<table>
<thead>
<tr>
<th>Time</th>
<th>Duration</th>
<th>Presenter</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30</td>
<td>0:30</td>
<td>Terry, Chris</td>
<td>Welcome/Intro</td>
</tr>
<tr>
<td>9:00</td>
<td>1:30</td>
<td>Trey, Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>10:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>10:45</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>12:00</td>
<td>0:45</td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>12:45</td>
<td>0:30</td>
<td></td>
<td>Demo</td>
</tr>
<tr>
<td>13:15</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>14:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>14:45</td>
<td>0:30</td>
<td>Trey</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>15:15</td>
<td>0:30</td>
<td>Jonathan</td>
<td>Integration &amp; Test</td>
</tr>
<tr>
<td>15:45</td>
<td>0:30</td>
<td>Ernie</td>
<td>Safety</td>
</tr>
<tr>
<td>16:15</td>
<td>0:15</td>
<td>Chris</td>
<td>Project Management</td>
</tr>
<tr>
<td>16:30</td>
<td>0:15</td>
<td>Maria</td>
<td>Operations</td>
</tr>
<tr>
<td>16:45</td>
<td>0:15</td>
<td>Chris</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>
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
  • Astrobeen 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, Astrobot will:
  • Complete design for flight (any open items)
  • Complete Prototype 4D testing
  • Proceed with Certification Unit procurements
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 Astrobot Design Document with a design overview (to subsystem level) that can be shown to meet requirements and key technical performance measures
- Astrobot 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 Astrobe is should move into the next lifecycle phase

• Please keep in mind...
  • Astrobe is an **element** within the HET2 **project**
  • PTR objectives
  • Astrobe is 7120.8 (Research & Technology) with ISS certs
  • Astrobe 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

HET-2 Project
Terry Fong (ARC)
Maria Bualat (ARC)

Astrobee Element
Chris Provencher (ARC)

SMA
Ernie Smith (ARC)

Teams
Mechanical, Avionics, Comm, FSW, GN&C, Prop, Thermal, GDS ARC/JPL

Robotics Engineering
Trey Smith (ARC)

Integration & Test
Jonathan Barlow (ARC)
ARC
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, OSSl 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)
Og Robotics Research Facility

AES, SPHERES Program, Researchers
Mobile Camera Tasks

ISS Program, FOD, POIC
Mobile Sensor Tasks

ISS Program, FOD, POIC
Dock & Resupply
<table>
<thead>
<tr>
<th>Time</th>
<th>Duration</th>
<th>Presenter</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30</td>
<td>0:30</td>
<td>Terry, Chris</td>
<td>Welcome/Intro</td>
</tr>
<tr>
<td>9:00</td>
<td>1:30</td>
<td>Trey, Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>10:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>10:45</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>12:00</td>
<td>0:45</td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>12:45</td>
<td>0:30</td>
<td></td>
<td>Demo</td>
</tr>
<tr>
<td>13:15</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>14:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>14:45</td>
<td>0:30</td>
<td>Trey</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>15:15</td>
<td>0:30</td>
<td>Jonathan</td>
<td>Integration &amp; Test</td>
</tr>
<tr>
<td>15:45</td>
<td>0:30</td>
<td>Ernie</td>
<td>Safety</td>
</tr>
<tr>
<td>16:15</td>
<td>0:15</td>
<td>Chris</td>
<td>Project Management</td>
</tr>
<tr>
<td>16:30</td>
<td>0:15</td>
<td>Maria</td>
<td>Operations</td>
</tr>
<tr>
<td>16:45</td>
<td>0:15</td>
<td>Chris</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>
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
System Data Flow Diagram
Current Robot Design

12.5 x 12.5 x 12.5 inches
8 kg mass target

FORWARD
Current Robot Design

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

PTR3, June 2016
- v4
  - Propulsion Module
  - Perching Arm
  - Robot + Central Module

Delta PTR3, Now
- v5
  - [Retrofit v4]
    - Nozzle servos
- v6
  - [Partial build]
    - Hard shell
    - Many updates
- v7
  - [Retrofit v6]
    - Add retention levers

- v5
  - Joint servos
  - Ultem structure
  - Gripper improvements
  - Wire/tendon routing

- v6
  - Metal frame
  - Many updates

- v4
  - PTR3,
  - June 2016
- v5
  - Delta PTR3,
  - Now

P4C
- P4D
Propulsion Module Versions

- **v4**
  - Propulsion Module
  - Nozzle servos

- **v5**
  - Retrofit v4
  - Hard shell
  - Many updates

- **v6**
  - Partial build
Perching Arm Versions

v4
- Joint servos
- Avionics

v5
- Gripper improvements
- Wire/tendon routing

v6
- Ultem structure

v7
- [Retrofit v6]
- Add retention levers
Robot / Central Module Versions

Robot + Central Module

P4C

Metal frame
Many updates

P4D
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

• 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

- 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

Dock Processor (same as LLP)
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
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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal LEDs</td>
<td>High / Low</td>
<td>-</td>
</tr>
<tr>
<td>Light signaling pattern</td>
<td>Med / Low</td>
<td>Follow up with crew office</td>
</tr>
<tr>
<td>Sound signal</td>
<td>Low / Low</td>
<td>Design sound &amp; follow up with crew office</td>
</tr>
<tr>
<td>Touch screen</td>
<td>Low / Low</td>
<td>Not started yet</td>
</tr>
</tbody>
</table>
# New/Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal LEDs</td>
<td>- New signal LED arrays on each prop module</td>
</tr>
<tr>
<td>Light signaling pattern</td>
<td>- New signaling LED patterns for each robot state</td>
</tr>
<tr>
<td>Sound signal</td>
<td>- Define useful situation</td>
</tr>
<tr>
<td>Touch screen</td>
<td>- Define useful situation as signal modality</td>
</tr>
</tbody>
</table>
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

**Robot Perspective**

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

Human

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

<table>
<thead>
<tr>
<th></th>
<th>Light</th>
<th>Sound</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength</strong></td>
<td>Visually perceived before consciously attention</td>
<td>Convey information without visibility restriction</td>
</tr>
<tr>
<td></td>
<td>Sophistically express states</td>
<td>Strong focus of attention</td>
</tr>
<tr>
<td><strong>Weakness</strong></td>
<td>Requires line of sight</td>
<td>Can be perceived as interference or annoyance</td>
</tr>
<tr>
<td></td>
<td>Interference from natural and artificial sources</td>
<td>Masked by other sound</td>
</tr>
</tbody>
</table>
Interaction Modality

Physical Distance

Separate (invisible)  Distant  Close

- **Alerting a state**
- **Alerting + voice command**
- **Motion**
- **Orientation, Gesture**
- **Conveying intent**
- **Conveying intent**
- **Conveying intent / information**
- **Receiving crew’s input**

- **Sound**
- **Movement**
- **Light**
- **Touch Screen**
- **Touch (Haptic)**
Signal Light Concept
## Notification Level

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

<table>
<thead>
<tr>
<th>Low awareness</th>
</tr>
</thead>
</table>

**Changes:**
- **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)
- **Ignore**: no change (let people aware of why robot is awaken / whether the robot is awaken)
Notification Level & Robot States

<table>
<thead>
<tr>
<th>Ambient State</th>
<th>Alert State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignore</td>
<td>Interrupt</td>
</tr>
<tr>
<td>Change Blind</td>
<td>Demand Action</td>
</tr>
<tr>
<td>Make Aware</td>
<td></td>
</tr>
</tbody>
</table>

- **Moving state**
  - **Progressive state**
    - (Battery charging / Data transmitting / Task executing)
  - **Instant state**
    - (Changing direction)
  - **Need help state**
    - (Blocked robot view / Low battery / Stuck by obstacles)
- **Less active state**
  - (Stationary / Perched / Hibernated /Docked)
- **Alert state**
  - (Running into crew)
## Signal Light Design

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
<th>Image 1</th>
<th>Image 2</th>
<th>Image 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hibernating</td>
<td>Blink, White</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Stationary</td>
<td>Blink, Green</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Moving</td>
<td>Flowing, Green</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Data Transmit / Task Execute</td>
<td>Spinning, Cyan</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>Running into Crew</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>

- Blink, White
- Blink, Green
- Flowing, Green
- Spinning, Cyan
- Blink, Amber
Crew Privacy

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

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Module</td>
<td>High / Low</td>
<td>- Implement P4D findings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Finalize battery retention system</td>
</tr>
<tr>
<td>Top Forward Module</td>
<td>High / Low</td>
<td>- Implement P4D findings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Incorporate AI. Structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Incorporate NavCam protection</td>
</tr>
<tr>
<td>Forward Group</td>
<td>High / Low</td>
<td>- Implement P4D findings</td>
</tr>
<tr>
<td>Aft Group</td>
<td>High / Low</td>
<td>- Implement P4D findings</td>
</tr>
<tr>
<td>Forward and Aft Bezels</td>
<td>Medium / Low</td>
<td>- Implement P4D findings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Finalize inlet screen</td>
</tr>
</tbody>
</table>
# New/Changes from PTR3

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

Central Core

Forward Top

Aft Top
Payload Layout

Perch Arm is larger than 1U

Core Connector
31 POS PLUG (M835130E03C)

2X Clevis

4X #8-32 Thread

1U Payload
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

“Un-Lock” Position

4X Fastener Payload Attachment

4X Captive Fasteners

“Lock” Position
Core and Forward Module

Top Forward Module (in ABS Prototype)

Forward Bezel

Not shown

Fwd Antennas

Air deflector

Battery Retainer
Aft Module

- DockCam
- Aft LED Light
- Perch Cam
- Aft Antennas
Astrobee Propulsion Subsystem

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenum</td>
<td>High/Low</td>
<td>Improve strength</td>
</tr>
<tr>
<td>Top Cover and Skins</td>
<td>High/Low</td>
<td>Finalize skin attachment methods. See Yun’s slides</td>
</tr>
<tr>
<td>Signal Lights</td>
<td>High/Low</td>
<td>See Yun’s slides</td>
</tr>
<tr>
<td>Restraint Straps</td>
<td>High/Low</td>
<td></td>
</tr>
<tr>
<td>Impact Mitigation</td>
<td>High/Low</td>
<td>Finalize bumper nomex cover design</td>
</tr>
<tr>
<td>Nozzles</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Impeller/Motor</td>
<td>High/Low</td>
<td></td>
</tr>
</tbody>
</table>
## New/Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenum</td>
<td>- Added features for covers and nozzle changes</td>
</tr>
<tr>
<td>Top Cover and Skins</td>
<td>- New Al. Top Cover with softlayer&lt;br&gt;- New skin design</td>
</tr>
<tr>
<td>Signal Lights</td>
<td>- New signal light design</td>
</tr>
<tr>
<td>Restraint Straps</td>
<td>- New restraint strap design</td>
</tr>
<tr>
<td>Impact Mitigation</td>
<td>- Finalized bumper materials&lt;br&gt;- Confirm bumper force performance with testing&lt;br&gt;- New softlayer design</td>
</tr>
<tr>
<td>Nozzles</td>
<td>- New vibration isolation and seal components&lt;br&gt;- Change to servo spline drive shaft&lt;br&gt;- Change drive shaft gear&lt;br&gt;- New servo thermal sensor</td>
</tr>
<tr>
<td>Impeller/Motor</td>
<td>- New stiffened impeller</td>
</tr>
</tbody>
</table>
Astrobee Design

Two identical Propulsion Modules on Astrobee

Left Propulsion Module

Right Propulsion Module

Front ISO View

Aft ISO View
Top Cover and Skins

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

Seven LEDs wrap around front and aft edges

Fifteen (each) LEDs on ~6” dia.

LED: ¼” Square Multi-color Adafruit NeoPixel
Restraint Straps

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

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

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

Strap is unfolded
1 fold

Strap is unfolded
2 folds

Fully Deployed
~ 10” Strap
Impact Bumpers & Surfaces

“Soft Layers” 1/16” thick foam

8X Corner Bumpers
Impact Bumpers

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

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

2X Captive Screws hold bumpers on
Nozzle Subassembly

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

Nozzle Isolation Testing

Vibration Isolators

Drive Gear

Idler Gear

Flapper Gear / Shaft

Flapper Gear / Shaft

Sec A-A

Sec B-B

Spline Coupling
Astrobee Propulsion Subsystem Avionics and Software

Delta-PTR3 Design Overview
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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prop Avionics Hardware</td>
<td>High/Low</td>
<td>Board layout updates required before Cert build</td>
</tr>
<tr>
<td>PMC SW</td>
<td>High/Low</td>
<td></td>
</tr>
</tbody>
</table>
## Summary of Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Servos</td>
<td>Replaced MKS DS92 with DS95</td>
</tr>
<tr>
<td>PMC Board</td>
<td>Added PWM chip for nozzle servo control</td>
</tr>
<tr>
<td>PMC Board</td>
<td>Added LED processor (Independent circuit from prop control)</td>
</tr>
<tr>
<td>Temp Sensors</td>
<td>Temperature sensors (AD590) added to all servos and impeller motor</td>
</tr>
</tbody>
</table>
Propulsion Module: Impeller Design
Propulsion
Electronic Components

**Motor Controller**
Maxon ESCON Module 24/2

**Pressure Transducer**
Honeywell HSCDRRN010MD2A3

**PMC Microcontroller**
Microchip PIC32MX795F512H

**Programming Ports**

**Connection to LLP/EPS boards**

**Servo connectors**
Align DS416M

**Impeller Motor**
Maxon EC45 Flat, 30W
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
Astrobee CDH, EPS, & Sensors Subsystem

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backplane board</td>
<td>High / Low</td>
<td>HW payload over current</td>
</tr>
<tr>
<td>Data bus</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Low level processor</td>
<td>High / Low</td>
<td>USB OTG support</td>
</tr>
<tr>
<td>Mid/High level processor</td>
<td>High / Low</td>
<td>Speaker+Mic, USB OTG support</td>
</tr>
<tr>
<td>Touchscreen</td>
<td>High / Med</td>
<td>Ribbon cable routing</td>
</tr>
<tr>
<td>Flashlights</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Payload connector</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Buttons/switches/LEDs</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>EPS</td>
<td>High / Low</td>
<td>HW over current, HW over temp</td>
</tr>
<tr>
<td>SpeedCam</td>
<td>Med / Low</td>
<td>More testing</td>
</tr>
</tbody>
</table>
# New/Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>- HW current limit for payload power</td>
</tr>
<tr>
<td></td>
<td>- HW over temperature protection</td>
</tr>
<tr>
<td></td>
<td>- Improved battery charging</td>
</tr>
<tr>
<td>Backplane</td>
<td>- HW current limit for payload power</td>
</tr>
<tr>
<td>MLP/HLP</td>
<td>- Speaker and Microphone fix</td>
</tr>
<tr>
<td></td>
<td>- Added Fastboot support</td>
</tr>
<tr>
<td></td>
<td>- SMA connector for WiFi antenna</td>
</tr>
<tr>
<td></td>
<td>- Additional mounting holes for heat sink</td>
</tr>
<tr>
<td>LLP</td>
<td>- GPIO line to MLP &amp; HLP volume for Fastboot</td>
</tr>
<tr>
<td>SpeedCam</td>
<td>- Big redesign</td>
</tr>
</tbody>
</table>
Avionics Stack
Avionics Stack
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
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
- $V_{\text{batt}}$, 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

Astrobee SpeedCam!

Accelerometer

TeraRanger

New Firmware

STUPID BUG...
Test Setup I
Result I

Linear Velocity (Y)

Time (s)

Number of Features

Time (s)
ISS is Messy
Test Setup II
Result II

Linear Velocity (Y)

Number of Features
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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Network Configuration</td>
<td>High / Med</td>
<td></td>
</tr>
<tr>
<td>Data Transfer</td>
<td>High / Med</td>
<td></td>
</tr>
<tr>
<td>DDS Routing Service</td>
<td>High / Med</td>
<td></td>
</tr>
<tr>
<td>Video Multicasting</td>
<td>Med / Med</td>
<td></td>
</tr>
</tbody>
</table>
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.

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

- **Astrobee**
  - Commands and Telemetry (DDS [UDP/IP])
  - Science Cam HD video (RTSP [UDP/IP])

- **KUIP**
  - KUIP

- **Ground Relay**
  - TReK-HPEG
    - Commands and Telemetry (DDS [UDP/IP])
    - Science Cam HD video (RTSP [UDP/IP])

- **Ground Control Station**

- **Crew Control Station**
Data Path: Video/Data Distribution

Legend
- Command & Control IP Stream
- Video
- USB

Future Capability
- JSC MCC
  - Operator Control Station
  - Screen
- MSFC POIC
  - Operator Control Station
  - Screen
- MSFC HOSC
- JSC Bldg 8 VCC
- ARC MMOC
  - Engineering Control Station
  - Screen
- Non-NASA Center
  - Guest Science CS
  - Screen

Crew Control Station -> Wi-Fi -> Astrobee

Data Path: Engineering Tools

Astrobee

TReK-HPEG

Engineering Tools (SSH [TCP/IP])

Engineering Workstation
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

Low adsorbent filler

Antenna location
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
The Astrobot 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.

**FSW Components and Design Maturity @ PTR-3**

- **OS (Communication Framework)**
- **Localization**
  - Marker less Flying
  - Docking
  - Perching
- **Offline mapping for localization**
- **Pose Estimation + Propulsion Control (GNC)**
- **Executive**
  - Mode Management
  - Sequencer (Plan Execution)
- **Mobility**
  - Generates and validates trajectories
  - Performs collision detection
- **Fault Management**

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Risk Components</td>
<td>Mature</td>
</tr>
<tr>
<td>Low Risk Components</td>
<td>Evolving design</td>
</tr>
<tr>
<td>Draft only</td>
<td></td>
</tr>
</tbody>
</table>

- **Guest Science**
- **User Interfaces**
- **Platform Management**
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)**
- **Executive**
  - Mode Management
  - Sequencer (Plan Execution)
- **Mobility**
  - Generates and validates trajectories
  - Performs collision detection
- **Fault Management**
- **Guest Science**
- **User Interfaces**
- **Platform Management**

**High Risk Components**

- have been mitigated early

**Low Risk Components**

- Low risk but critical Components for the overall system
- are addressed in future build

** Mostly designed**
Fault management
Fault Management Overview

- Fault detection is performed by the subsystems
- Subsystems use configurable limits to identify faults
- Subsystems are 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
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 $K \times K \times K$ 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 $\leq (R+K)^2$
  - 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)

![Diagram of collision detection](image)

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

$x(t) = x + vt + 0.5at^2$

Boundary Condition $t=0$

Boundary Condition $t=T$

Turning Point $t=j$

Turning Point $t=i$

$(R+K)^2$
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)
Onboard Guest Science

• Guest science benefits from a quad-core processor running Android
• Interface with guest science hardware through 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

<table>
<thead>
<tr>
<th>Firmware</th>
<th>Board Type</th>
<th>Update Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dock control firmware</td>
<td>PIC32MX795F512H</td>
<td>Dock Processor via I2C</td>
</tr>
<tr>
<td>EPS firmware</td>
<td>PIC32MX795F512H</td>
<td>LLP via I2C</td>
</tr>
<tr>
<td>PMC firmware</td>
<td>PIC32MX795F512H</td>
<td>LLP via I2C</td>
</tr>
<tr>
<td>Speedcam laser firmware</td>
<td>unknown</td>
<td>ground harness only</td>
</tr>
<tr>
<td>Speedcam velocity firmware</td>
<td>ARM Cortex M4</td>
<td>LLP via USB</td>
</tr>
<tr>
<td>Signal lights firmware</td>
<td>PIC32MX795F512H</td>
<td>LLP via I2C</td>
</tr>
<tr>
<td>PerchArm firmware</td>
<td>dsPIC33EP512MC806</td>
<td>MLP via Serial over USB</td>
</tr>
</tbody>
</table>
## Astrobee Software Categories

<table>
<thead>
<tr>
<th>Software</th>
<th>Board Type</th>
<th>Update Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wandboard Kernel</td>
<td>Wandboard Dual, Dual core i.MX6</td>
<td>Ethernet from Dock using Recovery</td>
</tr>
<tr>
<td>Inforce Kernel</td>
<td>Inforce, Quad core Snapdragon 805</td>
<td>fastboot over USB from LLP</td>
</tr>
<tr>
<td>Linux Base OS</td>
<td>['Wandboard', 'Inforce']</td>
<td>fastboot (Inforce) or recovery (Wandboard)</td>
</tr>
<tr>
<td>Android Base OS</td>
<td>Inforce</td>
<td>fastboot using USB from LLP</td>
</tr>
<tr>
<td>FSW Linux Dependencies</td>
<td>['Wandboard', 'Inforce']</td>
<td>apt using Ethernet from Dock</td>
</tr>
<tr>
<td>FSW for Linux</td>
<td>['Wandboard', 'Inforce']</td>
<td>apt using Ethernet from Dock</td>
</tr>
<tr>
<td>FSW for Android dock software repository</td>
<td>Inforce</td>
<td>adb over Ethernet from MLP</td>
</tr>
<tr>
<td></td>
<td>Wandboard</td>
<td>rsync over Ethernet from ground</td>
</tr>
</tbody>
</table>
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 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 \((21 + 6 \times \text{augmentations})^2\), increase from 4 to 16 is 576% increase, EKF had to be optimized by a factor 6

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

<table>
<thead>
<tr>
<th>Function</th>
<th>MathWorks “Optimized” Simulink-Generated C</th>
<th>FSW Hand Written C++ using Eigen</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>of_residual_and_h</td>
<td>87.0 s</td>
<td>2.0 s</td>
<td>98% (43x)</td>
</tr>
<tr>
<td>delta_state_and_cov</td>
<td>22.5 s</td>
<td>3.5 s</td>
<td>84% (6x)</td>
</tr>
<tr>
<td>covariance_multiply</td>
<td>18 s</td>
<td>&lt; 2 s</td>
<td>89% (~10x)</td>
</tr>
</tbody>
</table>
Video of Visual Odometry
Robustness to Lighting Condition

Lighting Conditions at the Day & Night Times on the ISS

Pyojin’s Algorithm

- Number of inlier points: 996
- Number of matched points: 119
- Estimated lighting condition: 120 lux
- Exposure time setting: x1

Localization Succeeds.

Original Algorithm

- Number of inlier points: 127
- Number of matched points: 183
- Estimated lighting condition: 999 lux
- Exposure time setting: x1

Localization Succeeds.
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 (HLP)

- Speakers
- Touch Screen
- Microphone
- Science Cam.
- Android User Interface
- Video Manager
- Guest Science
- USB Interface
- Guest Payloads
- Ground Data System
- Sequencer
- MLP Executive
- ROS Java: Limited or Full message set depending on level of guest science certification
- MLP
Communication Framework

<table>
<thead>
<tr>
<th>Candidates</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Flight Executive (CFE)</td>
<td></td>
</tr>
<tr>
<td>Robotic Operating System (ROS)</td>
<td></td>
</tr>
<tr>
<td>Mobile Robot Programing Toolkit (MRPT)</td>
<td></td>
</tr>
<tr>
<td>Joint Architecture for Unmanned Systems (JAUS)</td>
<td></td>
</tr>
<tr>
<td>IRG RoverSW (SORA + RAPID)</td>
<td></td>
</tr>
<tr>
<td>Data Distribution Service (DDS)</td>
<td></td>
</tr>
</tbody>
</table>

- 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

Selected solution is hybrid of:
- ROS for onboard messaging
- DDS for remote comm.
Localization Design Drivers

Localization Options

<table>
<thead>
<tr>
<th>Infrastructure + External Maps</th>
<th>ISS Wifi</th>
<th>Does not provide desired accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beacons (passive/active)</td>
<td>Modifications to ISS / change dependent</td>
</tr>
<tr>
<td>Robot Builds Maps</td>
<td>Stereo Vision</td>
<td>“Metric” (shape) maps makes matching difficult</td>
</tr>
<tr>
<td></td>
<td>3D sensors (LIDAR, ...</td>
<td>“Features” maps efficient to filter</td>
</tr>
<tr>
<td></td>
<td>Monocular Vision</td>
<td></td>
</tr>
</tbody>
</table>

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
Map of connected ISS Modules
(data from SmartSpheres project)
Platform architecture

Processors and communication links
Astrobee GN&C Subsystem

Delta PTR3 Design Overview
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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Controller</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Estimator</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>FAM</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Simulator</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Fault Management</td>
<td>High / Low</td>
<td>Implement faults from FMECA</td>
</tr>
</tbody>
</table>
## New/Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
</table>
| 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Requirement</th>
<th>Angular Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain Controllability</td>
<td>Up to 50 cm/s</td>
<td>Up to 45 deg/s</td>
</tr>
<tr>
<td>Max Acceleration</td>
<td>10 cm/s^2</td>
<td>10 deg/s^2</td>
</tr>
<tr>
<td>Pose Error (Nominal)</td>
<td>&lt; 20 cm</td>
<td>&lt; 20 deg</td>
</tr>
<tr>
<td>Pose Error (Assisted w/ AR tags, etc.)</td>
<td>&lt; 2 cm</td>
<td>&lt; 8 deg</td>
</tr>
<tr>
<td>Use Vision based navigation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GN&C: Overview
Architecture Diagram

62.5 Hz
Optical Flow
Mapped Landmarks

<5 Hz

62.5 Hz
IMU
Estimator (EST)
Pose Estimate
Pose Est

Command Shaper (CMD)
Controller (CTL)
Body Torque and Force

Force Allocation Module (FAM)

Mid-Level Processor (MLP)
Computer Vision System
Waypoint Cmd Sequencer

GN&C MLP Simulator
Computer Vision System
Waypoint Cmd Sequencer

OR

Low-Level Processor (LLP)

Propulsion Module (PM)
Motor/Impeller
Nozzles

Vehicle Dynamics
IMU
Propulsion Module
Environmental Model

OR

GN&C Robot Simulator

x2
Integration with FSW

- Matlab/Simulink models ARE the source code
- GN&C SW components are auto-coded and imported into a single high priority ROS node
Total of 45 states: 15 core states, 6 mapped landmark, and 24 optical flow augmented states

\[ x(t) = \begin{bmatrix} q & b_g & \text{iss } V & b_a & \text{iss } P & C_{\theta,ML} & \text{iss } C_{p,ML} & C_{\theta,OF,1} & \text{iss } C_{p,OF,1} & \cdots & C_{\theta,OF,5} & \text{iss } C_{p,OF,5} \end{bmatrix} \]
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.
• 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
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
The Astrobotic 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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Gripper</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Controller board</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Software</td>
<td>High / Low</td>
<td></td>
</tr>
<tr>
<td>Payload Attachment Mechanism</td>
<td>High / Low</td>
<td>Minor design updates</td>
</tr>
</tbody>
</table>
New/Changes from PTR3

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

- Torsional Spring – 6X
- Gripper Tendon – 2X
- Captive Screw – 2X

Opened Configuration

Closed Configuration

Gripper Motor
## Mass

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [g]</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>164.0</td>
<td>2 x motors for pan/tilt joint</td>
</tr>
<tr>
<td>Bolts</td>
<td>4.2</td>
<td>16 x M2-6 bolts, 2 x M3-10 bolts</td>
</tr>
<tr>
<td>Base Plate</td>
<td>181.6</td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>80.3</td>
<td>Ultem 9085 density = 1.34 g/cm³</td>
</tr>
<tr>
<td>Distal</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>Gripper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td>Spring</td>
<td>2.4</td>
<td>6 x torsional springs</td>
</tr>
<tr>
<td>Binding Post</td>
<td>20.8</td>
<td>4 x binding posts</td>
</tr>
<tr>
<td>Bolts/Cover</td>
<td>1.8</td>
<td>2 x #2 bolts and 2 x nuts</td>
</tr>
<tr>
<td>Palm/Proximal/Distal</td>
<td>165.7</td>
<td></td>
</tr>
<tr>
<td>Controller Board</td>
<td>40.0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>733</strong></td>
<td><strong>1.62 lb</strong></td>
</tr>
</tbody>
</table>

- 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

Payload Connector
- Payload Voltage (Battery Voltage)
- Middle-Level Processor (USB 2.0)

Perching Arm Avionics
- 6 V Regulator/Current Sensor (LM22670/MAX4372)
- 11 V Regulator/Current Sensor (LM22670/MAX4372)
- 3.3 V Regulator (TPS62162)
- USB-Serial Converter (FT231)
- Temperature Sensor (ADT7410)
- Microcontroller (dsPIC33E)

Load Switch (LTC4412)
- Load Switch (LTC4412)
- Level Shifter (TXS0104)
- Level Shifter (TXS0102)
- Current Limiter (MAX921)
- Level Shifter (TXS0102)
- COM Transceiver (MAX485)

Gripper Motor Driver (MC33926)
- Gripper Motor
- Proximal Arm Motor
- Distal Arm Motor
- Gripper Motor

3.3 V Regulator

6 V Regulator/Current Sensor

11 V Regulator/Current Sensor
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
Arm Motor
COMM Transceiver

• MAX485
  • A low-power transceiver for RS-485 communication
  • Allow to transmit up to 2.5Mbps
The Astrobée team is aiming for CDR-level of maturity for all system hardware.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Module</td>
<td>High / Low</td>
<td>None, Cert Unit Testing</td>
</tr>
<tr>
<td>Propulsion Blower Motor</td>
<td>High / Low</td>
<td>None, Cert Unit Testing</td>
</tr>
<tr>
<td>Nozzle Servos</td>
<td>High / Low</td>
<td>None, Cert Unit Testing</td>
</tr>
<tr>
<td>Perching Arm Servos</td>
<td>High / Low</td>
<td>None, Cert Unit Testing</td>
</tr>
<tr>
<td>Perching Arm Gripper Motor</td>
<td>High / Low</td>
<td>None, Cert Unit Testing</td>
</tr>
<tr>
<td>Dock Avionics</td>
<td>High / Low</td>
<td>None, Cert Unit Testing</td>
</tr>
<tr>
<td>Dock Linear Actuator</td>
<td>High / Low</td>
<td>None, Cert Unit Testing</td>
</tr>
</tbody>
</table>
New/Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>- Removed LLP Heatsink, Wires bundled to minimize airflow pressure resistance in core;</td>
</tr>
<tr>
<td>Hardware</td>
<td>- No Thermal Fuses; Added Perching Arm gripper DC motor current limiter; Nozzle servos covered;</td>
</tr>
<tr>
<td>COMPONENT</td>
<td>THERMAL MANAGEMENT</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| **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

Additional Core Air Inlet
May be deleted if unnecessary

Core Air Inlet

MLP/HLP
Heat Sink

Core Air Outlet

Plenum Floor

Fan Inlet

Cooling Fan Module
(inside view)

Cooling Fan Module
(downstream view)

Fan Exit
Current Design (Side View)

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

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°C
  • Temperature Limit Set 35°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

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dock housing</td>
<td>High/Low</td>
<td>Select dock color</td>
</tr>
<tr>
<td>AR Targets</td>
<td>Med / Low</td>
<td>Change attachment mechanism and target size</td>
</tr>
<tr>
<td>Bonding Strap</td>
<td>Med / Low</td>
<td>Attachment location</td>
</tr>
</tbody>
</table>
New/Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dock</td>
<td>- Reduced the overall width of the Dock due to removal of battery charger.</td>
</tr>
<tr>
<td>Dock</td>
<td>- Added an additional patch panel to accommodate more electrical components.</td>
</tr>
<tr>
<td>Dock</td>
<td>- Added air vent deflector to direct thermal exhaust.</td>
</tr>
<tr>
<td>Berth post</td>
<td>- New Modular attachment Bracket for Tilt and Non-Tilt Option</td>
</tr>
<tr>
<td>Berth post</td>
<td>- Lances change from horizontal to vertical alignment</td>
</tr>
<tr>
<td>Dock mounting</td>
<td>- Added additional attachment points for mounting brackets (velcro / seat track)</td>
</tr>
</tbody>
</table>
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
NOTE: Dimensions are in inches
ISO View
Dock –Flyer-Human
Dock

Front View With no attachment Brackets
Free Flyer Dock Interface
Front Side

Captive Screw – 4X
Lance -2X
Connector
20 Spring Loaded Pins
Total reaction Force = 2.7lb

Interface Plate

4 Magnets Located Behind Interface Plate
Total Holding Force = 10.9lb

Interface Plate Shown Transparent For Clarity

Dimensions:
(3.75) x (3.75)
Free Flyer Dock Interface Plate
Back Side

Magnet
KJ Magnetics

Linear Actuator
2X
L12-I FIRGELLI
30mm Stroke
210:1
The Astrobot team is aiming for CDR-level of maturity for all system hardware, however there are some known design gaps described below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller board</td>
<td>High / Low</td>
<td>New I2C lines</td>
</tr>
<tr>
<td>DC/DC board</td>
<td>Low / Med</td>
<td>New board</td>
</tr>
<tr>
<td>Dock adapter board</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Dock Processor</td>
<td>High</td>
<td>New Wandboard</td>
</tr>
<tr>
<td>Actuators</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>
New/Changes from PTR3

<table>
<thead>
<tr>
<th>Component</th>
<th>New / Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC/DC</td>
<td>- Reverting back to our original design</td>
</tr>
<tr>
<td>Smart Dock</td>
<td>- New Dock Processor</td>
</tr>
<tr>
<td>COTS Charger</td>
<td>- Removed from dock</td>
</tr>
</tbody>
</table>
Dock Avionics Diagram

ISS Network

Actuator
Dock Adapter
Dock Adapter
Actuator

Ethernet Switch
Charging Protection
Controller

DC/DC Board

Dock Processor
FAN

24 V

120 VDC from ISS

I²C
Power
Ethernet
Analog

3-A Circuit breaker
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
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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Maturity / Risk</th>
<th>Forward Design Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan Editor</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Plan Controller</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Teleoperation</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Guest Science</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Ground server</td>
<td>Med / Low</td>
<td>Specify server</td>
</tr>
<tr>
<td>Data Archive Interface</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Engineering Tools</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>
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.

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

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

- Plan info
- List view of Plan
- Element editor
- 3D model of Plan
Run Plan Tab

Select and upload Plan, and control Plan execution

Monitor plan execution

Model of loaded plan
Teleoperation Tab

- Buttons here can be changed via config file
- Construct and send movement commands
Teleoperation Tab

Reacquire position if Astrobee knocked accidentally
Teleoperation Tab
Teleoperation Tab

Details available from button on Health and Status view
Guest Science Tab

- Checkboxes to select Astrobees to command
- Status summaries
- Names of loaded Plans
- Monitor Astrobee positions in 3D window
- Command Astrobees
Advanced Guest Science

Select APK to see Status

Start and Stop APKs directly

View detailed telemetry from APKs

Preview and change APK command before sending
The Advanced Tab is a comprehensive tool for monitoring and managing the status of a system. It includes detailed health and status information, with options to view and change operating limits, as well as configure telemetry sent to a control station.

**Detailed Health and Status**
- Disables and disabled subsystems
- Plan status and temperature
- Battery status

**Triggered and Not Triggered Faults**
- Faults such as 'SciCam is inoperable' and 'Processor overheated'

**Operating Limits**
- Configure and view limits for various parameters
- Example: Profile Name, Flight Mode, Target Linear Velocity

**Disk Usage**
- View and configure data saved to disk

**Component States**
- Detailed status of various components
- Example: Component MLP, Current (A)
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

Legend
- Command & Control IP Stream
- Video
- USB

Future Capability
- JSC MCC
  - Operator Control Station
  - Screen
- MSFC HOSC
- JSC Bldg 8 VCC
- Non-NASA Center
  - Guest Science CS
  - Screen

ARC MMOC
- Engineering Control Station
  - Screen

MSFC POIC
- Operator Control Station
  - Screen

Crew Control Station

Wi-Fi
Data Flows After Operations

- Rosbag for immediate downlink (TReK CFDP)
- Rosbag for delayed downlink (Samba)
- ISS Data Storage
- Existing services
- Guest Science Location
- Guest Scientist Computer
- Web
- Data Archive Interface
- Ames TI Open
- SSH
- Astronaut Engineer Laptop
- Ground Data Storage
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
Outline

• Design maturity
• Key performance parameters (KPPs) and technical performance measures (TPMs)
DESIGN MATURITY
## Hardware Design Maturity Overview

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

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

* Marked rows indicate new items since PTR3 – either new processors, or significant scope increase
KPPS AND TPMS
# Key Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPHERES</th>
<th>Threshold Value (Minimum success)</th>
<th>Project Goal (Full success)</th>
<th>Corresponding Technical Performance Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max velocity</td>
<td>4 cm/sec</td>
<td>10 cm/sec</td>
<td>50 cm/sec</td>
<td>N/A – Design will achieve <strong>threshold</strong>; challenge is ensuring reliability at high speeds.</td>
</tr>
<tr>
<td>Max acceleration</td>
<td>10 cm/sec²</td>
<td>5 cm/sec²</td>
<td>10 cm/sec²</td>
<td>N/A – Design will achieve <strong>threshold</strong>. Propulsion thrust is on target; acceleration performance now depends on mass.</td>
</tr>
<tr>
<td>Localize &amp; position</td>
<td>+/- 3 cm</td>
<td>+/- 20 cm</td>
<td>+/- 2 cm</td>
<td><strong>TPMs 4, 6</strong></td>
</tr>
<tr>
<td>Measure angle &amp; point</td>
<td>+/- 2 deg</td>
<td>+/- 20 deg</td>
<td>+/- 8 deg</td>
<td><strong>TPMs 5, 7</strong></td>
</tr>
<tr>
<td>Flight time</td>
<td>0.5 hr</td>
<td>2 hr</td>
<td>5 hr</td>
<td><strong>TPM 1</strong></td>
</tr>
<tr>
<td>Dock &amp; resupply</td>
<td>Crew tended</td>
<td>Crew tended</td>
<td>Autonomous</td>
<td>N/A – Design will achieve goal</td>
</tr>
<tr>
<td># peripheral ports</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>N/A – Design will achieve threshold</td>
</tr>
<tr>
<td>Sorties supported with peripheral ports</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>N/A – Design will achieve goal</td>
</tr>
<tr>
<td>Consumables used per test session</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>N/A – Design will achieve goal</td>
</tr>
<tr>
<td>ISS operational space</td>
<td>2m x 2m x 2m</td>
<td>JEM, US Lab, and Node 2</td>
<td>All USOS</td>
<td>N/A – Design will achieve goal (modulo safety keepout zones that might include Cupola, Airlock)</td>
</tr>
</tbody>
</table>

[From IRG-FF001-Astrobee-Project-Management-Plan]
<table>
<thead>
<tr>
<th>#</th>
<th>Topic</th>
<th>Measure</th>
<th>KPP?</th>
<th>Threshold</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPM 1</td>
<td>Flight Time (h)</td>
<td></td>
<td>x</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>TPM 2</td>
<td>Mass (kg)</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>TPM 3</td>
<td>Noise @ Max Thrust (SPL dBA)</td>
<td></td>
<td></td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>TPM 4</td>
<td>Pose Estimation Error</td>
<td>Translation (cm)</td>
<td>x</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>TPM 5</td>
<td></td>
<td>Rotation (deg)</td>
<td>x</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>TPM 6</td>
<td>Pose Control Error</td>
<td>Translation (cm)</td>
<td>x</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>TPM 7</td>
<td></td>
<td>Rotation (deg)</td>
<td>x</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>TPM 8</td>
<td>Navigation MTBF (h)</td>
<td></td>
<td></td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>TPM 9</td>
<td>Max Computing Processor Load</td>
<td></td>
<td></td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>TPM 10</td>
<td>Max Computing Memory Consumption</td>
<td></td>
<td></td>
<td>100%</td>
<td>-</td>
</tr>
</tbody>
</table>

[From IRG-FF002-02-Astrobee-Technical-Performance-Measures]
TPM Schedule and Maturity Targets

- PTR2
- P4 IR
- P4 TR
- PTR3

Threshold Value
- Mass
- Flight time, position estimation and control
- Noise
- Computing

Delta
Cert
TR

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

10/1/15 11/1/15 12/1/15 1/1/16 2/1/16 3/1/16 4/1/16 5/1/16 6/1/16 7/1/16 8/1/16 9/1/16 10/1/16 11/1/16 12/1/16 1/1/17 2/1/17 3/1/17 4/1/17

3 dB
6 dB
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

<table>
<thead>
<tr>
<th>#</th>
<th>Topic</th>
<th>Update Approach</th>
<th>TPM Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPM 1</td>
<td>Flight Time (h)</td>
<td>No update (no major changes to avionics / batteries)</td>
<td>High</td>
</tr>
<tr>
<td>TPM 2</td>
<td>Mass (kg)</td>
<td>Improved design detail, weigh some P4D parts</td>
<td>Medium</td>
</tr>
<tr>
<td>TPM 3</td>
<td>Noise (dBA)</td>
<td>No update (no new integrated prop module prototype)</td>
<td>Low</td>
</tr>
<tr>
<td>TPM 4</td>
<td>Est. Error (cm)</td>
<td>No update (next update part of upcoming P4D testing)</td>
<td>Low</td>
</tr>
<tr>
<td>TPM 5</td>
<td>Est. Error (deg)</td>
<td>“</td>
<td>Low</td>
</tr>
<tr>
<td>TPM 6</td>
<td>Control Error (cm)</td>
<td>“</td>
<td>Low</td>
</tr>
<tr>
<td>TPM 7</td>
<td>Control Error (deg)</td>
<td>“</td>
<td>Low</td>
</tr>
<tr>
<td>TPM 8</td>
<td>Nav MTBF (h)</td>
<td>“</td>
<td>Low</td>
</tr>
<tr>
<td>TPM 9</td>
<td>CPU (%)</td>
<td>“</td>
<td>Low</td>
</tr>
<tr>
<td>TPM 10</td>
<td>Memory (%)</td>
<td>“</td>
<td>Low</td>
</tr>
<tr>
<td>#</td>
<td>TPM</td>
<td>Thresh</td>
<td>Desired Margin</td>
</tr>
<tr>
<td>----</td>
<td>----------------------</td>
<td>--------</td>
<td>----------------</td>
</tr>
<tr>
<td>1</td>
<td>Flight time (h)</td>
<td>≥ 2</td>
<td>15%</td>
</tr>
<tr>
<td>2</td>
<td>Mass (kg)</td>
<td>≤ 8</td>
<td>15%</td>
</tr>
<tr>
<td>3</td>
<td>Noise (dBA)</td>
<td>≤ 65</td>
<td>3 dB</td>
</tr>
<tr>
<td>4</td>
<td>Estimation Error (cm)</td>
<td>≤ 20</td>
<td>15%</td>
</tr>
<tr>
<td>5</td>
<td>Estimation Error (deg)</td>
<td>≤ 20</td>
<td>15%</td>
</tr>
<tr>
<td>6</td>
<td>Control Error (cm)</td>
<td>≤ 20</td>
<td>15%</td>
</tr>
<tr>
<td>7</td>
<td>Control Error (deg)</td>
<td>≤ 20</td>
<td>15%</td>
</tr>
<tr>
<td>8</td>
<td>Navigation MTBF (h)</td>
<td>≥ 10</td>
<td>15%</td>
</tr>
<tr>
<td>9</td>
<td>CPU (%)</td>
<td>≤ 100%</td>
<td>50%</td>
</tr>
<tr>
<td>10</td>
<td>Memory (%)</td>
<td>≤ 100%</td>
<td>50%</td>
</tr>
</tbody>
</table>
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
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:

<table>
<thead>
<tr>
<th>Action</th>
<th>Status</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accept the mass slip and relax mass threshold requirement to 8 kg, restoring healthy margin</td>
<td>Done</td>
<td></td>
</tr>
<tr>
<td>(Optional) Execute known lightweighting opportunities, possibly reducing mass below 7 kg estimate</td>
<td>Mostly not executed</td>
<td>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.</td>
</tr>
<tr>
<td>(Optional) Increase propulsion module rated max thrust to restore acceleration at or near 10 cm/s² (without changing hardware design)</td>
<td>Not executed</td>
<td>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.</td>
</tr>
</tbody>
</table>
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/s², 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

<table>
<thead>
<tr>
<th>Time</th>
<th>Duration</th>
<th>Presenter</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30</td>
<td>0:30</td>
<td>Terry, Chris</td>
<td>Welcome/Intro</td>
</tr>
<tr>
<td>09:00</td>
<td>1:30</td>
<td>Trey, Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>10:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>10:45</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>12:00</td>
<td>0:45</td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>12:45</td>
<td>0:30</td>
<td></td>
<td>Demo</td>
</tr>
<tr>
<td>13:15</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>14:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>14:45</td>
<td>0:30</td>
<td>Trey</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>15:15</td>
<td>0:30</td>
<td>Jonathan</td>
<td>Integration &amp; Test</td>
</tr>
<tr>
<td>15:45</td>
<td>0:30</td>
<td>Ernie</td>
<td>Safety</td>
</tr>
<tr>
<td>16:15</td>
<td>0:15</td>
<td>Chris</td>
<td>Project Management</td>
</tr>
<tr>
<td>16:30</td>
<td>0:15</td>
<td>Maria</td>
<td>Operations</td>
</tr>
<tr>
<td>16:45</td>
<td>0:15</td>
<td>Chris</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Facility</th>
<th>Prototype 4D</th>
<th>Certification</th>
<th>Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite Lab</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>MGTF</td>
<td>✗</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>EMI/EMC facility</td>
<td>✔ Ames</td>
<td>✔ JSC</td>
<td>✗</td>
</tr>
<tr>
<td>Engineering Evaluation Lab</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Off-gassing White Sands</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Anechoic</td>
<td>✔ Ames</td>
<td>✔ JSC</td>
<td>✗</td>
</tr>
<tr>
<td>JSL at JSC</td>
<td>✗</td>
<td>✔</td>
<td>✗</td>
</tr>
</tbody>
</table>
## Prototype 4D Risk reduction

<table>
<thead>
<tr>
<th>Risk</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit</td>
<td>Integration Complete, Fit issues being addressed in mechanical design</td>
</tr>
<tr>
<td>New Material manufacturing and tolerances</td>
<td>Integration Complete, New materials performed adequately</td>
</tr>
<tr>
<td>Gripper Performance</td>
<td>Complete, test report in progress.</td>
</tr>
<tr>
<td>Sensor Placement</td>
<td>Testing planned for week of 01/23</td>
</tr>
<tr>
<td>Crew Serviceability</td>
<td>Testing planned for week of 01/23</td>
</tr>
<tr>
<td>Wi-fi Interference</td>
<td>Testing planned for week of 01/23</td>
</tr>
<tr>
<td>Avionics Functionality</td>
<td>Testing planned for week of 01/23</td>
</tr>
<tr>
<td>EMI</td>
<td>Testing planned for week of 01/30</td>
</tr>
<tr>
<td>Acoustic</td>
<td>Testing planned for week of 01/30</td>
</tr>
<tr>
<td>Margin for Docking Performance</td>
<td>Testing planned for week of 01/30</td>
</tr>
<tr>
<td>Retractable Magnets</td>
<td>Testing planned for week of 01/30</td>
</tr>
<tr>
<td>Software Update Functionality</td>
<td>Testing planned for week of 01/30</td>
</tr>
<tr>
<td>Human Factors</td>
<td>Testing planned for week of 02/06</td>
</tr>
<tr>
<td>Glass Shattering</td>
<td>Testing planned for week of 02/06</td>
</tr>
<tr>
<td>Thermal Operating Limits</td>
<td>Testing planned for week of 02/13</td>
</tr>
<tr>
<td>Element</td>
<td>Status</td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Visual Environment</td>
<td>✔ Partial Module</td>
</tr>
<tr>
<td>Lighting</td>
<td>✔ Incorrect geometry, correct illumination</td>
</tr>
<tr>
<td>Ground Truth Data</td>
<td>✔ Visualeyez</td>
</tr>
<tr>
<td>Wireless Network</td>
<td>✗ JSL WAP</td>
</tr>
<tr>
<td>Dock Power</td>
<td>✗ 120V power supply</td>
</tr>
<tr>
<td>Positioning</td>
<td>✗ Goniometer In progress</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Element</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Environment</td>
<td>✔ Full Module</td>
</tr>
<tr>
<td>Lighting</td>
<td>✖ Correct geometry, correct illumination</td>
</tr>
<tr>
<td>Ground Truth Data</td>
<td>✖ Visualeyez</td>
</tr>
<tr>
<td>Wireless Network</td>
<td>✖ JSL WAP</td>
</tr>
<tr>
<td>Dock Power</td>
<td>✔ NA</td>
</tr>
<tr>
<td>Positioning</td>
<td>✖ Gimbal and Gantry</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Time</th>
<th>Duration</th>
<th>Presenter</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30</td>
<td>0:30</td>
<td>Terry, Chris</td>
<td>Welcome/Intro</td>
</tr>
<tr>
<td>9:00</td>
<td>1:30</td>
<td>Trey, Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>10:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>10:45</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>12:00</td>
<td>0:45</td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>12:45</td>
<td>0:30</td>
<td></td>
<td>Demo</td>
</tr>
<tr>
<td>13:15</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>14:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>14:45</td>
<td>0:30</td>
<td>Trey</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>15:15</td>
<td>0:30</td>
<td>Jonathan</td>
<td>Integration &amp; Test</td>
</tr>
<tr>
<td>15:45</td>
<td>0:30</td>
<td>Ernie</td>
<td>Safety</td>
</tr>
<tr>
<td>16:15</td>
<td>0:15</td>
<td>Chris</td>
<td>Project Management</td>
</tr>
<tr>
<td>16:30</td>
<td>0:15</td>
<td>Maria</td>
<td>Operations</td>
</tr>
<tr>
<td>16:45</td>
<td>0:15</td>
<td>Chris</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>
Astrobee Delta PTR3

Safety
Safety Status

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

<table>
<thead>
<tr>
<th>Topic</th>
<th>HR#</th>
<th>Disposition</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Data Package</td>
<td>28626</td>
<td>Approved with Mods</td>
<td>Minor additional details requested, update to Delta PTR-3 maturity</td>
</tr>
<tr>
<td>Standard Hazards:</td>
<td>9075</td>
<td>Approved with Mods</td>
<td>Mostly clarifications, move vibration to Glass HR, remove External Charger (covered by GeoCam Project)</td>
</tr>
<tr>
<td>Material Flammability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials Off-gassing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical/Sharp Edges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Touch Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shatterable Materials (lenses)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electromagnetic Radiation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lasers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Mate/Demate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotating Equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Translation Paths Interference</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vented Containers Failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topic</td>
<td>HR#</td>
<td>Disposition</td>
<td>Comments</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------</td>
<td>----------------------</td>
<td>-------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Collision</td>
<td>28628</td>
<td>Approved with Mods</td>
<td>Hazard Control plus Equivalent Safety Non-Compliance Report</td>
</tr>
<tr>
<td>Li-Ion Battery</td>
<td>28635</td>
<td>Approved with Mods</td>
<td>Update EP-03 form and attach to hazard</td>
</tr>
<tr>
<td>Mate/Demate &amp; Electrical Shock</td>
<td>30631</td>
<td>Approved with Mods</td>
<td>Split out UOP Mate/Demate into a separate Cause, remove External Charger</td>
</tr>
<tr>
<td>Battery Charger</td>
<td>30720</td>
<td>Approved with Mods</td>
<td>Remove External Charger</td>
</tr>
<tr>
<td>Connectivity To ISS UOP Power</td>
<td>32417</td>
<td>Approved with Mods</td>
<td>Expand beyond the power cable to include implications for dock internal electronics</td>
</tr>
<tr>
<td>Astrobee Glass Lenses</td>
<td>34164</td>
<td>Approved with Mods</td>
<td>Move vibration testing to this hazard</td>
</tr>
</tbody>
</table>
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

20.66 m
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)

- Approach path
- Thin polycarbonate laminate
- 0.44” thick Schott BK7 optical glass (not tempered)
Collision Analogy/Mitigation

• “Bowling ball with knee pads”
  • Astrobot 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/s² 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")

Bumpers at all cube corners
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 Astrobe mass
    - Case 2: 1/2 Astrobe mass (with load distributed evenly over two bumpers, one bumper gets 1/2 mass)
    - Case 3: 1/4 Astrobe 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 Astrobe 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

![Diagram of bumper collision test rig](image)
# Conclusion

<table>
<thead>
<tr>
<th>Obstacle type</th>
<th>Hazard classification</th>
<th>Reasoning behind classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew</td>
<td>Critical</td>
<td>Crew can translate at high speed and run into stationary or moving Astrobee, possibly suffering minor injuries. <strong>Will pursue equivalent-safety NCR.</strong></td>
</tr>
</tbody>
</table>
| 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 |
<p>| ISS Structure     | Marginal              | <strong>Pending approval by ISS structures experts, based on force data from bumper collision test rig.</strong> 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 |</p>
<table>
<thead>
<tr>
<th>Time</th>
<th>Duration</th>
<th>Presenter</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30</td>
<td>0:30</td>
<td>Terry, Chris</td>
<td>Welcome/Intro</td>
</tr>
<tr>
<td>9:00</td>
<td>1:30</td>
<td>Trey, Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>10:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>10:45</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>12:00</td>
<td>0:45</td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>12:45</td>
<td>0:30</td>
<td></td>
<td>Demo</td>
</tr>
<tr>
<td>13:15</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>14:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>14:45</td>
<td>0:30</td>
<td>Trey</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>15:15</td>
<td>0:30</td>
<td>Jonathan</td>
<td>Integration &amp; Test</td>
</tr>
<tr>
<td>15:45</td>
<td>0:30</td>
<td>Ernie</td>
<td>Safety</td>
</tr>
<tr>
<td>16:15</td>
<td>0:15</td>
<td>Chris</td>
<td>Project Management</td>
</tr>
<tr>
<td>16:30</td>
<td>0:15</td>
<td>Maria</td>
<td>Operations</td>
</tr>
<tr>
<td>16:45</td>
<td>0:15</td>
<td>Chris</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>
BACKUP SLIDES
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

• (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

Sharp object / thick glass
“Gravel on the windshield”
Stresses localized
Surface scratched, chipped, or punctured

Blunt object / thin glass
“Structural failure”
Stresses distributed broadly across pane
Glass deflects like a beam, then breaks
(This is our main concern – Astrobot 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

![Diagram of Crack propagation and Tension](image-url)
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

<table>
<thead>
<tr>
<th>Tier</th>
<th>Safety critical?</th>
<th>Purpose</th>
<th>Controls</th>
</tr>
</thead>
</table>
| 1    | No               | Ensure that Astrobot will seldom collide with an obstacle at any speed. | • Crew awareness  
• Automated path validation  
• Manual path validation  
• Obstacle avoidance |
| 2    | No               | Ensure that Astrobot 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 Astrobot 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 Astrobot is flying
    - Activities will be scheduled using timelines, covered in daily briefings, announced by Capcom
  - Astrobot 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
  - Astrobot 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**
  - Astrobot 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 $10 \text{ cm/s}^2$ 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

- NavCam
- DockCam
- PerchCam

Mid-Level Processor:
- Image Analysis

Low-Level Processor:
- Sensor Fusion

Main IMU

Shutoff command

Power Controller

Power

Stop command

Propulsion Controllers

Disable line

Microcontroller:
- SpeedCam Firmware
- Optical Flow Camera
- IR ToF Rangefinder
- Ultrasonic Rangefinder
- SpeedCam IMU
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
• 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.

<table>
<thead>
<tr>
<th>Impact</th>
<th>I.D.</th>
<th>Mass</th>
<th>Bumper Test No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corner</td>
<td>C</td>
<td>1M</td>
<td>4</td>
</tr>
<tr>
<td>Core Edge</td>
<td>E1</td>
<td>½ M</td>
<td>1</td>
</tr>
<tr>
<td>Prop Edge</td>
<td>E2</td>
<td>½ M</td>
<td>6</td>
</tr>
<tr>
<td>Core Face</td>
<td>F1</td>
<td>¼ M</td>
<td>3</td>
</tr>
<tr>
<td>Prop Face</td>
<td>F2</td>
<td>¼ M</td>
<td>2</td>
</tr>
</tbody>
</table>
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
## Budget

<table>
<thead>
<tr>
<th></th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTE</td>
<td>11</td>
<td>12</td>
<td>12</td>
<td>6</td>
<td>41</td>
</tr>
<tr>
<td>Procurement ($M)</td>
<td>2.55</td>
<td>3.15</td>
<td>2.95</td>
<td>2.4</td>
<td>11.05</td>
</tr>
</tbody>
</table>
# Parts Costs

<table>
<thead>
<tr>
<th>Free Flyer</th>
<th>$165,400</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>$55,000</td>
</tr>
<tr>
<td><strong>CDH</strong></td>
<td>$12,500</td>
</tr>
<tr>
<td><strong>FSW</strong></td>
<td>-</td>
</tr>
<tr>
<td><strong>Prop</strong></td>
<td>$81,000</td>
</tr>
<tr>
<td><strong>EPS</strong></td>
<td>$6,200</td>
</tr>
<tr>
<td><strong>GNC</strong></td>
<td>$1,900</td>
</tr>
<tr>
<td><strong>Comm</strong></td>
<td>$300</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td>$500</td>
</tr>
<tr>
<td><strong>Arm</strong></td>
<td>$8,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dock</th>
<th>$50,000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>$44,000</td>
</tr>
<tr>
<td><strong>Avionics</strong></td>
<td>$6,000</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Shop Costs (≈ 50% CS Labor, 50% Proc)</th>
<th>$45K *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$40K *</td>
</tr>
</tbody>
</table>

Material & fab cost only
Assembly costs not included
Top Risks

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

Criticality:
- **High**
- **Med**
- **Low**

Affinity:
- T - Technical
- C - Cost
- Sa - Safety
- Sc - Schedule

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

*Risk numbers not sequential*
<table>
<thead>
<tr>
<th>Time</th>
<th>Duration</th>
<th>Presenter</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30</td>
<td>0:30</td>
<td>Terry, Chris</td>
<td>Welcome/Intro</td>
</tr>
<tr>
<td>9:00</td>
<td>1:30</td>
<td>Trey, Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>10:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>10:45</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>12:00</td>
<td>0:45</td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>12:45</td>
<td>0:30</td>
<td></td>
<td>Demo</td>
</tr>
<tr>
<td>13:15</td>
<td>1:15</td>
<td>Team Leads</td>
<td>Design</td>
</tr>
<tr>
<td>14:30</td>
<td>0:15</td>
<td></td>
<td>Break</td>
</tr>
<tr>
<td>14:45</td>
<td>0:30</td>
<td>Trey</td>
<td>Systems Engineering</td>
</tr>
<tr>
<td>15:15</td>
<td>0:30</td>
<td>Jonathan</td>
<td>Integration &amp; Test</td>
</tr>
<tr>
<td>15:45</td>
<td>0:30</td>
<td>Ernie</td>
<td>Safety</td>
</tr>
<tr>
<td>16:45</td>
<td>0:15</td>
<td>Chris</td>
<td>Project Management</td>
</tr>
<tr>
<td>16:30</td>
<td>0:15</td>
<td>Maria</td>
<td>Operations</td>
</tr>
<tr>
<td>16:45</td>
<td>0:15</td>
<td>Chris</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Minimum Success Criteria</th>
<th>Full Success Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS Demonstration of:</td>
<td>ISS demonstration of:</td>
</tr>
<tr>
<td>• Ground control</td>
<td>• Crew control</td>
</tr>
<tr>
<td>• JEM/Node 2/US Lab map</td>
<td>• USOS map</td>
</tr>
<tr>
<td>• Software upgrade</td>
<td>• Signal lights</td>
</tr>
<tr>
<td>• Hazard detection</td>
<td>• Perch/unperch</td>
</tr>
<tr>
<td>• Dock/undock</td>
<td>• Multi-robot operations</td>
</tr>
<tr>
<td>• Streamed video</td>
<td>• Mobile camera operations</td>
</tr>
<tr>
<td>• Payload &amp; Guest Science (GS) operations</td>
<td></td>
</tr>
<tr>
<td>Handover of all deliverables</td>
<td>Completion of all transfer activities within FY18</td>
</tr>
</tbody>
</table>
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
- Astrobot “B” and “C” Commissioning
- Demonstration (Sensor surveys, 0g research capabilities, Host payloads)
## Handover Success Criteria

<table>
<thead>
<tr>
<th>Deliverable</th>
<th>Success Criteria</th>
<th>Artifact</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrobee Hardware</td>
<td>Verification of requirements &amp; KPPs</td>
<td>Successfully executed procedures</td>
<td>I&amp;T</td>
</tr>
<tr>
<td>Astrobee Simulation</td>
<td>Validation that sim is accurate to flight performance</td>
<td>Sim vs. Flight analysis report</td>
<td>Ops</td>
</tr>
<tr>
<td>Flight Software</td>
<td>Verification of requirements &amp; KPPs</td>
<td>Successfully executed procedures</td>
<td>I&amp;T</td>
</tr>
<tr>
<td>Ground Software</td>
<td>Verification of requirements</td>
<td>Successfully executed procedures</td>
<td>I&amp;T</td>
</tr>
<tr>
<td>Documentation</td>
<td>Reviewed at final PTR by SPHERES PM</td>
<td>Signature sheet</td>
<td>PM</td>
</tr>
<tr>
<td>Astrobee Final Report</td>
<td>Validation of flight performance</td>
<td>Final report</td>
<td>PM</td>
</tr>
</tbody>
</table>
Commissioning Schedule

### Milestones
- Launch
- Install & Activate
- Initial Map
- Basic Mobility
- Autonomous Mobility
- Payload Demo
- Astrobee B/C
- Crew I/F
- Incremental Map
- PTR 5 Closeout

### ISS Activities
- FY 17
- FY 18

### Ground Activities
- FY 17
- FY 18

- Training
- Procedures
- Operational Readiness Tests

- Facilities ready for ORTs
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

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

<table>
<thead>
<tr>
<th>Success Criteria</th>
<th>Compliance Approach</th>
<th>Mapped Products</th>
</tr>
</thead>
</table>
| 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 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

<table>
<thead>
<tr>
<th>Success Criteria</th>
<th>Compliance Approach</th>
<th>Mapped Products</th>
</tr>
</thead>
</table>
| 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

<table>
<thead>
<tr>
<th>Success Criteria</th>
<th>Compliance Approach</th>
<th>Mapped Products</th>
</tr>
</thead>
</table>
| Adequate technical margins exist.                                                | • Identify technical performance measures that support Astrobee KPPs and key requirements.  
• Margins listed for major milestones.                                             | • 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.                                        | • Astrobee Risk Register  
• GCD Quarterly Reports                                                              |
**Success Criteria**

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

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