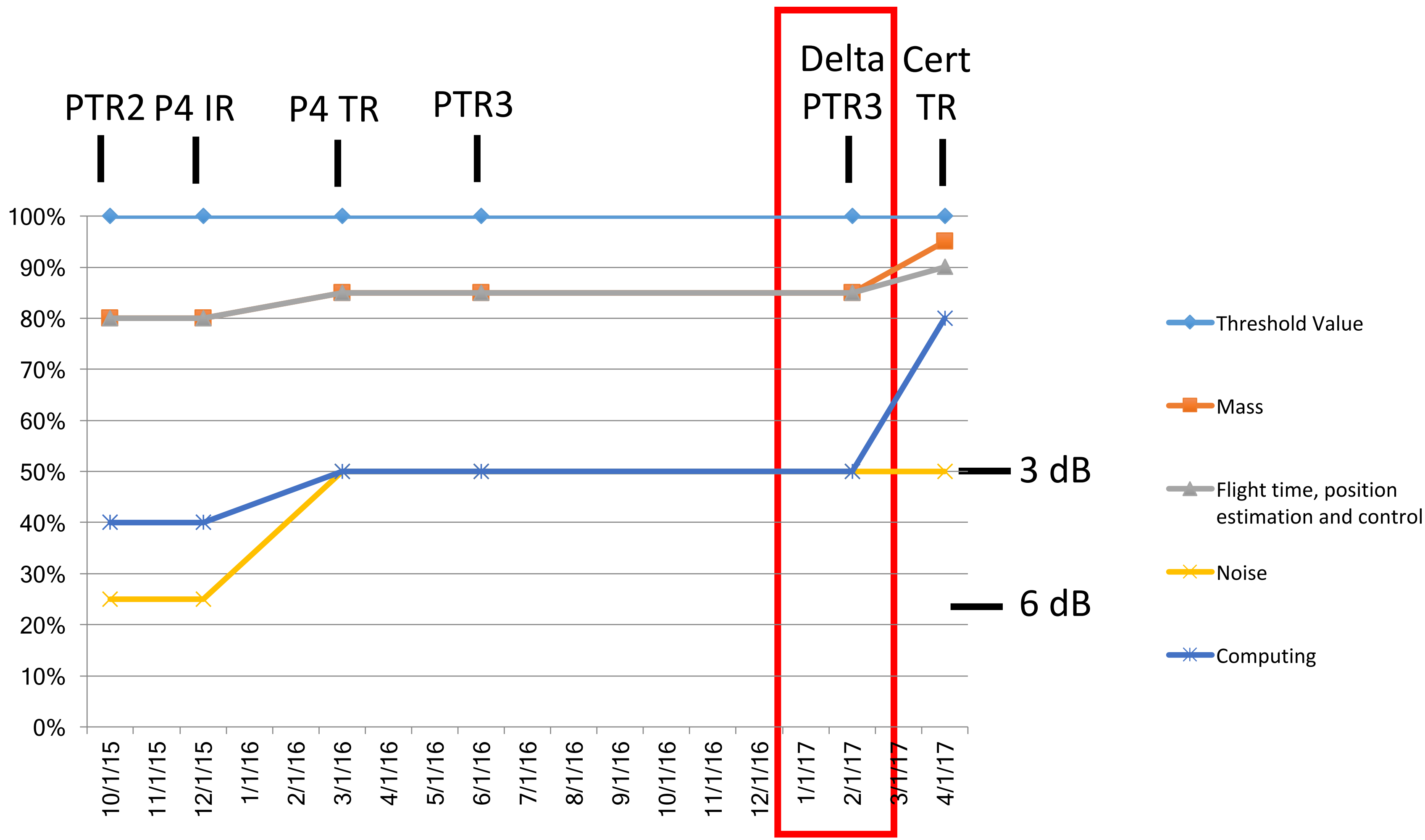
[From IRG-FF001-Astrobee-Project-Management-Plan]

Technical Performance Measures

#	Topic	Measure	KPP?	Threshold	Goal
TPM 1	Flight Time (h)		x	2	5
TPM 2	Mass (kg)			8	-
TPM 3	Noise @ Max Thrust (SPL dBA)			65	-
TPM 4	Pose Estimation Error	Translation (cm)	x	20	2
TPM 5		Rotation (deg)	x	20	8
TPM 6	Pose Control Error	Translation (cm)	x	20	2
TPM 7		Rotation (deg)	x	20	8
TPM 8	Navigation MTBF (h)			10	-
TPM 9	Max Computing Processor Load			100%	-
TPM 10	Max Computing Memory Consumption			100%	-

[From IRG-FF002-02-Astrobee-Technical-Performance-Measures]

TPM Schedule and Maturity Targets



Software-Driven TPMs

- Performance for some TPMs largely driven by software
  - TPMs 4-10 (position estimation and control accuracy, navigation MTBF, CPU and memory)
- Flight software final delivery will likely occur after hardware certification is complete
- As we update the project schedule, we may stretch the maturity timeline for TPMs 4-10 to reference it to software final delivery

TPM Updates PTR3 to Delta PTR3

#	Topic	Update Approach	TPM Accuracy
TPM 1	Flight Time (h)	No update (no major changes to avionics / batteries)	**High**
TPM 2	Mass (kg)	Improved design detail, weigh some P4D parts	**Medium**
TPM 3	Noise (dBA)	No update (no new integrated prop module prototype)	**Low**
TPM 4	Est. Error (cm)	No update (next update part of upcoming P4D testing)	**Low**
TPM 5	Est. Error (deg)	“	**Low**
TPM 6	Control Error (cm)	“	**Low**
TPM 7	Control Error (deg)	“	**Low**
TPM 8	Nav MTBF (h)	“	**Low**
TPM 9	CPU (%)	“	**Low**
TPM 10	Memory (%)	“	**Low**

TPM Status

#	TPM	Thresh	Desired Margin	Threshold with margin	Current best estimate	PTR2 Status	PTR3 Status
TPM 1	Flight time (h)	≥ 2	15%	≥ 2.3	3.1	Good	Good
TPM 2	Mass (kg)	≤ 8	15%	≤ 6.8	8.7	Good	Off target
TPM 3	Noise (dBA)	≤ 65	3 dB	≤ 62	62.25	Insufficient margin	Insufficient margin
TPM 4	Estimation Error (cm)	≤ 20	15%	≤ 17	8.6	Good	Good
TPM 5	Estimation Error (deg)	≤ 20	15%	≤ 17	3.7	Good	Good
TPM 6	Control Error (cm)	≤ 20	15%	≤ 17	9.3	Good	Good
TPM 7	Control Error (deg)	≤ 20	15%	≤ 17	8.5	Good	Good
TPM 8	Navigation MTBF (h)	≥ 10	15%	≥ 11.5	> 1000	Good	Good
TPM 9	CPU (%)	≤ 100%	50%	≤ 50%	49%	Good	Good
TPM 10	Memory (%)	≤ 100%	50%	≤ 50%	47%	Good	Good

CPU TPM

- Haven't formally re-evaluated this TPM, but may no longer have sufficient margin
- Visual odometry improvements increased CPU consumption in the estimator loop
- Flight software team does not consider this a major concern
  - Control loop is reliable, in practice
  - Optimizations are available if needed to increase efficiency, but many other reliability improvements take priority for now

Noise TPM

- At PTR3, we reported the TPM estimate was 64.5 dBA, too close to the threshold requirement of 65 dBA; the margin should have been 3 dB
- Our plan was to start on further acoustic testing and possibly design rework to regain noise margin
- Further testing showed that the noise measurements were very sensitive to details of experimental setup
  - We switched modes on our sound meter per advice from JSC acoustics experts, and saw reduction from 64.5 dBA to 62.25 dBA (almost on target)
  - There's also still debate about how to position the microphone so as to experience the "worst-case noise" but not have the sound measurement thrown off because the microphone is directly in the air flow path
- Completed minor design rework to reduce noise:
  - We evaluated several COTS servo models for the nozzles, trying to find one that was both quieter and rugged enough to survive extended stall conditions if a nozzle was jammed. We ended up with a model that is very rugged, but not much quieter.
  - We added isolators between the nozzle servos and the plenum body, to avoid the plenum acting as a sounding board to amplify the servo noise.
  - We haven't had a chance to evaluate the resulting improvements yet.
- Proposed forward approach:
  - Acoustics appear to be on target for now, but some risk that prop module structural changes will increase the noise level
    - The new structure may act as a sounding board, or simply absorb less noise than the old foam lid
  - Next full acoustic test will be on cert unit propulsion modules
  - If rework is needed, there will likely be a significant schedule impact

Mass TPM – Post-PTR3 Review

- At PTR3, we reported the mass TPM had negative margin (7.0 kg > 6.0 kg)
- We developed the following plan:

Action	Status	Notes
Accept the mass slip and relax mass threshold requirement to 8 kg, restoring healthy margin	Done	
(Optional) Execute known lightweighting opportunities, possibly reducing mass below 7 kg estimate	Mostly not executed	The mechanical team spent almost 100% time between PTR3 and today making the design close functionally, particularly finishing significant prop module changes. Most of the lightweighting options were not executed due to lack of time.
(Optional) Increase propulsion module rated max thrust to restore acceleration at or near 10 cm/s^2 (without changing hardware design)	Not executed	There are three main constraints on max thrust: (1) the physical capability of the power system and motor, (2) limiting kinetic energy in a collision, and (3) noise limits. Recent testing shows there is plenty of headroom for (1), but (2) and (3) still require further testing before we could promise increased thrust. We are getting closer to being able to run the relevant tests, and will continue to assess whether this opportunity exists.

Mass TPM – Recent Update

- At PTR3, we reported that there was a risk of further mass growth, estimated < 0.5 kg, due to low design maturity of some components, particularly the propulsion modules
- Since then, we actually saw mass grow from 7.0 kg to 8.7 kg, significantly exceeding the new mass threshold set at PTR3
- Where the growth came from:
  - The largest hardware design change was replacing the fragile foam plenum lid with a more rugged structure
  - Our tight schedule during that redesign forced straightforward design choices such as solid panels that have sub-optimal strength-to-weight, but are easier to work with
  - Constraints of supporting crew servicing and minimizing redesign of other parts of the prop module led us to a design that's probably more complex than it needs to be, further driving up the mass
  - (Frankly, everyone was surprised how heavy this design worked out to be)

Mass TPM – Forward Plan

- Our baseline plan is to accept the new mass estimate
- Design maturity is much higher now, so we don't expect this to happen again
- Relax mass threshold requirement to 10.5 kg (8.7 kg + ~15% margin)
  - Increased mass will reduce max acceleration to 5.7 cm/s^2, assuming we don't increase max thrust
  - Increased mass may also require reducing max velocity below 50 cm/s to mitigate collision hazard, pending further testing of SpeedCam and bumpers
- We have other mitigation options:
  - Old lightweighting opportunities still exist, and the redesigned prop module has more low-hanging fruit
  - May still be able to increase rated max thrust to restore acceleration
  - But realistically, we don't have time to execute these options without schedule relief

Agenda

Time	Duration	Presenter	Topic
8:30	0:30	Terry, Chris	Welcome/Intro
9:00	1:30	Trey, Team Leads	Design
10:30	0:15		*Break*
10:45	1:15	Team Leads	Design
12:00	0:45		*Lunch*
12:45	0:30		*Demo*
13:15	1:15	Team Leads	Design
14:30	0:15		*Break*
14:45	0:30	Trey	Systems Engineering
15:15	0:30	Jonathan	Integration & Test
15:45	0:30	Ernie	Safety
16:15	0:15	Chris	Project Management
16:30	0:15	Maria	Operations
16:45	0:15	Chris	Conclusion

Integration & Test

Overview and Status

Integration and Test Status

- Prototype 4D
  - Created for Additional Risk Reduction
  - All flight-like core, repurposed propulsion module, ABS top-forward module
  - Integration Complete
  - Testing in progress
- Certification Unit
  - Cert Unit Integration Procedures beginning review
  - Continuing coordination with Code Q (Quality Assurance)

Integration and Test Facilities

Facility	Prototype 4D	Certification	Flight
Granite Lab	✔	✔	✔
MGTF	✖	✔	✖
EMI/EMC facility	✔ Ames	✔ JSC	✖
Engineering Evaluation Lab	✔	✔	✔
Off-gassing White Sands	✖	✖	✖
Anechoic	✔ Ames	✔ JSC	✖
JSL at JSC	✖	✔	✖

Prototype 4D Risk reduction

Risk	Status
Fit	Integration Complete, Fit issues being addressed in mechanical design
New Material manufacturing and tolerances	Integration Complete, New materials performed adequately
Gripper Performance	Complete, test report in progess.
Sensor Placement	Testing planned for week of 01/23
Crew Serviceability	Testing planned for week of 01/23
Wi-fi Interference	Testing planned for week of 01/23
Avionics Functionality	Testing planned for week of 01/23

Risk	Status
EMI	Testing planned for week of 01/30
Acoustic	Testing planned for week of 01/30
Margin for Docking Performance	Testing planned for week of 01/30
Retractable Magnets	Testing planned for week of 01/30
Software Update Functionality	Testing planned for week of 01/30
Human Factors	Testing planned for week of 02/06
Glass Shattering	Testing planned for week of 02/06
Thermal Operating Limits	Testing planned for week of 02/13

Granite Lab Facility Development

Element	Status
Visual Environment	✔ Partial Module
Lighting	✔ Incorrect geometry, correct illumination
Ground Truth Data	✔ Visualeyez
Wireless Network	✖ JSL WAP
Dock Power	✖ 120V power supply
Positioning	✖ Goniometer In progress

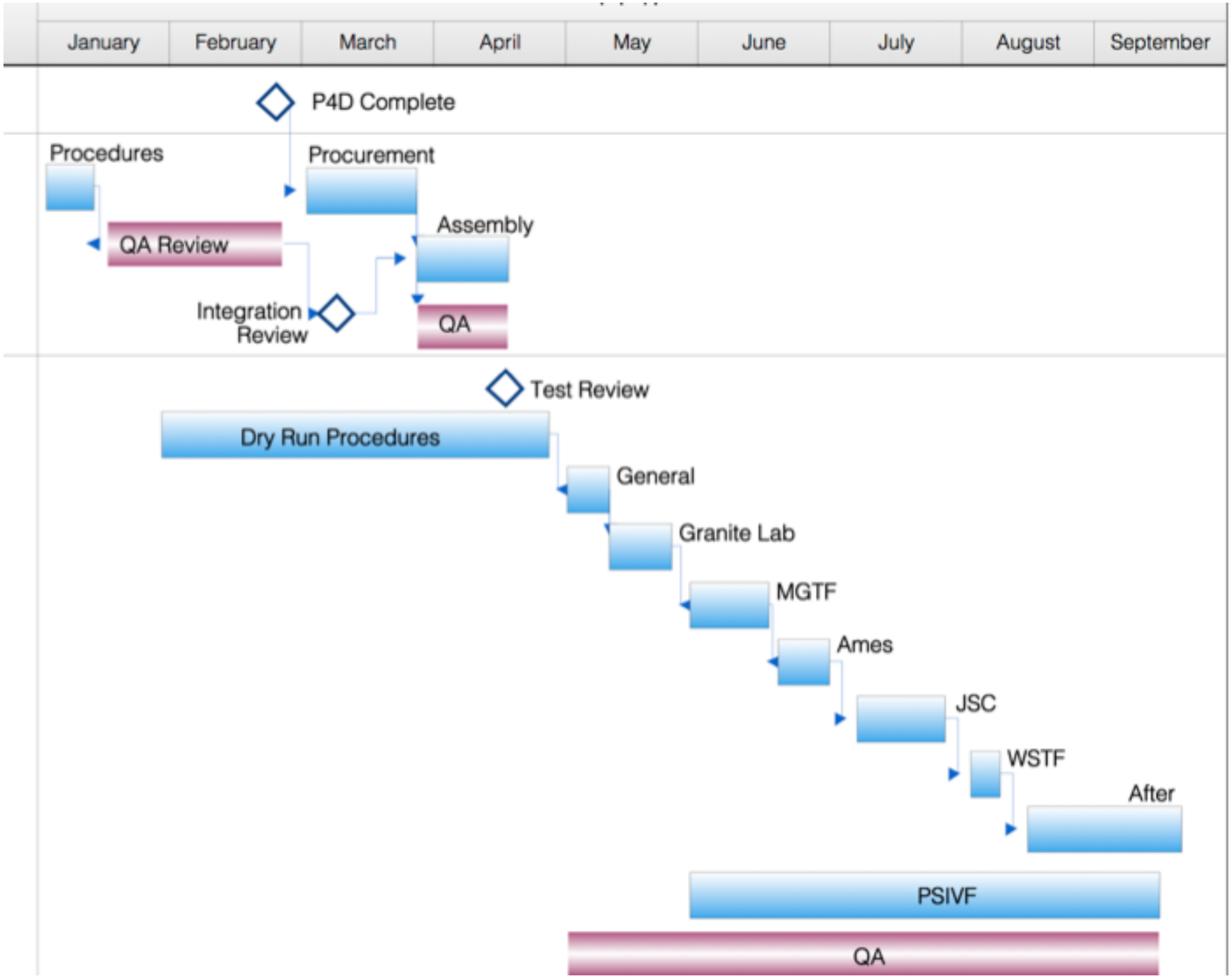
- Impacts
  - Testing limited in orientations
  - Power Supply nearly complete and not used until Cert
  - Small WAP in use

MGTF Facility Development

Element	Status
Visual Environment	✔ Full Module
Lighting	✖ Correct geometry, correct illumination
Ground Truth Data	✖ Visualeyez
Wireless Network	✖ JSL WAP
Dock Power	✔ NA
Positioning	✖ Gimbal and Gantry

- Impacts
  - Temporary illumination similar to Granite Lab
  - Small WAP in use
  - Positioning limited to 5-DOF
  - Remaining visualeyez LEDs on order

Cert Schedule



Agenda

Time	Duration	Presenter	Topic
8:30	0:30	Terry, Chris	Welcome/Intro
9:00	1:30	Trey, Team Leads	Design
10:30	0:15		*Break*
10:45	1:15	Team Leads	Design
12:00	0:45		*Lunch*
12:45	0:30		*Demo*
13:15	1:15	Team Leads	Design
14:30	0:15		*Break*
14:45	0:30	Trey	Systems Engineering
15:15	0:30	Jonathan	Integration & Test
15:45	0:30	Ernie	Safety
16:15	0:15	Chris	Project Management
16:30	0:15	Maria	Operations
16:45	0:15	Chris	Conclusion

Astrobee Delta PTR3

Safety

Safety Status

- PSRP Delta Phase 2 held January 11 & 12, 2017; covered the following:

Topic	HR#	Disposition	Comments
Safety Data Package	28626	Approved with Mods	Minor additional details requested, update to Delta PTR-3 maturity
Standard Hazards: Material Flammability Materials Off-gassing Mechanical/Sharp Edges Touch Temperature Shatterable Materials (lenses) Electromagnetic Radiation Lasers Electrical Power Electrical Mate/Demate Rotating Equipment Translation Paths Interference Vented Containers Failure	9075	Approved with Mods	Mostly clarifications, move vibration to Glass HR, remove External Charger (covered by GeoCam Project)

Safety Status (Cont)

Topic	HR#	Disposition	Comments
Collision	28628	Approved with Mods	Hazard Control plus Equivalent Safety Non-Compliance Report
Li-Ion Battery	28635	Approved with Mods	Update EP-03 form and attach to hazard
Mate/Demate & Electrical Shock	30631	Approved with Mods	Split out UOP Mate/Demate into a separate Cause, remove External Charger
Battery Charger	30720	Approved with Mods	Remove External Charger
Connectivity To ISS UOP Power	32417	Approved with Mods	Expand beyond the power cable to include implications for dock internal electronics
Astrobee Glass Lenses	34164	Approved with Mods	Move vibration testing to this hazard

History

- A PSRP Delta Phase 2 review was requested at the first Phase 2 review June 7 & 8, 2016 primarily due to:
  - Clarification associated with Collision analysis and need for a Equivalent Safety NCR for crew impacting the free flyer
  - Electrical Mate/Demate hazards needed to be collected into a single hazard and expanded
  - Clarifications for hazards including details of the internal free flyer charger, and for connecting to ISS UOP power
- Many splinter meetings and technical exchanges leading up to the Delta Phase 2 review

Delta Phase 2 Primary Results

- All hazards were approved with mods
  - Mostly clarifications, some additional coverage, format updates
- Most discussion centered around:
  - Collision hazard (more later)
    - Reviewed our analysis and testing plans
    - Equivalent Safety NCR – the PSRP Chairman intends to recommend approval to the ISS Program
  - Electrical hazards
    - Li-Ion battery hazard accepted with most of the testing/analysis already completed (from Geocam project)
    - Some reformatting requested for Mate/Demate and Electrical Shock. Expanding coverage in some areas
    - Decided to withdraw the External Charger hazard because it is already covered by the Geocam project
  - Firmware use related to safety critical hardware
    - No specific impacts to hazards identified so far

Other Results

- Electrical:
  - Agreement on smart battery self protections
  - Agreement on use of <3A and very limited short circuit duration rather than an upstream power inhibit for battery insertion/removal from free flyer
  - Agreement on depth of battery enclosure on free flyer for molten metal protection (2.25”)
  - More details on wiring diagrams requested
  - Free flyer battery “hot swaps” will require an Ops Control to disable propulsion and Payload

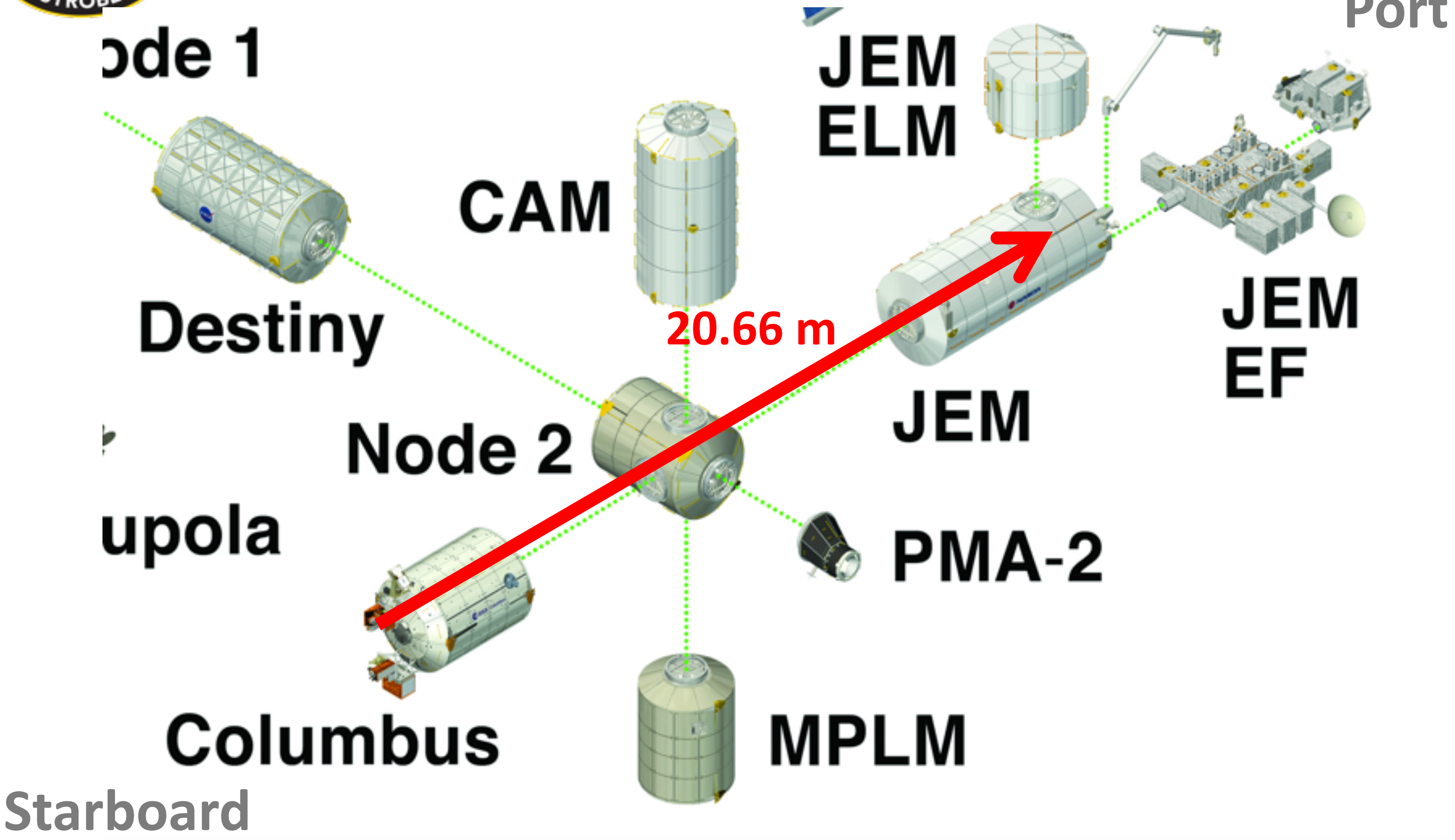
Other Results (cont)

- Flight Software - still non-Safety Critical
  - Any free flyer software updates by future Payload users must be monitored by SPHERES/Astrobee Program Office
  - Any changes to free flyer software would have to be reviewed/approved by PSRP
- Discussion of addressing Maintenance hazards for Phase 3
- Discussion of “Verify Once” versus “Verify Each Flight” for verification closures

Collisions: Worst-Case Runaway

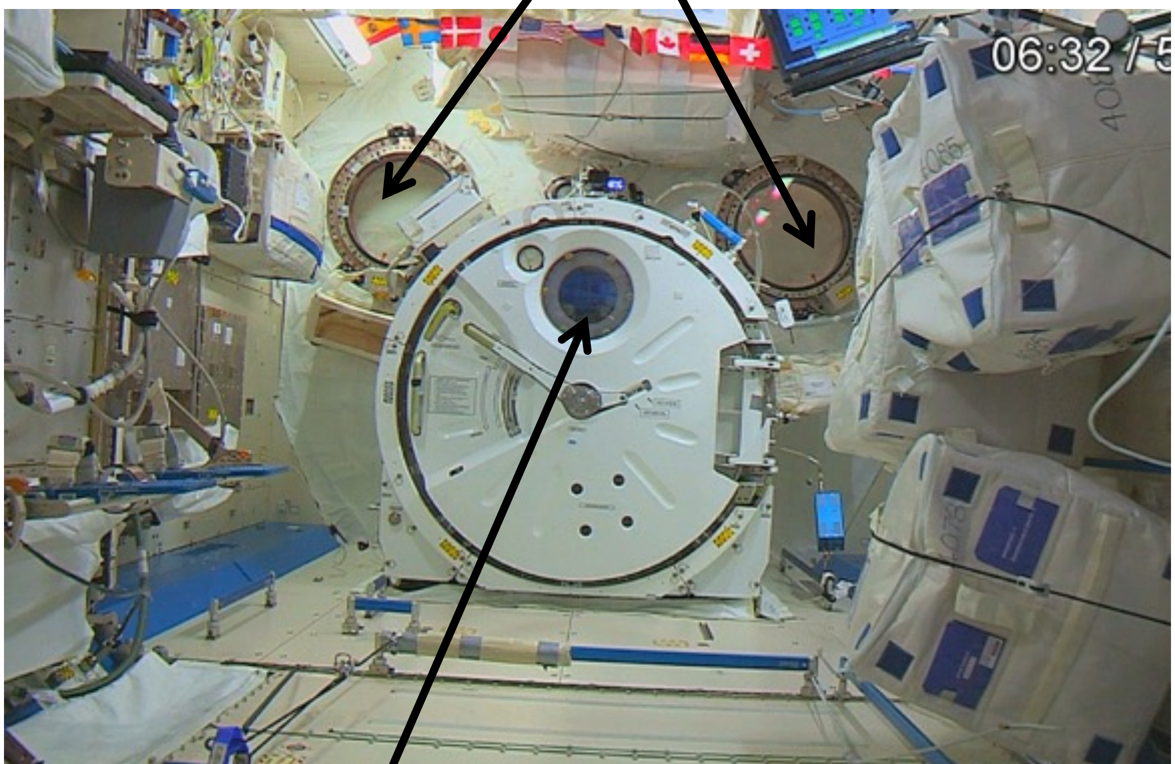
- **This is the challenging case from a safety perspective**
- Worst case is accelerating all the way down the longest corridor on ISS at max thrust
  - ~60-ft Columbus module to JEM windows
  - Note that PSRP Chairman might be willing to consider this full length unrealistic if we need relief
- Max velocity ~2.1 m/s, ~5 mph (jogging speed)
- Collision types/severity
  - Crew (primarily crew impacting free flyer) – Critical (NCR)
  - Windows - Marginal because of scratch panes
  - Structure - Marginal by staying within 125 lbf
  - Projecting hardware (e.g. laptop on Bogen arm) - Marginal
- Accept risk that Astrobee may be inoperable after collision

Worst-Case Runaway



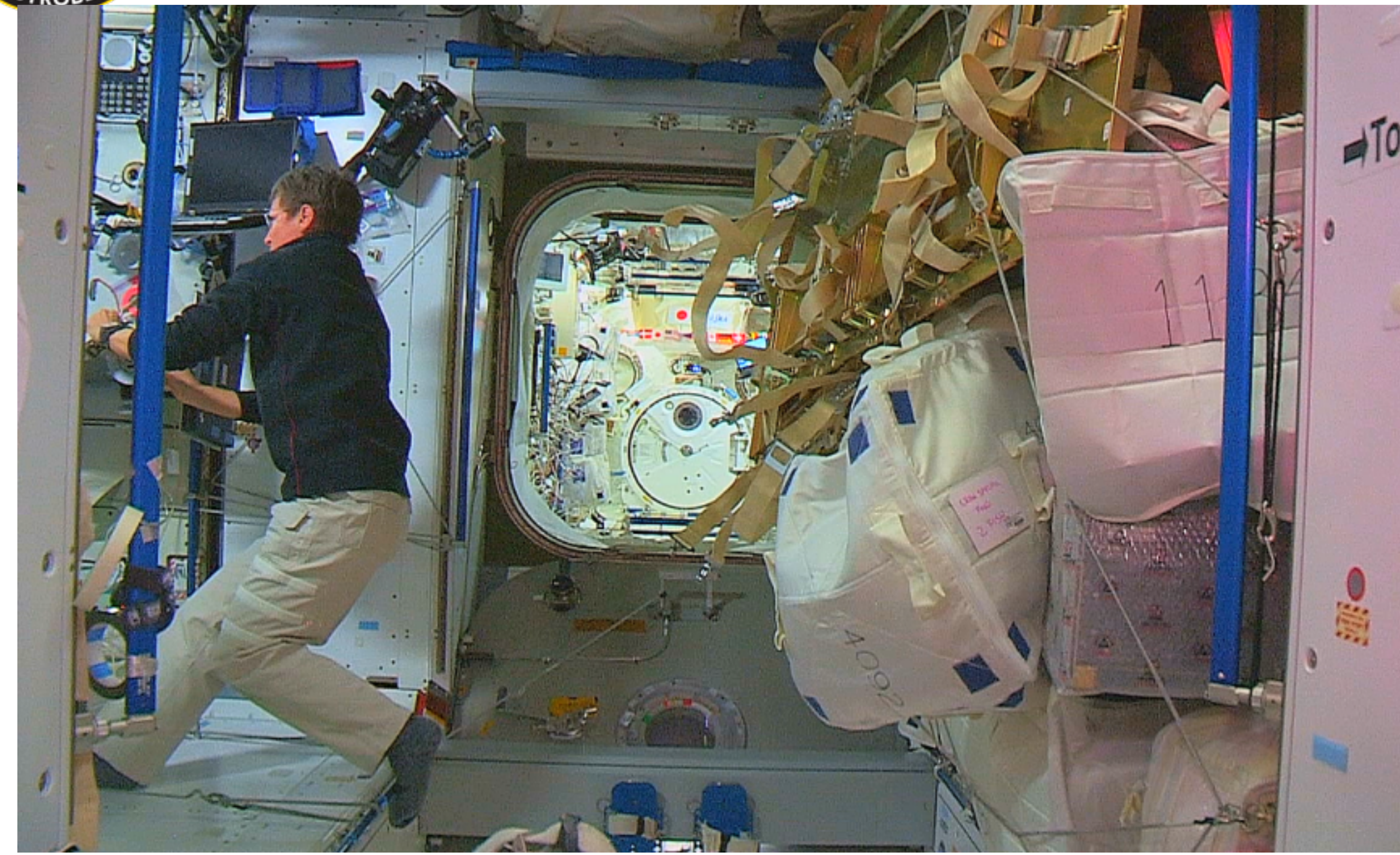
JEM Port End Windows

20” diameter bulkhead windows
port end cone

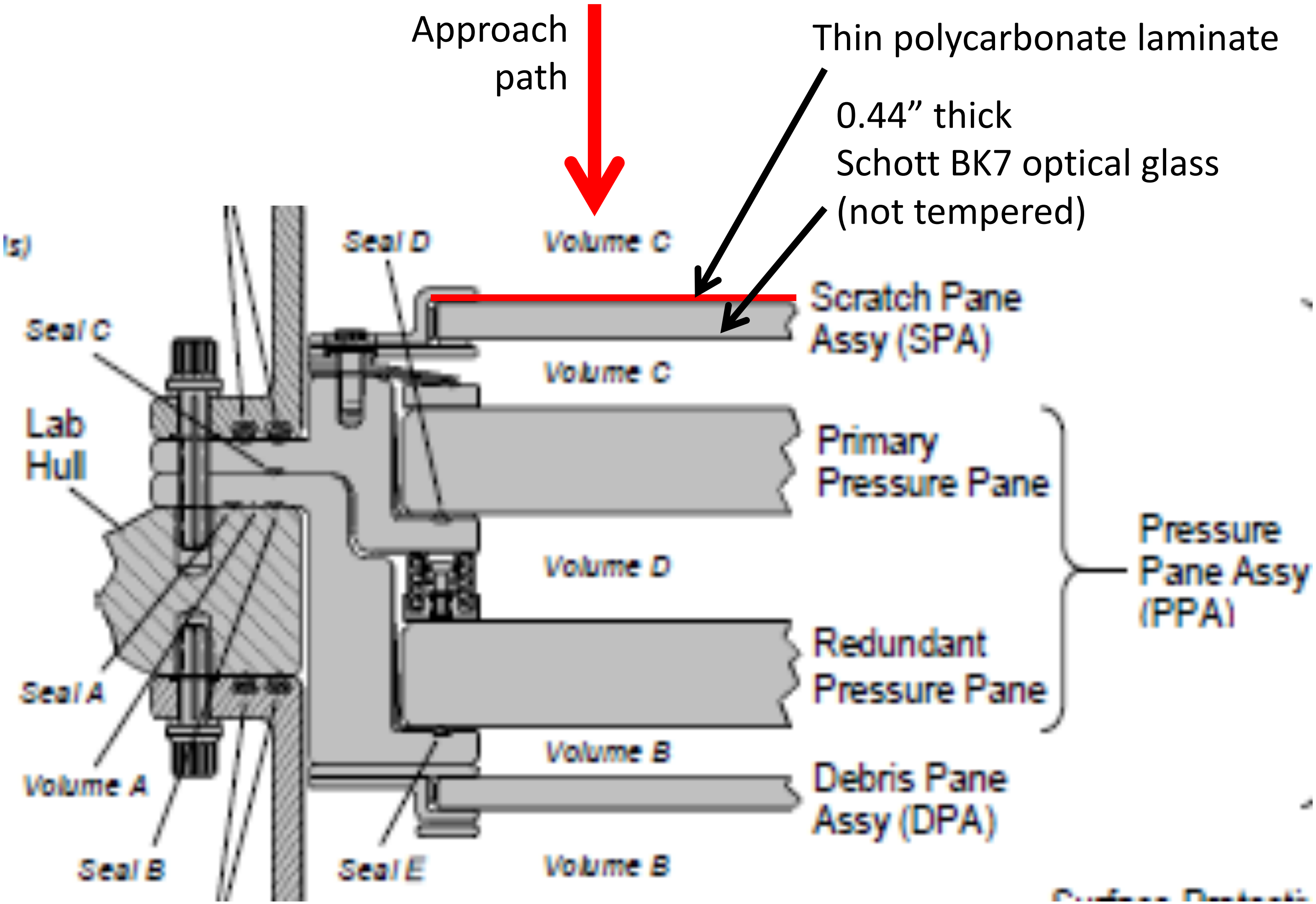


8” diameter airlock hatch window

From Bulkhead Of Columbus Module Looking Towards JEM Thru Node 2



JEM Bulkhead Window (Typical)

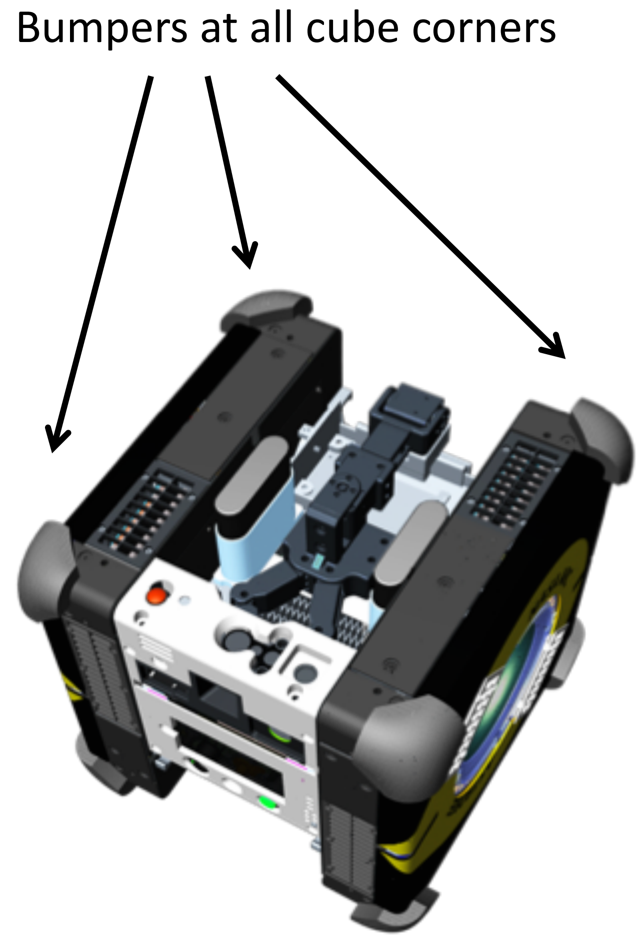


Collision Analogy/Mitigation

- "Bowling ball with knee pads"
  - Astrobee mass (8 kg) comparable to bowling ball (7.25 kg)
  - Bumpers similar material to knee pads
- Analogous drop height in Earth gravity
  - Nominal ops: 50 cm/s = 1.3 cm or 0.5 inch drop
  - Worst-case: 2.1 m/s = 23 cm or 9 inch drop
- Mitigation:
  - Thrust limiting
    - Stakeholders require 10 cm/s^2 acceleration
    - Design propulsion hardware to ensure thrust can't go more than 20% above that
    - Limits maximum impact energy
  - Foam bumpers
    - Foam bumpers on propulsion modules; impact-damping material similar to athletic knee pads
      - Foam bounces back after impact and can be reused
    - Rigid hardware is recessed behind bumpers so it doesn't contact obstacle in a collision

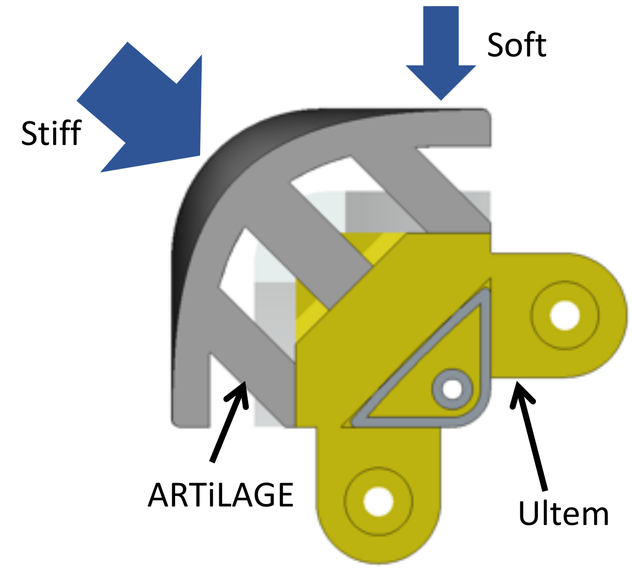
Bumper Geometry

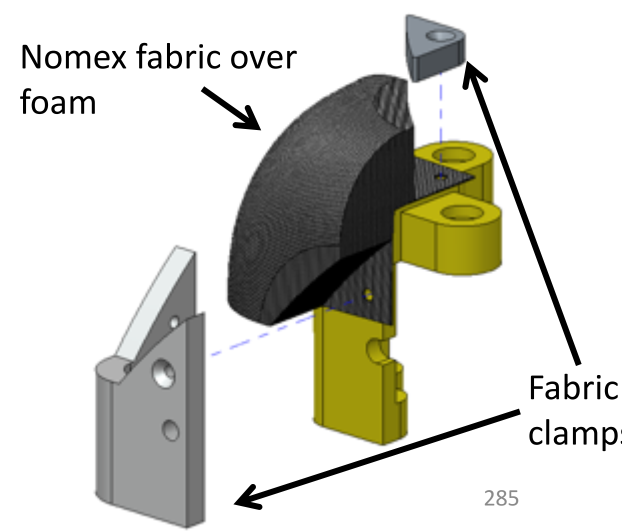
- Geometry ensures any collision will compress bumpers by 0.5 inches of travel before contacting any hard parts (“bottoming out”)



Bumper Design

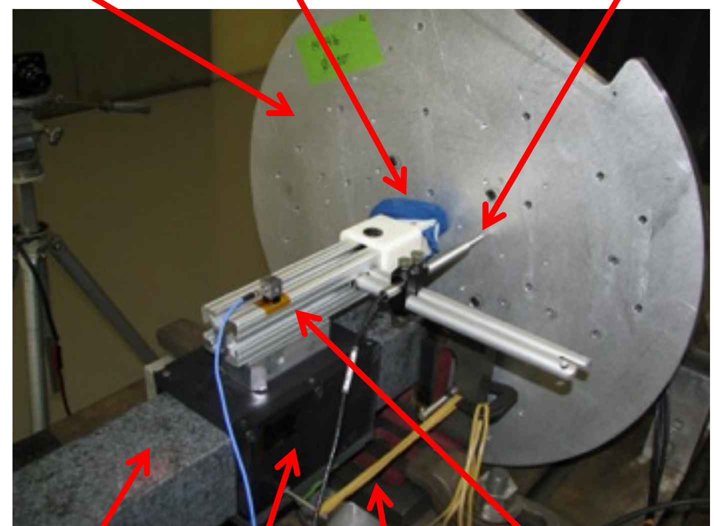
- Bumper material is ARTiLAGE foam
  - Typically used for e.g. athletic knee pads
  - Bounces back after collision, reusable (unlike earlier baseline design using crushable foam)
- Bumper shape includes inward-facing ribbing
  - Bumper stiffness tunable by changing rib width
  - By design, stiffness is non-isotropic under different load directions:
    - Stiffest in case 1 (load aligned with ribs)
    - Softest in case 3 (ribs buckle more easily under transverse load)
  - Vendor produces custom bumper shape by injection molding
- Nomex fabric cover controls flammability hazard
  - And robustly contains foam
  - Foam also glued to Ultem to minimize slip





Bumper Collision Test Rig

- Single bumper mounted on an air carriage that slides along a granite post, and impacts target (aluminum plate)
  - Carriage accelerated using rubber bands
- Test single bumper, simulating collision cases 1-3
  - Vary bumper orientation to match case
  - Vary air carriage mass:
    - Case 1: Full Astrobee mass
    - Case 2: 1/2 Astrobee mass (with load distributed evenly over two bumpers, one bumper gets 1/2 mass)
    - Case 3: 1/4 Astrobee mass (with load distributed evenly over four bumpers, one bumper gets 1/4 mass)
  - Cases 2 and 3 actually have multiple possible orientations due to non-symmetry of bumper ribbing (see next page)
- Approach is conservative
  - Rigid air carriage absorbs less impact energy than more compliant Astrobee structure
  - Target also very rigid
- Instrumentation
  - Target mounted on force table to measure force vs. time
  - Impact velocity measured by differentiating position, as measured with LVDT
  - Carriage also instrumented with accelerometer



Conclusion

Obstacle type	Hazard classification	Reasoning behind classification
Crew	Critical	Crew can translate at high speed and run into stationary or moving Astrobee, possibly suffering minor injuries. **Will pursue equivalent-safety NCR.**
Window	Marginal ***but*** request continuing PSRP involvement	No window damage in collisions below 75 cm/s; force remains below crew pushoff load. At faster speeds, scratch pane may fracture, but: • Polycarbonate film excludes glass from crew cabin • Neither pressure pane is at risk
ISS Structure	Marginal	**Pending approval by ISS structures experts, based on force data from bumper collision test rig.** Basic intuition is robot is too light, slow, and soft to damage structure.
Projecting Hardware	Marginal	Projecting hardware should already be robust to crew pushoff loads, is typically mounted on compliant structure such as a Bogen arm (reducing peak force), and is typically ORU / non-critical-path

Agenda

Time	Duration	Presenter	Topic
8:30	0:30	Terry, Chris	Welcome/Intro
9:00	1:30	Trey, Team Leads	Design
10:30	0:15		*Break*
10:45	1:15	Team Leads	Design
12:00	0:45		*Lunch*
12:45	0:30		*Demo*
13:15	1:15	Team Leads	Design
14:30	0:15		*Break*
14:45	0:30	Trey	Systems Engineering
15:15	0:30	Jonathan	Integration & Test
15:45	0:30	Ernie	Safety
16:15	0:15	Chris	Project Management
16:30	0:15	Maria	Operations
16:45	0:15	Chris	Conclusion

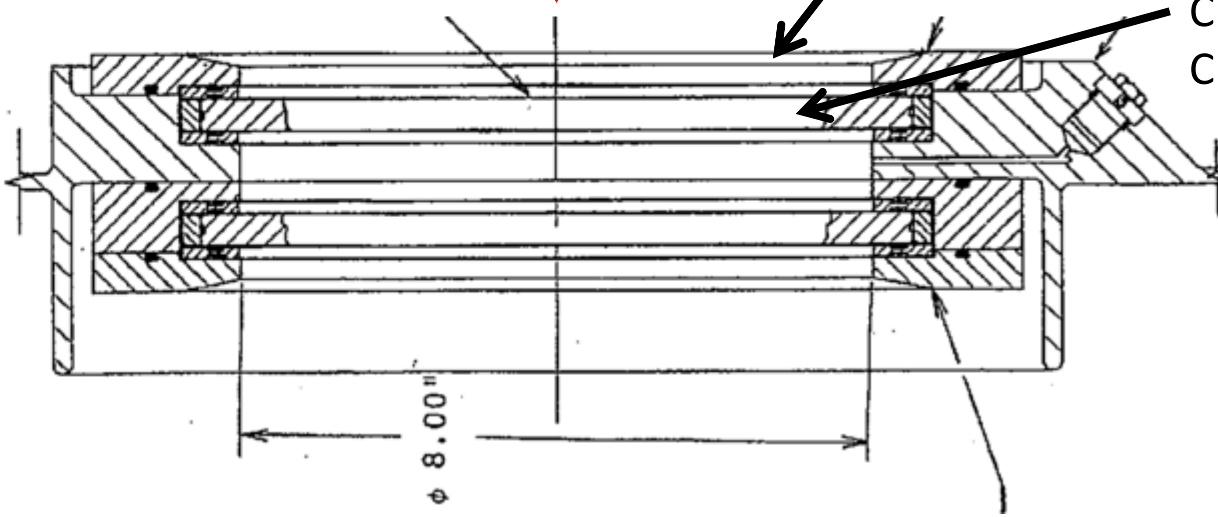
BACKUP SLIDES

JEM Airlock Hatch Window Structure

Inboard polycarbonate protective cover.
Designed for 187.5 lbf load
PG3-0139 Control 1

Approach path

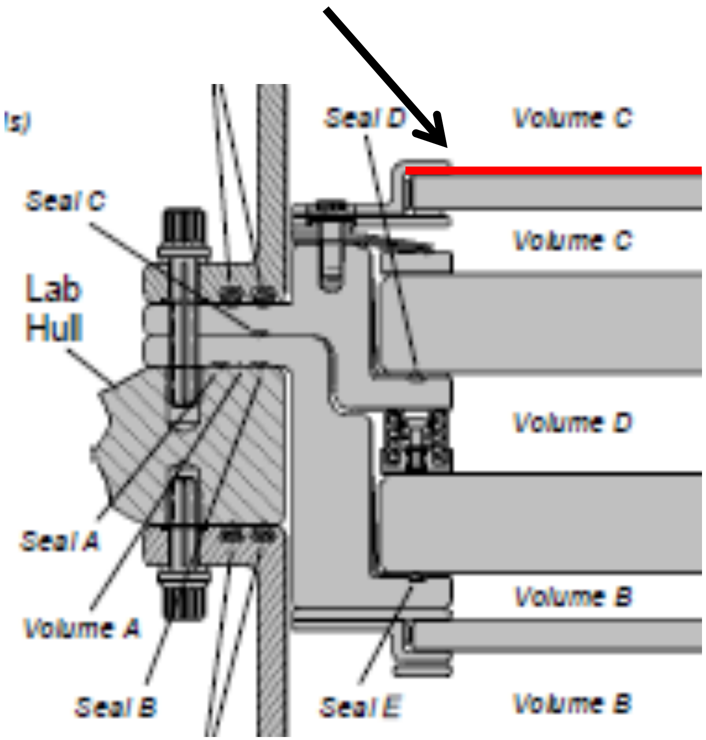
0.4” thick
CHEMCOR (Lithium silicate)
Chemically tempered glass



We can focus impact analysis on the bulkhead windows, because hatch windows are less vulnerable. They are (1) protected by a cover, (2) made of tempered glass, (3) smaller.

Bulkhead Window Collision Consequences

Thin polycarbonate film



- (This is based on common sense rather than rigorous engineering analysis.)
- At the relevant impact energy, main concern is scratch pane structural failure
  - At speeds below 75 cm/s, Astrobee bumpers are designed to keep peak force below 125 lbf, which is the rated/tested max force the scratch pane can withstand without damage
  - At speeds between 75 cm/s and 2.1 m/s, the scratch pane may fracture, but further damage, such as puncturing the polycarbonate film, or damaging a pressure pane, is viewed as extremely unlikely
- If scratch pane fractures, polycarbonate film will prevent fragments from entering the crew cabin: no risk to crew
- This leads to “marginal” hazard classification

New Hazard Definitions

- **4.2 HAZARD LEVELS**
  - Hazards are classified according to potential as follows:
    - **4.2.1 MARGINAL HAZARD**
      - Any condition which may cause **damage to an ISS element in a non-critical path or minor crew discomfort** that does not require medical intervention from a second crewmember, and/or consultation with a Flight Surgeon.
    - **4.2.2 CRITICAL HAZARD**
      - Any condition which may cause a non-disabling personnel injury or illness, loss of a major ISS element, loss of redundancy (i.e. with only a single hazard control remaining) for on-orbit life sustaining function, or loss of use of the SSRMS.
    - **4.2.3 CATASTROPHIC HAZARDS**
      - Any condition which may cause a disabling or fatal personnel injury or one of the following: loss of ISS, loss of a crew-carrying vehicle, or loss of a major ground facility.
- **[From DCN4 of SSP 51700]**

Different Types of Glass Fracture

<u>Sharp object / thick glass</u>

"Gravel on the windshield"

Stresses localized

Surface scratched, chipped, or punctured

<u>Blunt object / thin glass</u>

"Structural failure"

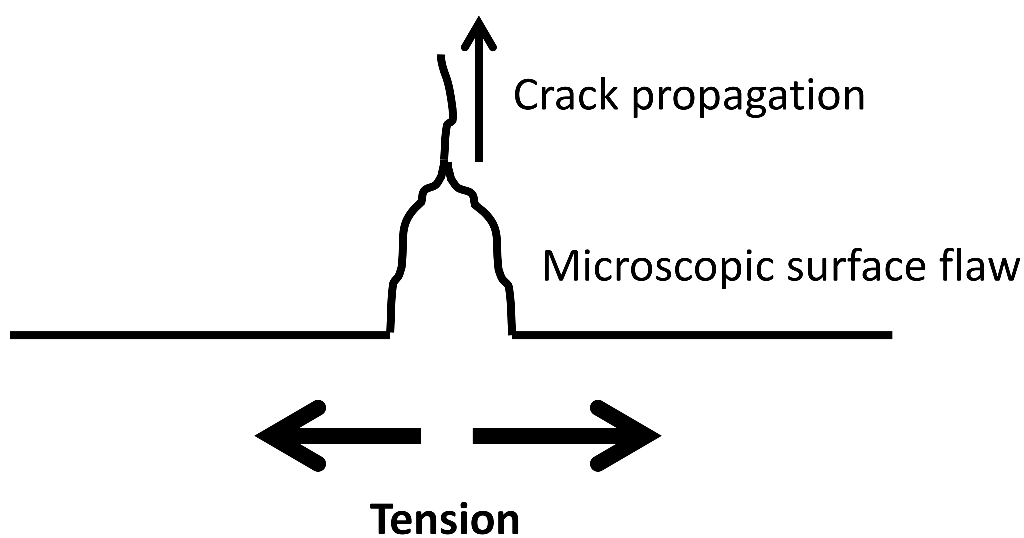
Stresses distributed broadly across pane

Glass deflects like a beam, then breaks

(This is our main concern – Astrobee is a blunt object, much softer than glass)

Glass Structural Failure

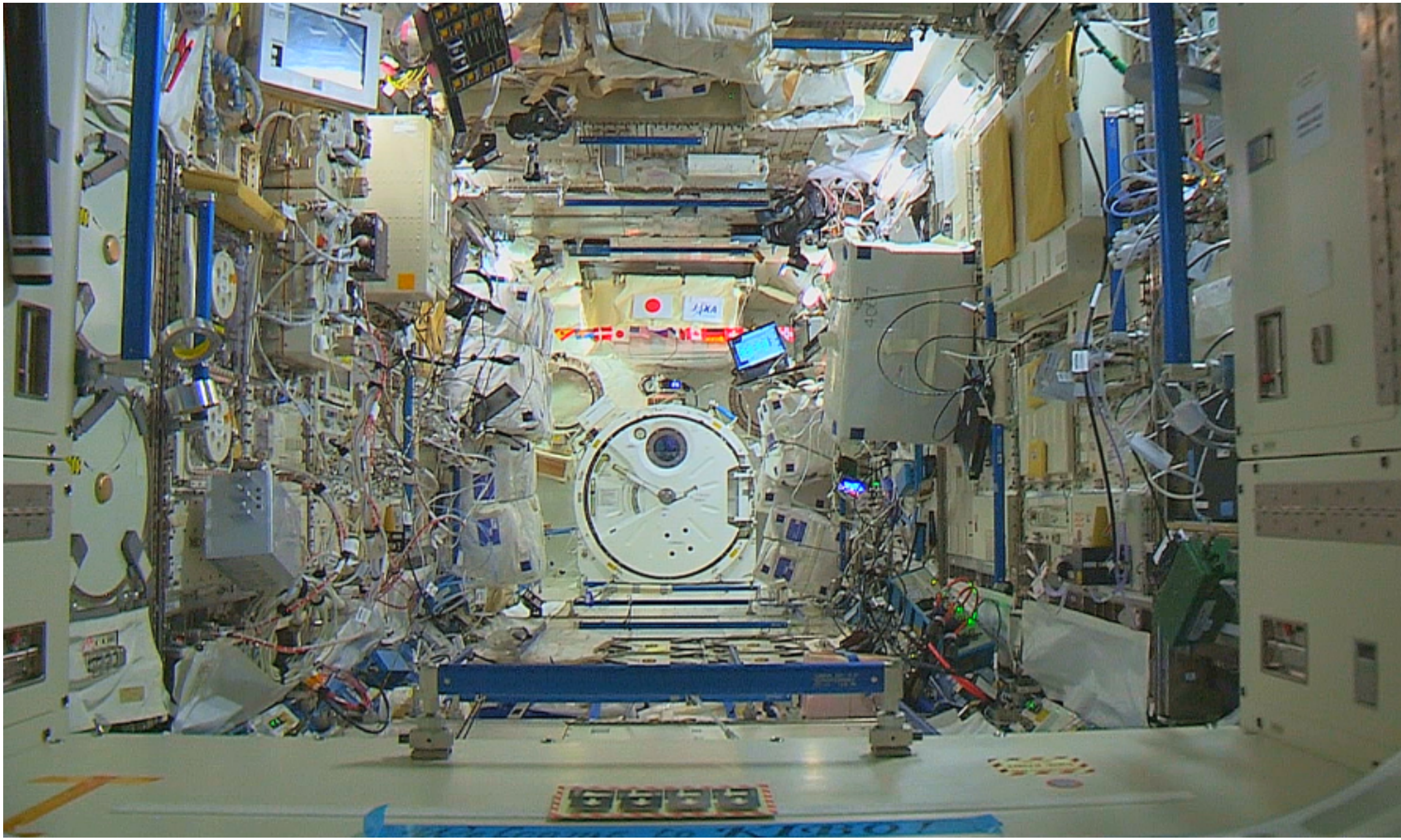
- Glass is much stronger under compression than under tension (several orders of magnitude!)
- Sheet glass structural failure almost always occurs due to microscopic cracks on the surface propagating inward when the glass is under tension



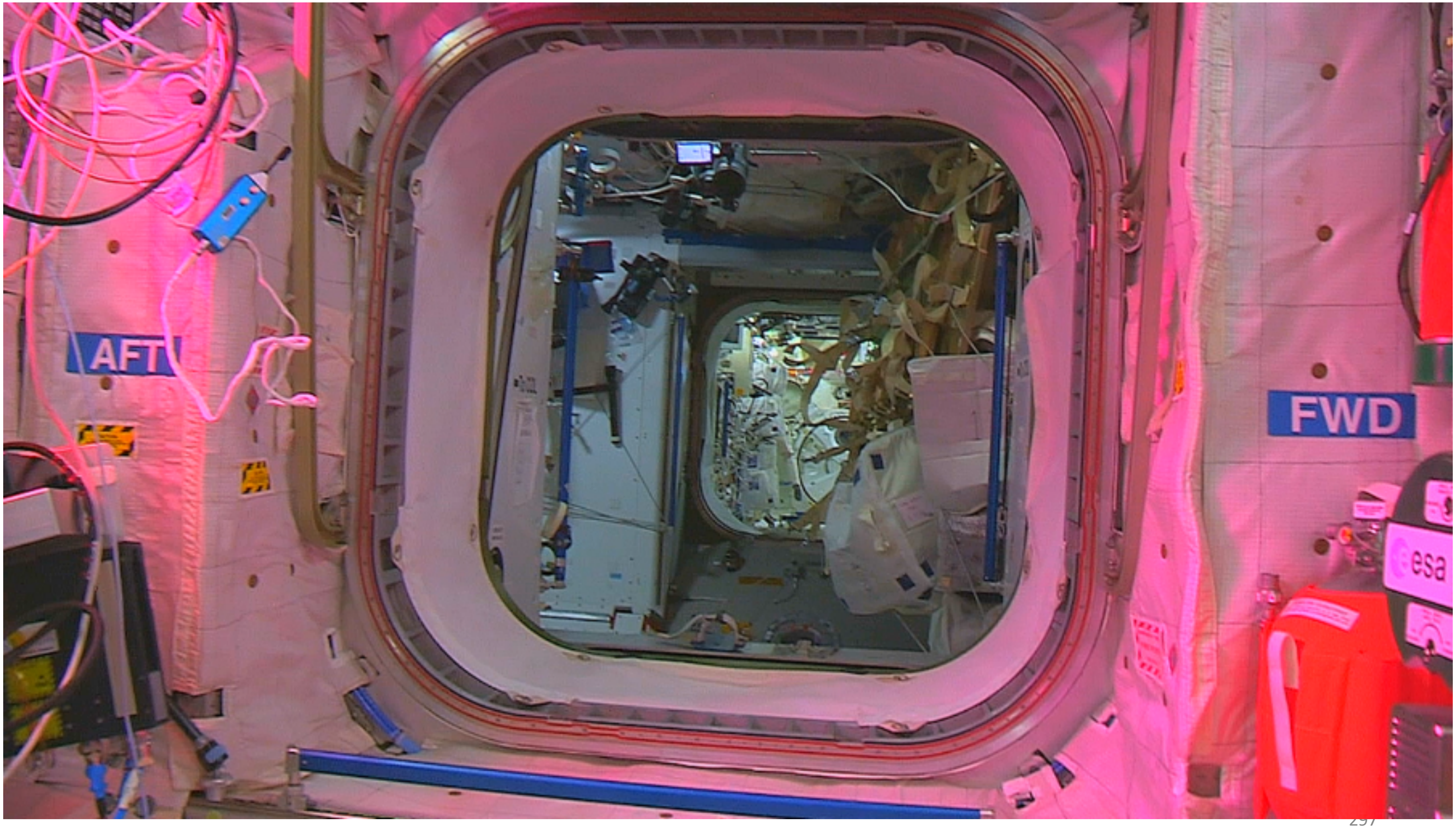
Tensile Strength

- The effective tensile strength of sheet glass depends on the number and size of flaws on the surface
- Different panes of glass in the same batch can have substantially different strength due to random flaws
  - Likelihood of breaking under load often modeled with Weibull distribution
- Mechanical and chemical polishing can reduce the number of flaws
- Effective tensile strength of the glass also depends on:
  - The amount of surface area placed under tension – a larger area is more likely to have a large flaw, thus weaker
  - The duration of the tension – shorter durations leave less time for crack propagation, thus glass is effectively stronger

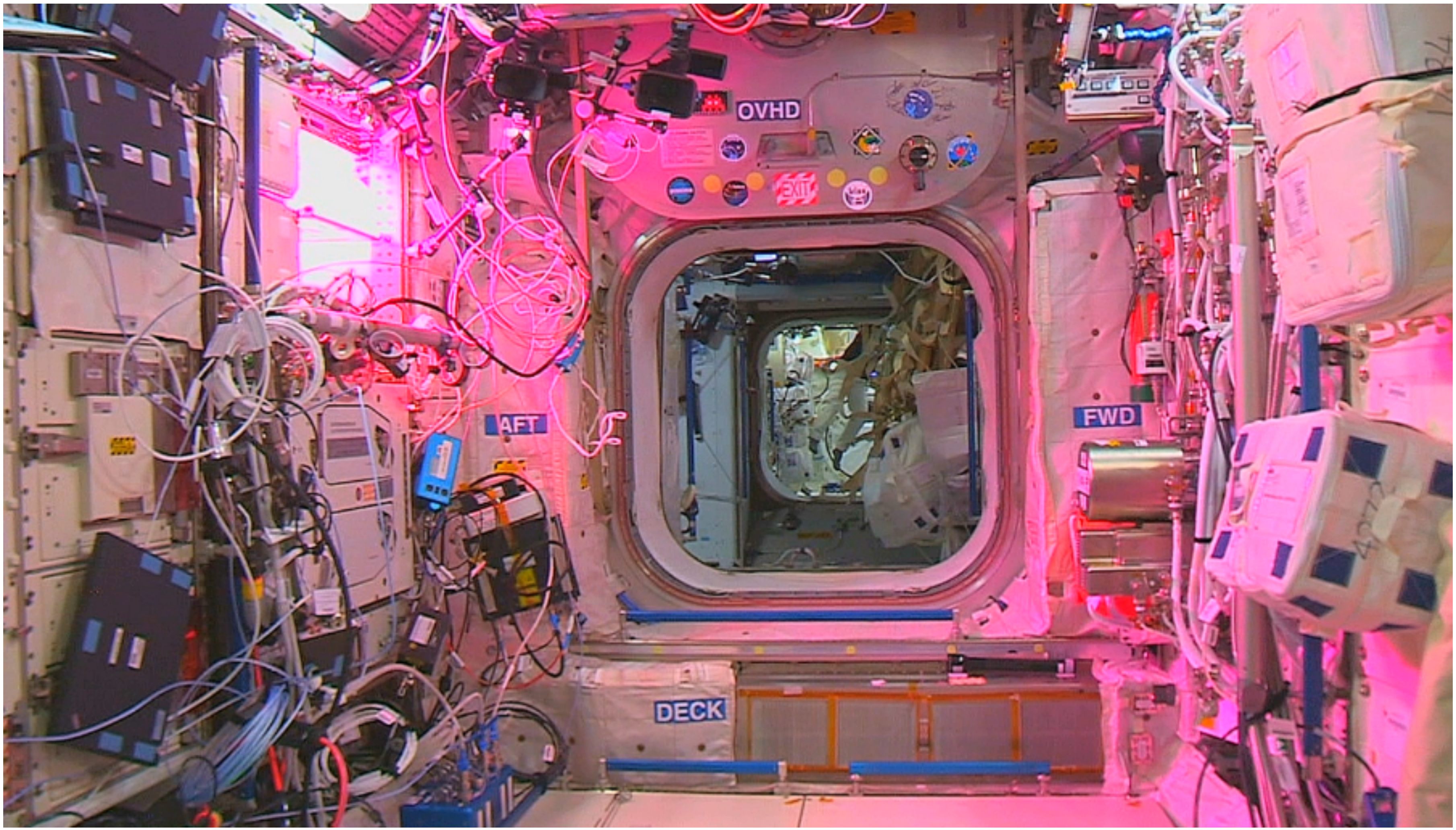
Looking Into JEM From Node 2



From Hatch-End Columbus Module Looking Towards JEM Thru Node 2



From Mid-Columbus Module Looking Towards JEM Thru Node 2



Collision Mitigation Tiers

Tier	Safety critical?	Purpose	Controls
1	No	Ensure that Astrobee will seldom collide with an obstacle at any speed.	• Crew awareness • Automated path validation • Manual path validation • Obstacle avoidance
2	No	Ensure that Astrobee is unlikely to ever collide with an obstacle at speed greater than 75 cm/s.	• Single fault tolerant over-speed propulsion cutoff
3	Yes	Ensure that Astrobee will never endanger critical path ISS functions or crew health.	• Thrust limiting • Foam bumpers

Tier 1 Controls (Non-Safety Critical)

- Crew awareness
  - Crew will be advised when/where Astrobee is flying
    - Activities will be scheduled using timelines, covered in daily briefings, announced by Capcom
  - Astrobee flight plans will avoid high-traffic areas with poor visibility
    - Prefer to operate in wide open spaces and “dead end” modules like Columbus/JEM when possible
    - Avoid areas where crew is moving around a lot, e.g. cargo transfer ops
  - Astrobee will use signal lights and speakers to notify crew that it is present
    - Details TBD; consulting with crew office, balance with minimizing crew annoyance
- Automated path validation
  - Control station has list of keepout zones such as known obstacles, areas with high disturbance air flow, areas with sensitive equipment, etc.
  - Automatic validation checks that path maintains sufficient distance from keepouts
- Manual path validation
  - Control station provides visualization of planned path in 3D model of ISS prior to execution
  - Operator can validate path based on their situation awareness about ISS environment
- Obstacle avoidance
  - Astrobee can detect unknown obstacles ahead with its HazCam
  - The robot will stop and wait for operator assistance to continue

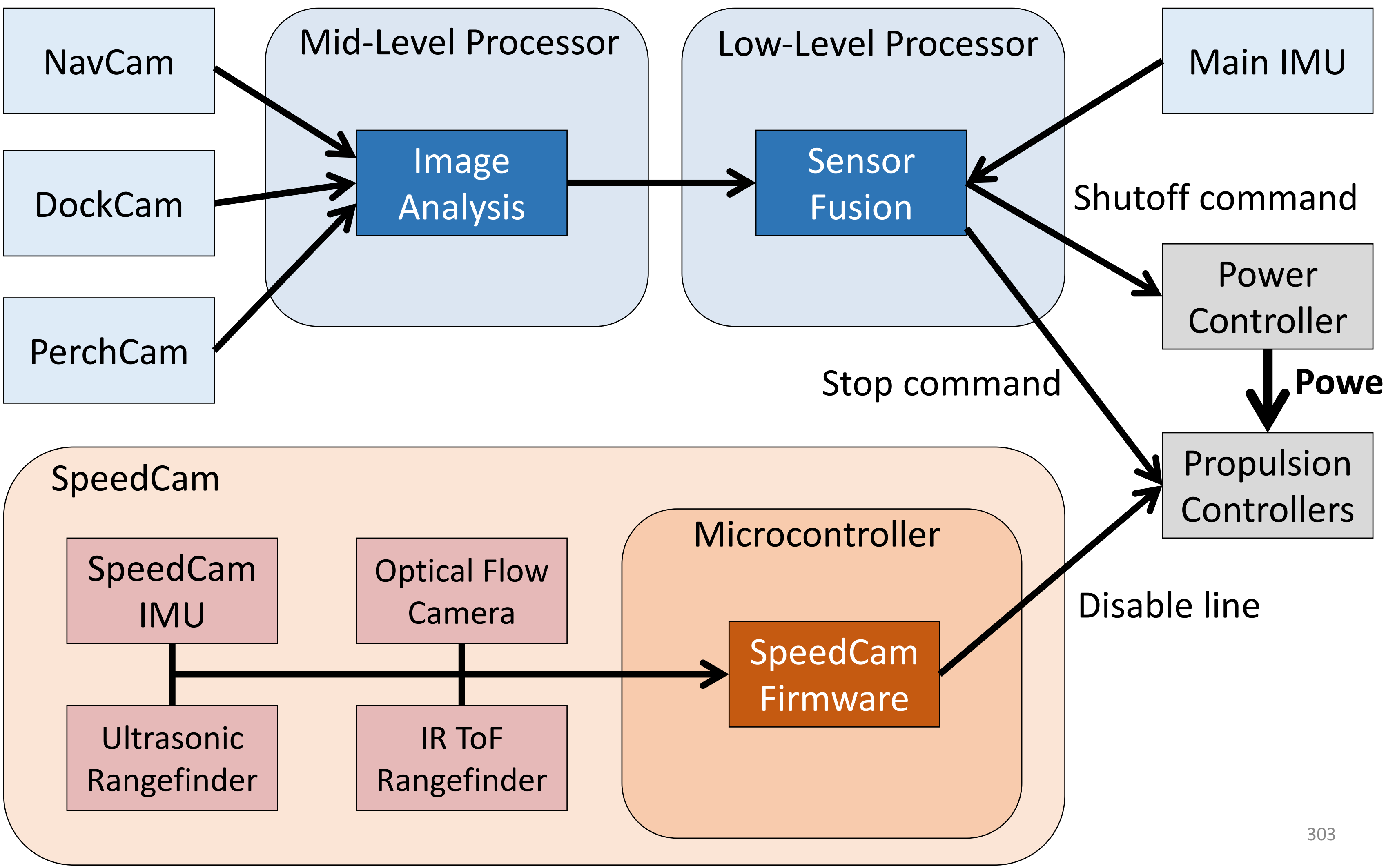
Tier 2 Controls (Non-Safety Critical)

- Single fault tolerant over-speed cutoff
  - Two independent over-speed cutoffs
    - Primary pose estimator running on Low-Level Processor
    - Dedicated velocity estimator running in SpeedCam firmware
  - Each can independently shut off propulsion
  - Both estimate speed using robust approach
    - Take into account history of previous samples
    - Track both the speed estimate and confidence/accuracy
  - Tiered response:
    - If speed estimate confidence is too low, or there is a "mild over-speed" condition (~50-75 cm/s), command a stop and signal an error to the operator.
      - This response will be somewhat configurable, with caution, in case certain guest science experiments interfere with accurate speed sensing.
      - Example: Might disable this response, but add ops controls such as requiring crew supervision.
    - If speed exceeds 75 cm/s, shut off propulsion.
      - This response will not be configurable.

Tier 3 Controls (Safety Critical)

- Thrust limiting
  - Stakeholders require 10 cm/s^2 acceleration
  - Design propulsion hardware to ensure thrust can’t go more than 20% above that
  - Limits maximum impact energy
- Foam bumpers
  - Foam bumpers on propulsion modules; impact-damping material similar to athletic knee pads
    - Foam bounces back after impact and can be reused
  - Rigid hardware is recessed behind bumpers so it doesn’t contact obstacle in a collision

Over-Speed Cutoff Approach



Over-Speed Cutoff Verification

- Test each of the cutoff systems independently (by disabling the other cutoff system)
- Use gantry testing facility, accelerate to over-speed condition
- Verify propulsion module is shut off as intended

Thrust Limiting Approach

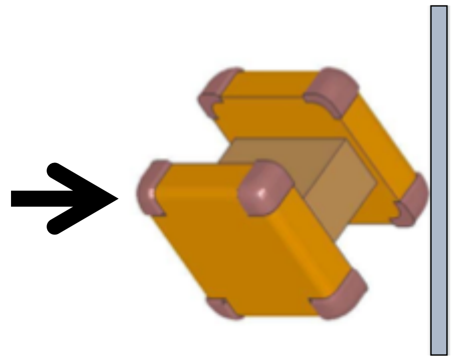
- Impeller motor controller firmware (COTS, proprietary) controls thrust of each prop module
  - During integration, set impeller motor controller max RPM rate
    - Configures what impeller RPM rate is implied by the max PWM command from our software
  - Flight software can't accidentally reconfigure the controller on-orbit; that would require connecting a laptop to a debug port
  - Assuming motor controller behaves correctly, there is no way for our software to command excessive RPM rates
- Off-axis thruster geometry provides redundant limit
  - If a single propulsion module somehow goes over the thrust limit, due to off-axis thrusters, the robot will fly in circles
  - To follow a straight path at higher acceleration, ***both*** propulsion modules would need to malfunction simultaneously

Thrust Limiting Verification

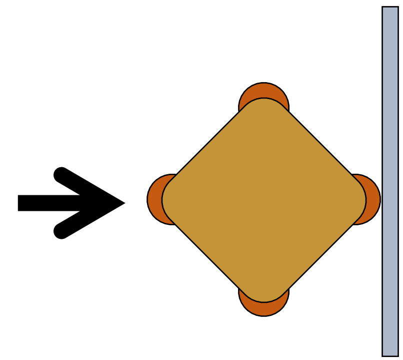
- Test worst-case commands
  - Max PWM command to impeller motor controller
  - Nozzles controls set to maximize thrust
  - Verify thrust is below limit

Collision Geometry

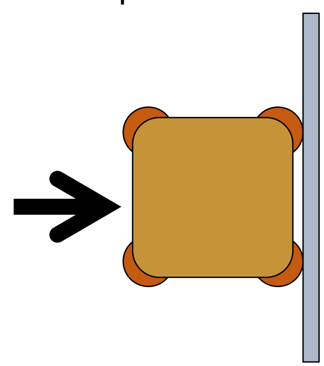
- Bumper design aims to keep force below 125 lbf limit in a 75 cm/s collision
  - Limit derived from scratch pane load limit: scratch panes were tested under simulated crew pushoff load
- Bumper stiffness optimized to minimize peak force at 75 cm/s
  - Bumpers will bottom out in higher-speed collisions, less effective
  - But they still absorb some impact energy and spread load over a wider contact area
- Can focus design/testing on extreme collision cases 1-3 (shown at right)
  - Bumpers need to be stiff enough to avoid bottoming out in case 1 (highest pressure)
  - Bumpers need to be soft enough to keep total force low in case 3 (highest contact area)
- Typical impact is less challenging than extreme cases, because force is distributed across multiple bumpers that strike at different times, keeping the peak total force lower



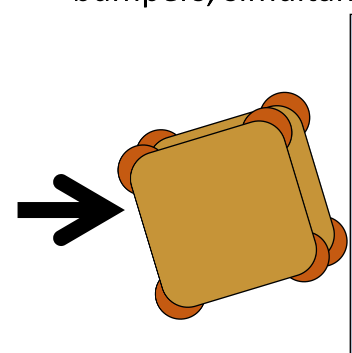
1. Perfect corner impact: All load on 1 bumper



2. Perfect edge impact: Load evenly distributed over 2 bumpers, simultaneous

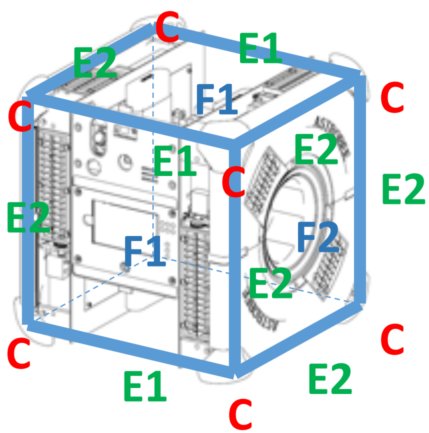


3. Perfect face impact: Load evenly distributed over 4 bumpers, simultaneous



Typical impact: Load unevenly distributed over 4 bumpers, non-simultaneous

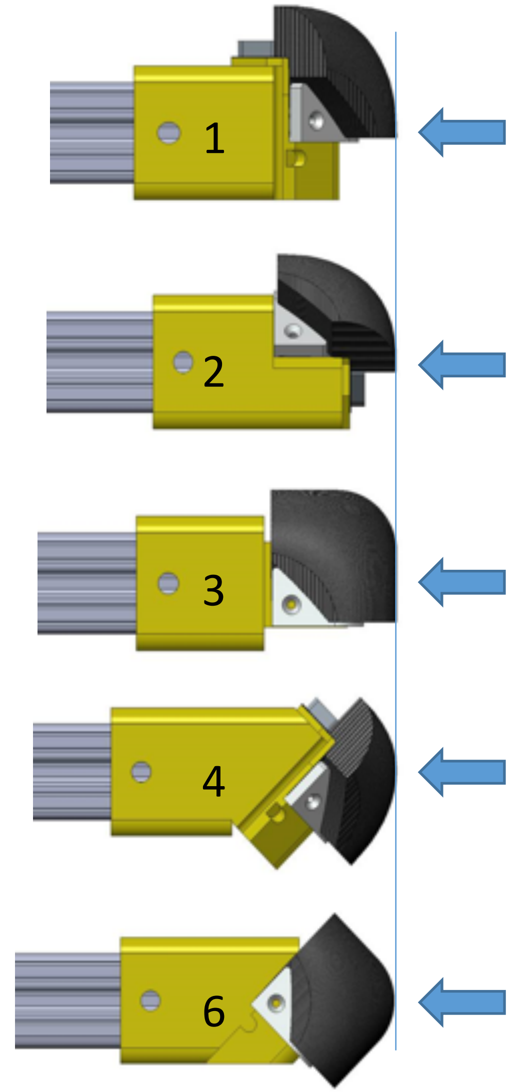
COLLISION TESTING



Due to non-symmetry of bumper ribbing, not all impact directions are equal.

Impact	I.D.	Mass	Bumper Test No.
Corner	C	1M	4
Core Edge	E1	½ M	1
Prop Edge	E2	½ M	6
Core Face	F1	¼ M	3
Prop Face	F2	¼ M	2

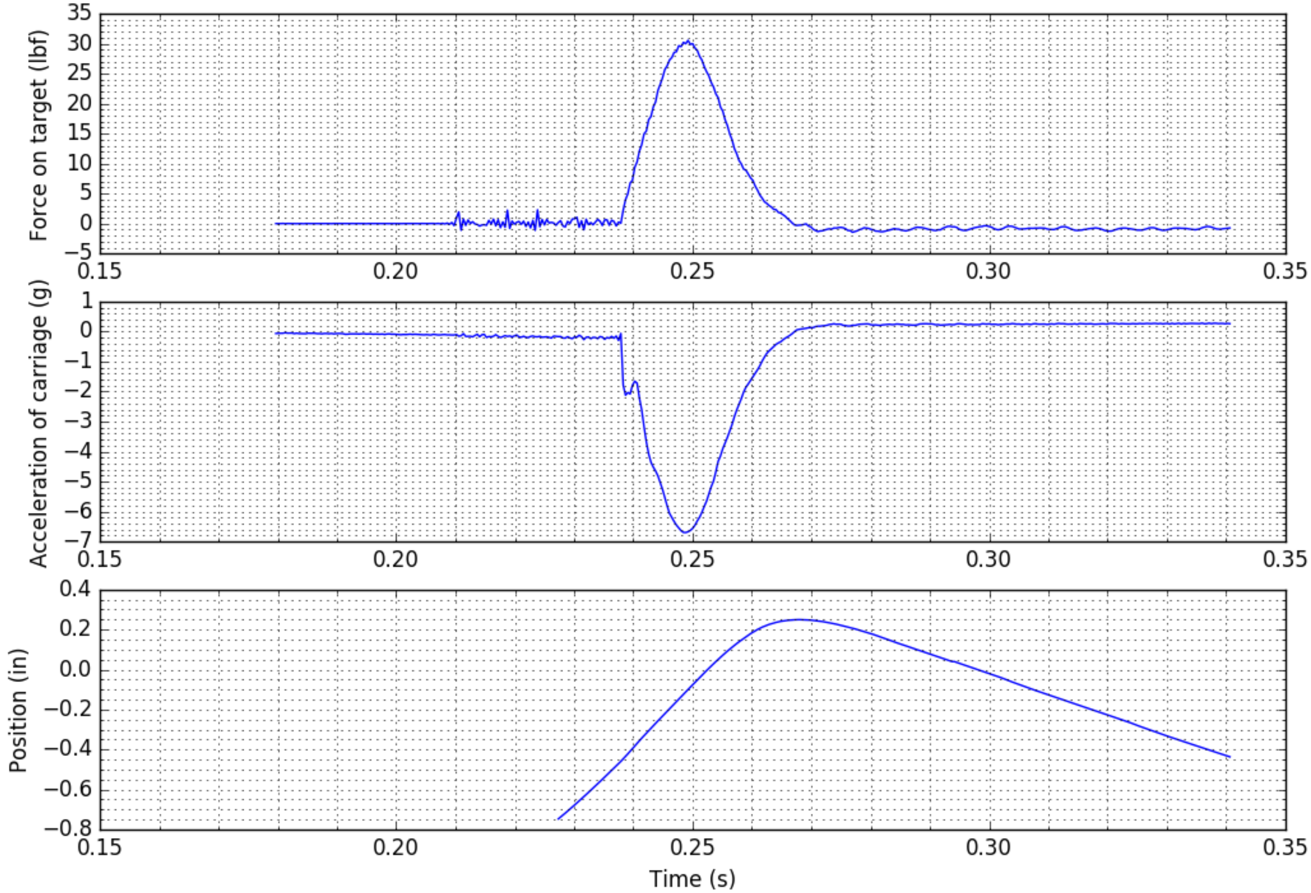
Bumper Test No.



Collision Testing Status

- Initially tested ribbed bumper 3D printed in rubber material (“Tango”), selected for quick prototyping turnaround
- First Tango test results at 75 cm/s show peak force under or close to crew pushoff limit for all collision cases
  - Actual ARTiLAGE material has 1.4x lower Young’s modulus than Tango, so forces are expected to be lower (under limit)
- We just received our first molded ARTiLAGE bumpers from the vendor
  - Gearing up for collision testing over the next 1-2 weeks
  - New tests will include runs at 2.1 m/s – ideally, the force measurements from this test will allow us to classify the high-speed structure collision risk as “marginal”

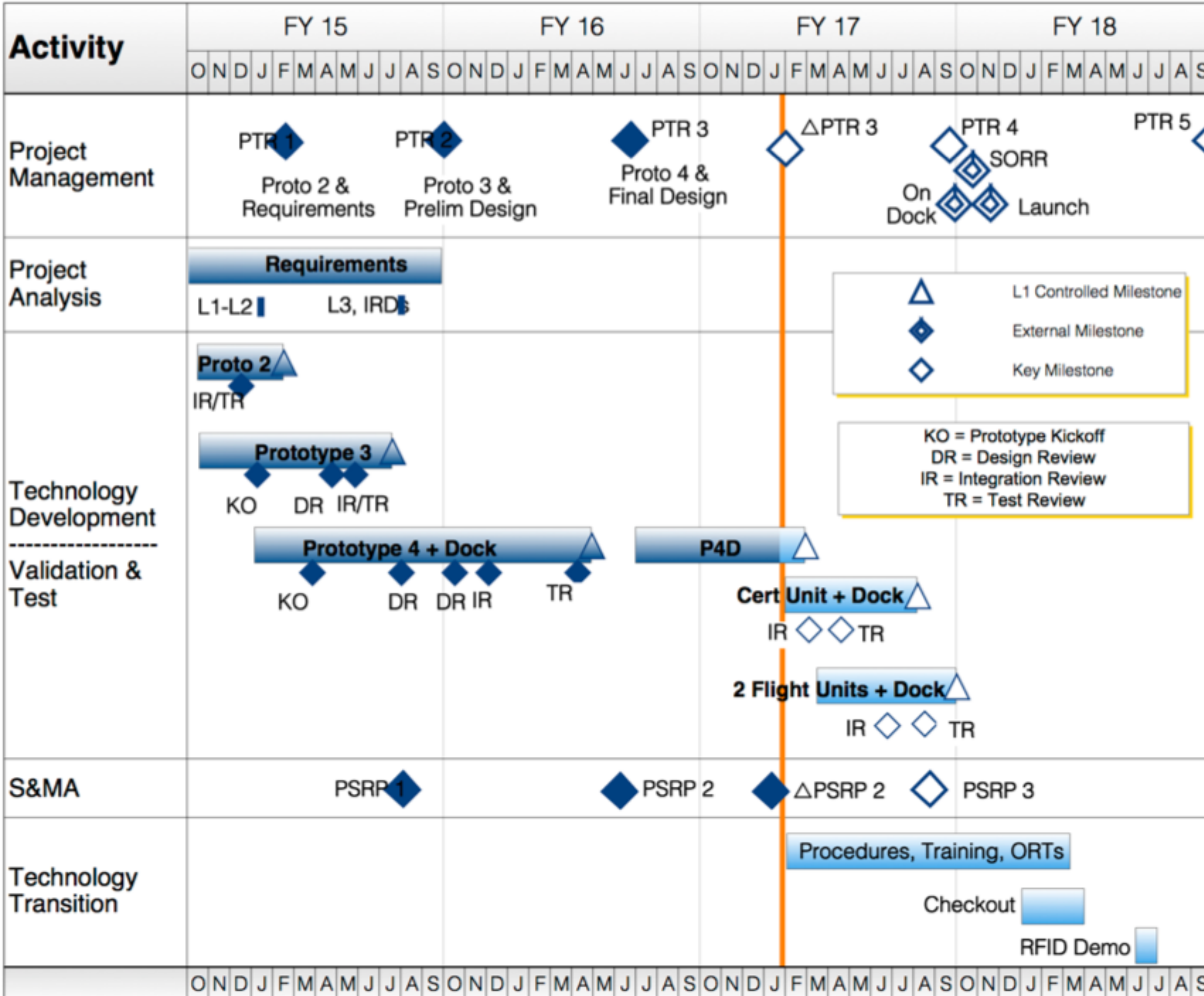
Sample Collision Data*



* The setup from this test is not finalized/correct for requirements verification, just provided as a reference example. Run 24: Tango bumper, collision case 3, ~75 cm/s impact velocity.

Astrobee Project Management

Schedule, Budget, Top Risks


Activity
FY 15
FY 16
FY 17
FY 18
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
Project Management
PTR 1
Proto 2 & Requirements
PTR 2
Proto 3 & Prelim Design
PTR 3
Proto 4 & Final Design
△PTR 3
PTR 4
SORR
On Dock
Launch
PTR 5
Project Analysis
Requirements
L1-L2
L3, IRDs
L1 Controlled Milestone
External Milestone
Key Milestone
Technology Development
Validation & Test
Proto 2
IR/TR
Prototype 3
KO
DR
IR/TR
KO = Prototype Kickoff
DR = Design Review
IR = Integration Review
TR = Test Review
Prototype 4 + Dock
KO
DR
DR
IR
TR
P4D
Cert Unit + Dock
IR
TR
2 Flight Units + Dock
IR
TR
S&MA
PSRP 1
PSRP 2
△PSRP 2
PSRP 3
Technology Transition
Procedures, Training, ORTs
Checkout
RFID Demo
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S

Budget

	FY15	FY16	FY17	FY18	Total
FTE	11	12	12	6	41
Procurement ($M)	2.55	3.15	2.95	2.4	11.05

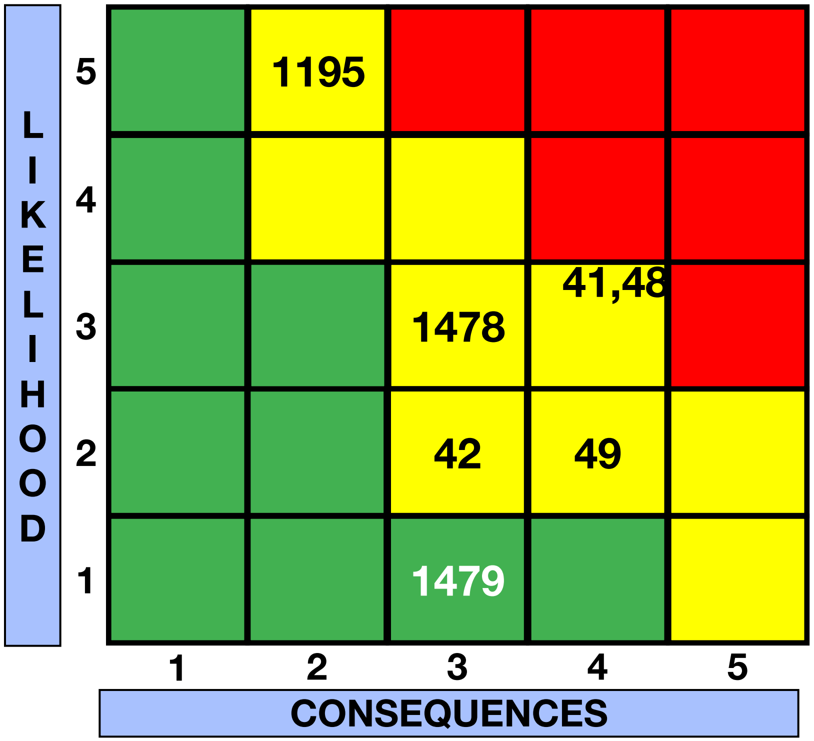
Parts Costs

		Shop Costs (~ 50% CS Labor, 50% Proc)
Free Flyer	**$165,400**	
Structure	***$55,000***	*$45K **
CDH	***$12,500***	
FSW	***-***	
Prop	***$81,000***	*$40K **
EPS	***$6,200***	
GNC	***$1,900***	
Comm	***$300***	
Thermal	***$500***	
Arm	***$8,000***	
Dock	**$50,000**	
Structure	***$44,000***	*$40K **
Avionics	***$6,000***	

** Possibly reduce by 50% by using outside vendors.*
Still assembling quotes.

Material & fab cost only
Assembly costs not included

Top Risks



Criticality

- High
- Med
- Low

Affinity

T - Technical
C - Cost
Sa – Safety
Sc - Schedule

Approach

M - Mitigate
W - Watch
A - Accept
R - Research

Risk ID Trend*	Approach *Affinity*	Risk Name
48	**M** *Sc*	Flight Unit schedule
41	**M** *Sc*	Cert Unit schedule
1195	**M** *T*	Negative mass margin
1478	**R** *C, Sc*	Flight hardware costs & phasing
49	**W** *Sa*	PSRP approval for operations without crew tending
42	**M** *T*	Pose accuracy with vision based navigation
1479	**W** *C, Sc*	QA & QC requirements
1449		*Dock placement not determined*

** Risk numbers not sequential*

Agenda

Time	Duration	Presenter	Topic
8:30	0:30	Terry, Chris	Welcome/Intro
9:00	1:30	Trey, Team Leads	Design
10:30	0:15		*Break*
10:45	1:15	Team Leads	Design
12:00	0:45		*Lunch*
12:45	0:30		*Demo*
13:15	1:15	Team Leads	Design
14:30	0:15		*Break*
14:45	0:30	Trey	Systems Engineering
15:15	0:30	Jonathan	Integration & Test
15:45	0:30	Ernie	Safety
16:15	0:15	Chris	Project Management
16:30	0:15	Maria	Operations
16:45	0:15	Chris	Conclusion

Operations

Technology Transition Plans

Level 1 Requirements to be Verified on ISS

- Remote control (FFREQ-75)
- Sensor surveys (FFREQ-77)
- Autonomous resupply (FFREQ-80)
- Store science data (FFREQ-81)
- 0g research capabilities (FFREQ-82)
- Host payloads (FFREQ-83)
- Compatible with ISS crew (FFREQ-84)
- Software upgrades (FFREQ-87)
- Stream/record high quality video (FFREQ-89)
- Multi free flyer operations (FFREQ-90)

Success Criteria

Minimum Success Criteria	Full Success Criteria
ISS Demonstration of: • Ground control • JEM/Node 2/US Lab map • Software upgrade • Hazard detection • Dock/undock • Streamed video • Payload & Guest Science (GS) operations	ISS demonstration of: • Crew control • USOS map • Signal lights • Perch/unperch • Multi-robot operations • Mobile camera operations
Handover of all deliverables	Completion of all transfer activities within FY18

Activity Task Sequence

- Crew Training
- Ground Training
- Crew Procedures
- Ground Procedures
- Operational Readiness Test
- On-orbit Operations

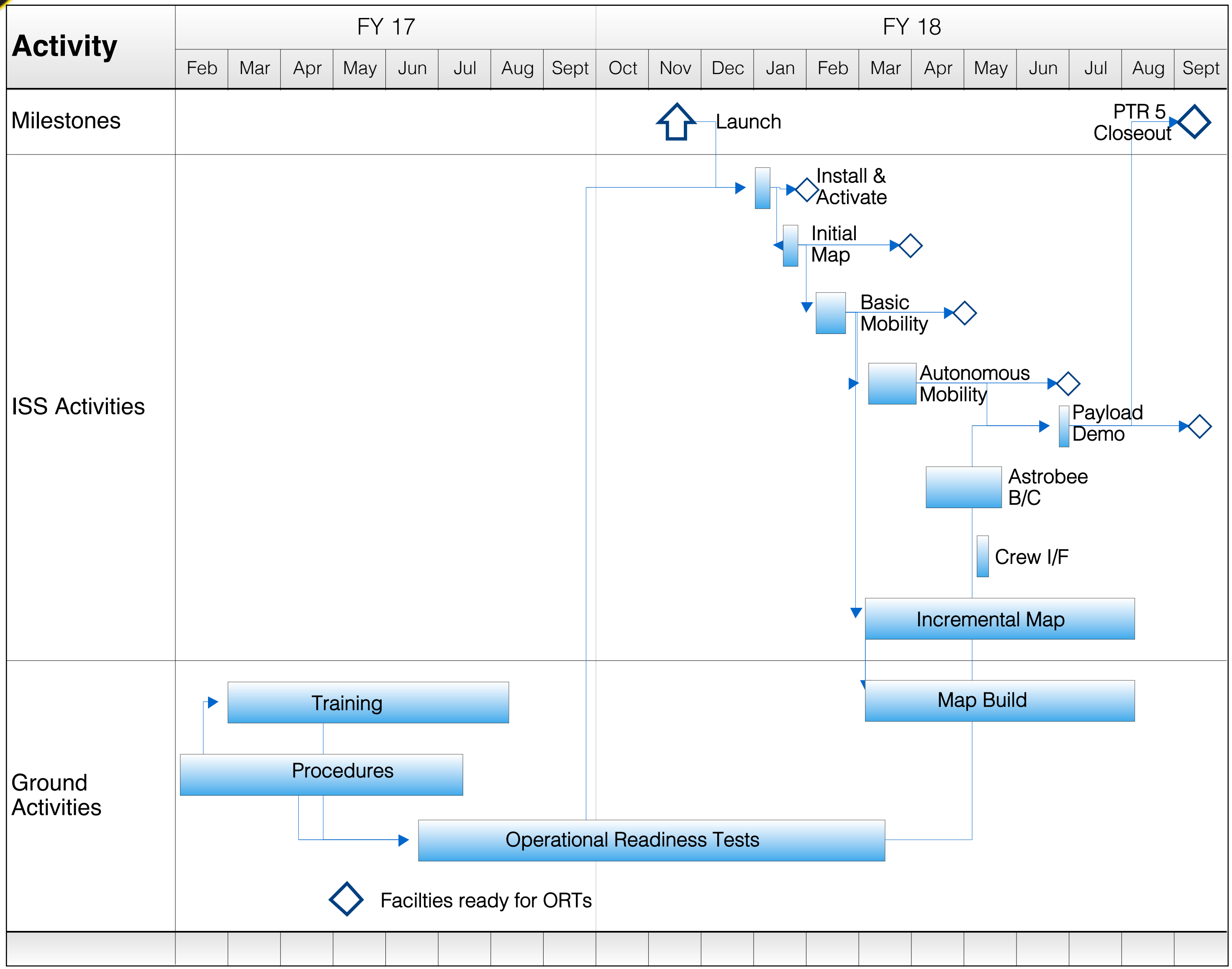
ISS Activities

- Installation
- Comm Checks (Store science data, Software upgrades, High quality video)
- Component Checkouts
- Initial Mapping
- Basic Mobility (Remote control)
- Autonomous Mobility (Autonomous resupply)
- Crew Interface Checkout (Compatible with ISS crew)
- Incremental Mapping
- Astrobee “B” and “C” Commissioning
- Demonstration (Sensor surveys, 0g research capabilities, Host payloads)

Handover Success Criteria

Deliverable	Success Criteria	Artifact	Responsibility
Astrobee Hardware	Verification of requirements & KPPs	Successfully executed procedures	I&T
Astrobee Simulation	Validation that sim is accurate to flight performance	Sim vs. Flight analysis report	Ops
Flight Software	Verification of requirements & KPPs	Successfully executed procedures	I&T
Ground Software	Verification of requirements	Successfully executed procedures	I&T
Documentation	Reviewed at final PTR by SPHERES PM	Signature sheet	PM
Astrobee Final Report	Validation of flight performance	Final report	PM

Commissioning Schedule



Risks

- Assumes hardware on dock and launches on time
- Crew time required for first several activities
  - Mitigation: significant schedule margin
- REALM required for payload demo (minimum success criteria)
  - Mitigation: SPHERES will develop its own test payload
- Success-based planning (no crew) for advanced mobility checkout and incremental mapping; may need crew to “rescue” us
  - Mitigation: activities will be structured to minimize the risk that crew will be needed

Agenda

Time	Duration	Presenter	Topic
8:30	0:30	Terry, Chris	Welcome/Intro
9:00	1:30	Trey, Team Leads	Design
10:30	0:15		*Break*
10:45	1:15	Team Leads	Design
12:00	0:45		*Lunch*
12:45	0:30		*Demo*
13:15	1:15	Team Leads	Design
14:30	0:15		*Break*
14:45	0:30	Trey	Systems Engineering
15:15	0:30	Jonathan	Integration & Test
15:45	0:30	Ernie	Safety
16:15	0:15	Chris	Project Management
16:30	0:15	Maria	Operations
16:45	0:15	Chris	Conclusion

Astrobee

Delta PTR 3 Closing

PTR schedule

- Feb 1 – Delta PTR 3
- Feb 1 – Release technical data package for review
- Feb 15 – Comments due
- Mar 1 – Triage comments for impact to design and Cert Unit procurements
- Mar 15 – Disposition all comments, update documents/technical baseline

Forward Work

- Astrobee Design
  - Open work described in Design Overview documents
  - Design mods from Prototype 4D testing (if any)
- SPHERES: Continue technology transition
- REALM: Continue payload integration, API development
- Cert/Flight Unit builds

Success Criteria

Success Criteria	Compliance Approach	Mapped Products
The detailed design is expected to meet the requirements with adequate margins at an acceptable level of risk.	• Requirements trace to components in the subsystem architectures. • Review completed design. • **Technical risks identified.**	• IRG-FF006 requirements • IRG-FF017 Astrobee Design Overview • Astrobee Risk Register
Interface control documents are sufficiently mature to proceed with fabrication, assembly, integration, and test	• Hardware interfaces in requirements documents & CAD models • Software ICD's documented • Astrobee IRB baselined	• IRG-FF006 System Requirements • A9SP- and IRG-FFDW- drawings • IRG-FF025 GNC ICD • IRG-FF026 Comm ICD
The element cost and schedule, are credible and within GCD/HET 2 constraints.	• HET Project Plan updated via GCD CR process. • **Cost & schedule risks identified in risk register.**	• HET-2 Project Plan • IRG-FF001 Astrobee PM Plan • Astrobee IMS • Astrobee Risk Register

Success Criteria

Success Criteria	Compliance Approach	Mapped Products
High confidence exists in the product baseline, and adequate documentation exists to allow proceeding with fabrication, assembly, integration, and test.	• Subsystem requirements trace to components in the subsystem architectures. • Technical risks identified. • Build-to based on procedures and drawings.	• IRG-FF006 L3 requirements • IRG-FF017 Astrobee Design Overview • Astrobee Risk Register • IRG-FFDW and A9SP
The product V&V requirements and plans are complete.	• Develop VM and verification description for each req.	• IRG-FF006 requirements • IRG-FF007 I&T Plan
The testing approach is comprehensive, and the planning for system assembly, integration, test, and launch site and mission operations is sufficient to progress into the next phase.	• I&T procedures drafted and practiced with Prototype 4.	• IRG-FFTEST-XXX Integration, Checkout & Test Procedures

Success Criteria

Success Criteria	Compliance Approach	Mapped Products
Adequate technical margins exist.	• Identify technical performance measures that support Astrobee KPPs and key requirements. • Margins listed for major milestones. • **Risk opened for negative margin.**	• IRG-FF002-02 Astrobee TPMs • Astrobee Risk Register
Risks to mission success are understood and credibly assessed, and plans and resources exist to effectively manage them.	• Risks identified and action plans formulated. • Top risks elevated to HET-2 and GCD.	• Astrobee Risk Register • GCD Quarterly Reports

Success Criteria

Success Criteria	Compliance Approach	Mapped Products
SMA has been adequately addressed in system and operational designs, and is at the appropriate maturity level for this phase of the life cycle.	• Compliance with safety requirements and PSRP processes. • SMA Plan based on customer agreement with Code QS.	• IRG-FF018 Astrobee Safety Data Package • Astrobee Standard & Unique Hazards • IRG-FF003 SMA Plan
The operational concept has matured, is at the appropriate level of detail, and has been considered in test planning.	• Detailed conops and functional flows developed to resolve system & subsystem requirements and interactions • Develop Ops Con with POIC	• IRG-FF009 Astrobee ConOps • IRG-FFB-XXX Functional Blocks

Success Criteria

Success Criteria	Compliance Approach	Mapped Products
Engineering prototypes have been developed and tested per plan.	• Iterative design, development and testing on multiple prototypes.	• IRG-FF001 Astrobee PM Plan • Astrobee IMS
The element has demonstrated an appropriate implementation of ISS, Ames and NASA requirements, standards, processes, and procedures.	• Compliance with ISS/JSC/MSFC processes for ISS payloads. • Compliance with ISS launch and on-orbit requirements for ISS payloads. • PM and SE practices leveraged from NPR/APR/Handbooks.	• Astrobee Payload Integration Agreement. • Astrobee IRB • IRGFFRP-003 PTR3 data package, which includes all Astrobee planning documents.
Open items/issues are clearly identified with acceptable plans and schedule for their disposition.	• Open design identified. • Forward work captured in these charts. • CR comments in consolidated form.	• JIRA “Astrobee-TBD” filter • IRGFFRP-003D PTR3D data package • CR007

Closing Remarks