Astrobee: A Free Flying Robot Enabling Technology Demonstrations

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Agenda

1. Introduction to Astrobee
2. Final commissioning results
3. Current Users and Achievements
4. Possibilities for future investigations

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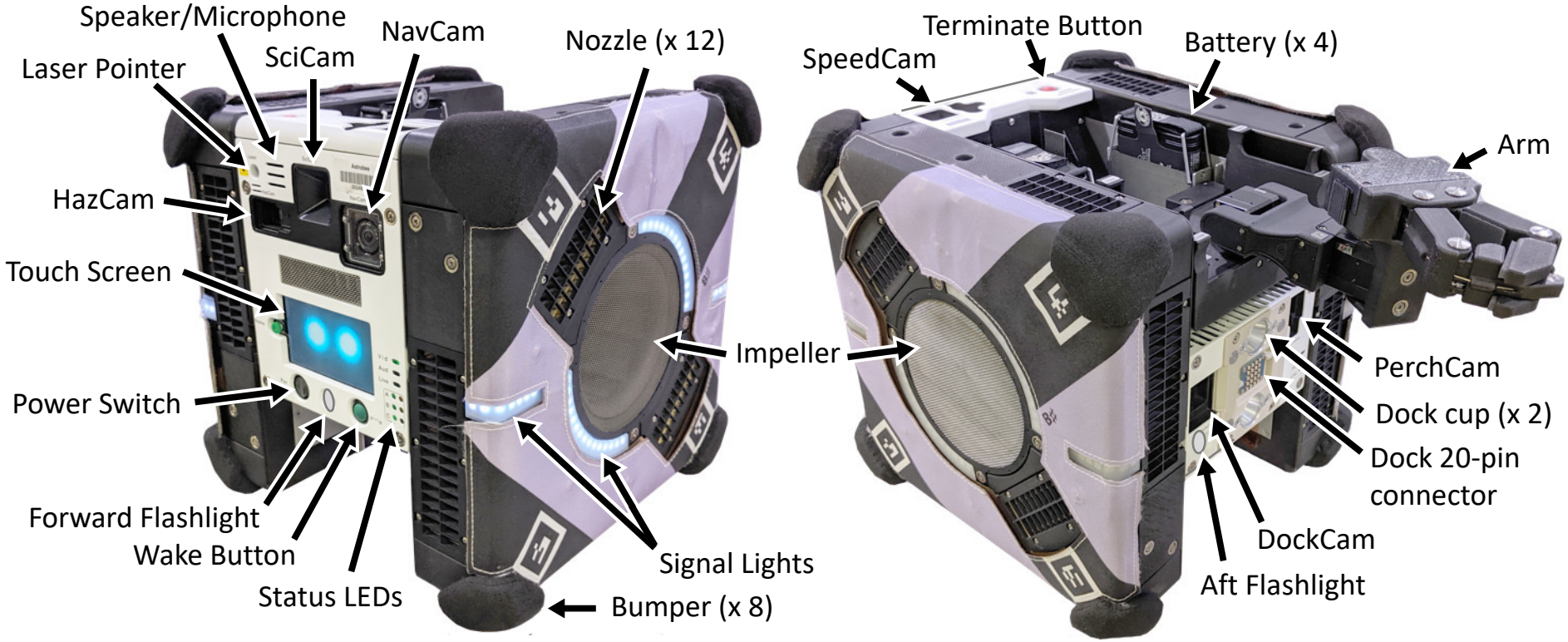
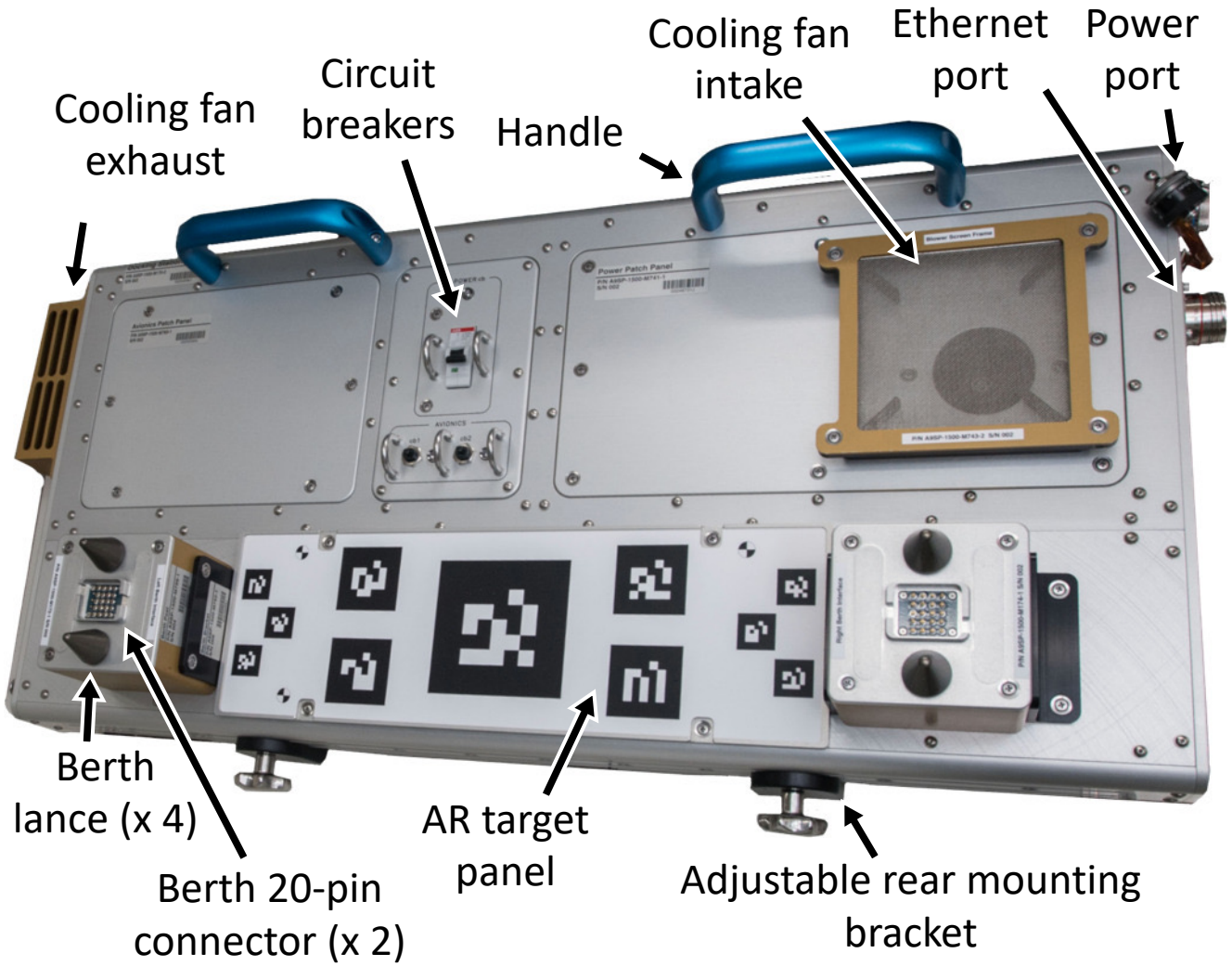
Astrobee Free Flyers

- Three free flying Astrobee robots will operate inside the ISS
- Battery-powered fan propulsion
- 32 cm wide, 9.1 kg (+ payloads)
- Six cameras
- Arm for perching on handrails
- Three payload bays for guest science



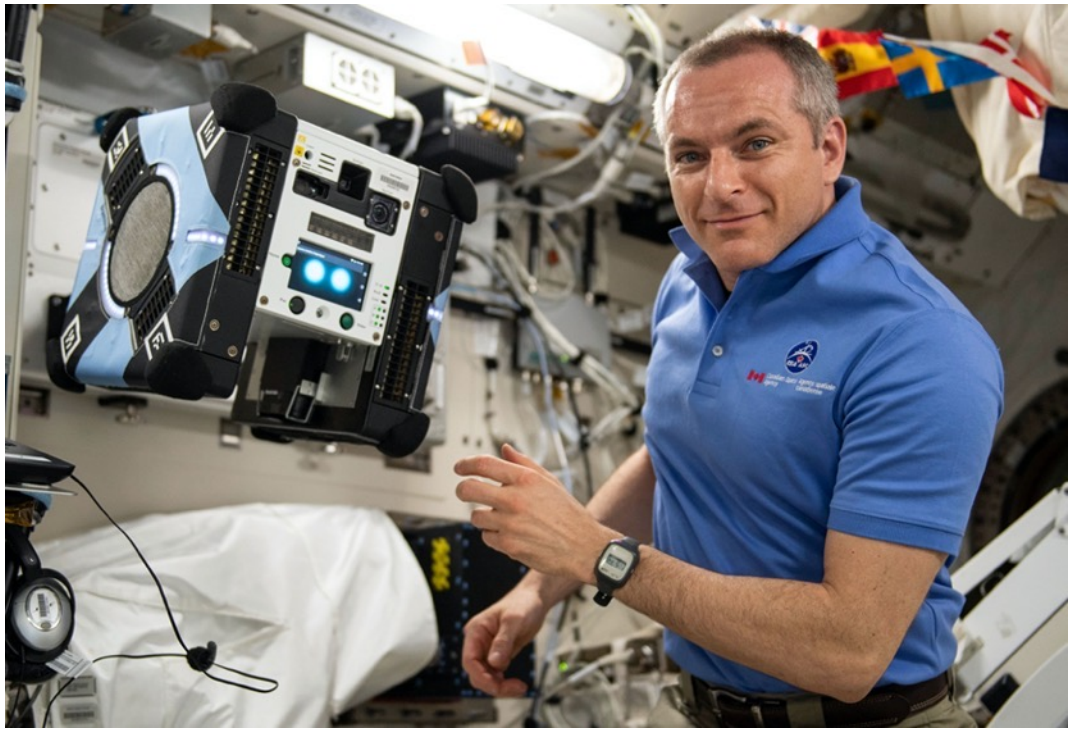
Astrobee Dock

- One dock on ISS, has berths for two Astrobees (stow the third)
- Provides battery charging power and network to Astrobee when docked
- Design supports autonomous docking



Astrobee Purpose

- Objectives
  - Provide a microgravity robotic research facility inside the ISS US Orbital Segment (USOS), which has replaced the existing SPHERES facility
  - Demonstrate feasibility of intra-vehicular robot caretaking for future human exploration vehicles
  - Provide an opportunity for future automation of certain ISS operations
- Driving use cases
  - Guest science experiments
  - Remotely operated mobile camera
  - Sensor surveys



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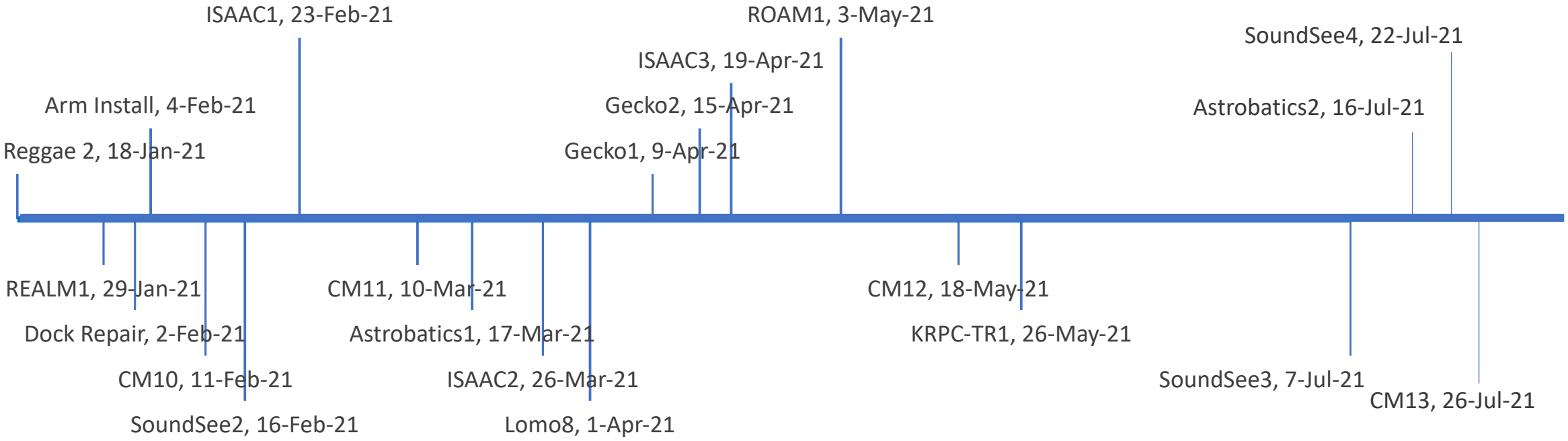
On-Orbit Commissioning

- The goal of Astrobee commissioning is to validate system-level performance on-orbit and **deliver a fully functional system** for guest science and ISS operational use
- The commissioning schedule:
  - Originally from launch through the end of September 2019 (the end date of the technology development project)
  - Was extended into 2020, then delayed due to COVID-19.
  - Proceeds incrementally from basic to complex activities
  - Includes repeat activities, because complex robotic systems never work right the first time in a unique new environment

2021 Activity Timeline

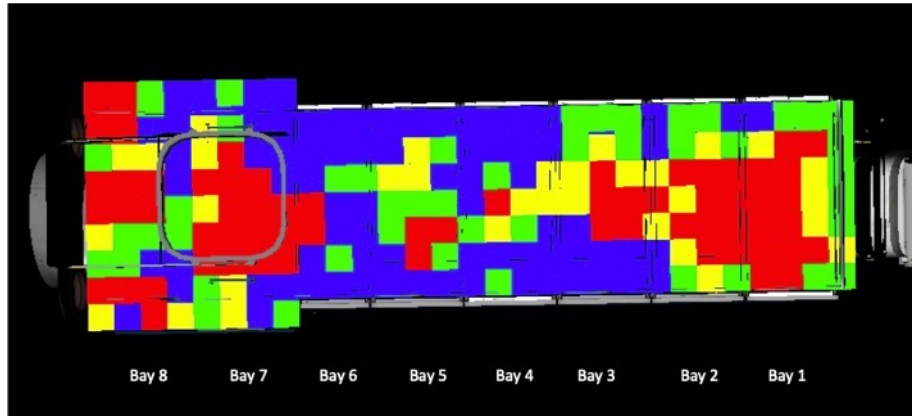


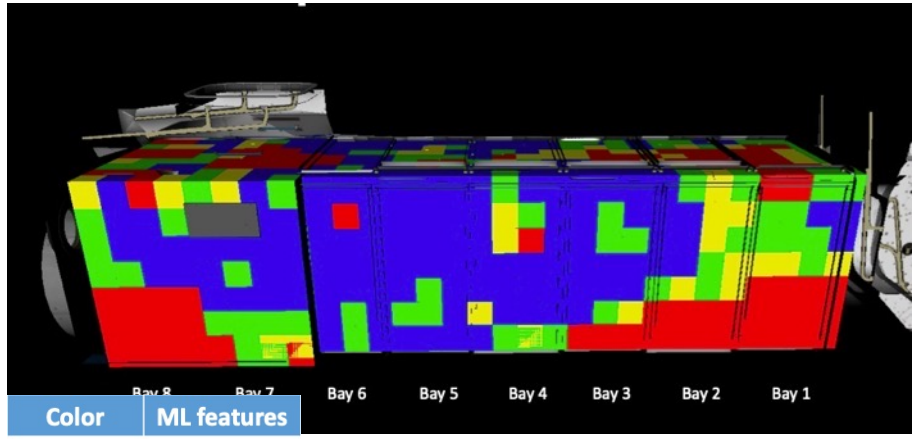
Commissioning Status

Activity	Robot	Status
Checkout	Bumble	Complete
Calibration & Mapping	Bumble	Complete
Localization & Mobility	Bumble	Complete
Checkout & Calibration	Honey	Complete
Localization & Mobility	Honey	Complete
Perching Checkout & Installation	Both	Complete
Perching Demonstration	Honey	Complete

Mapping Improvements

- Astrobee uses natural landmarks to generate an off-line map for use in localization.
- Astrobee needs to find some landmarks to get a position estimate, the more the better
- The entire JEM has been mapped
- Periodic updates performed through crew-minimal activities to gather more recent imagery
- Overall coverage analysis is being performed to look for gaps and determine performance



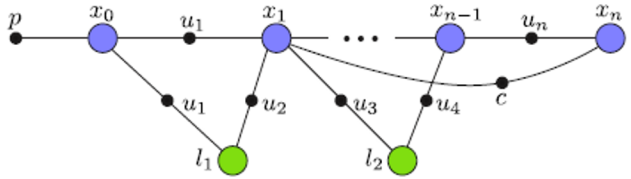


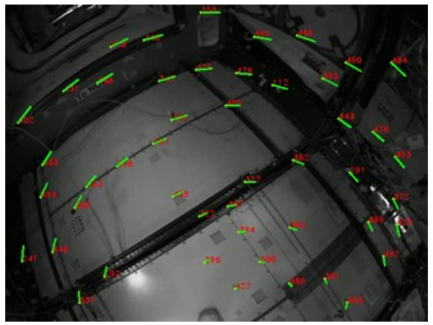
Color	ML features
Red	0-10
Yellow	11-20
Green	21-40
Blue	40+

Localization Improvements

- Major Astrobee Facility challenge: localization
  - Robot would get lost, could not turn quickly
  - (Gentle) collisions common
  - Crew intervention needed to recover
  - Frequent ISS data collection activities required to update prior map, map very sensitive to new objects and lighting changes
- The baseline localization algorithm used an Extended Kalman Filter (EKF) to fuse:
  - Prior map updates: Based on matching visual landmarks to a prior map. These updates provide an absolute position fix but come in at a slow rate and aren't available when landmarks aren't recognized.
  - Visual/inertial odometry (VIO) updates: Based on IMU and optical flow measurements. These come in at a higher update rate with more reliable availability but only provide a relative pose update, so they can only be used to maintain a fix established from the prior map, with accuracy that degrades over time until the next prior map update.
- Replaced EKF with a new graph-based localizer
  - Does a better job of fusing the same sensor measurements
  - Greatly improves the stability of VIO when there are no prior map updates for extended periods
  - Compared baseline to graph localizer on a data set of 12 ISS telemetry sequences
    - Reduced number of "lost robot" events where position diverged wildly from 2 to 0
    - Even excluding periods when the baseline system got lost, the graph localizer had 54% smaller position error on average
- **Since deployment, multiple Astrobee ISS activities have logged 2+ hours of free flying with no crew intervention**

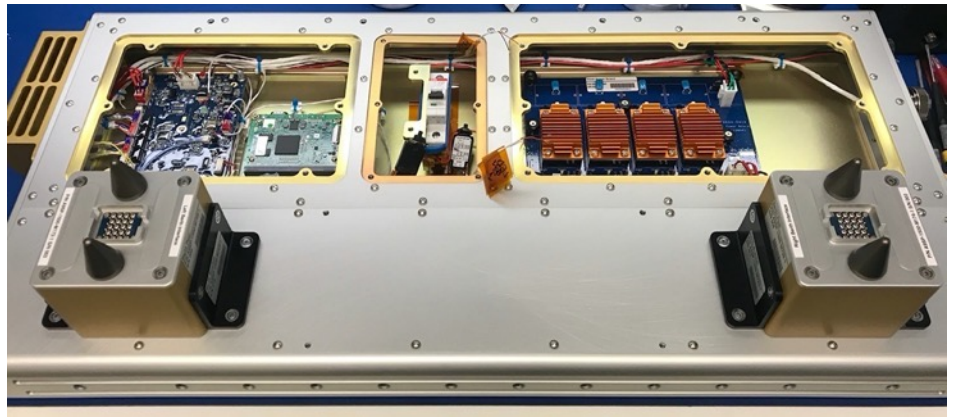
Robust Graph Localizer

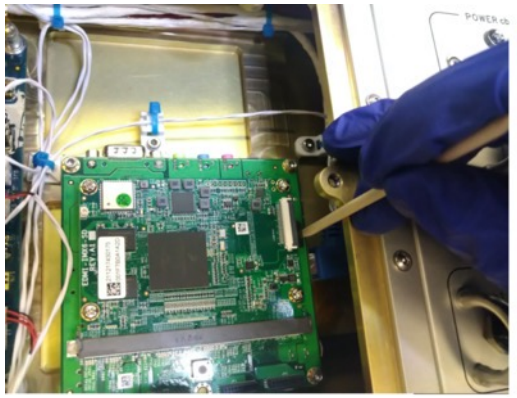




Dock Repair

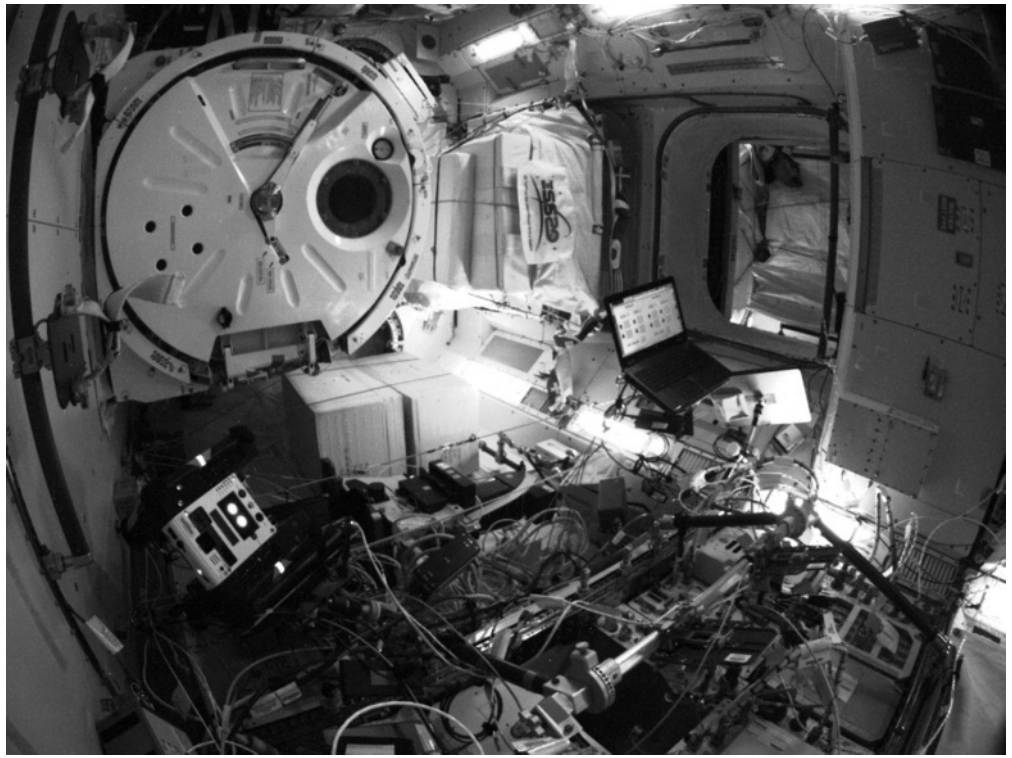
- Lost communication with the Dock
- Root cause analysis pointed at corrupted memory card
- Dock designed for on-orbit repair
- Spare memory card launched as part of on-orbit spares
- Crew performed replacement
- Dock restored to functionality

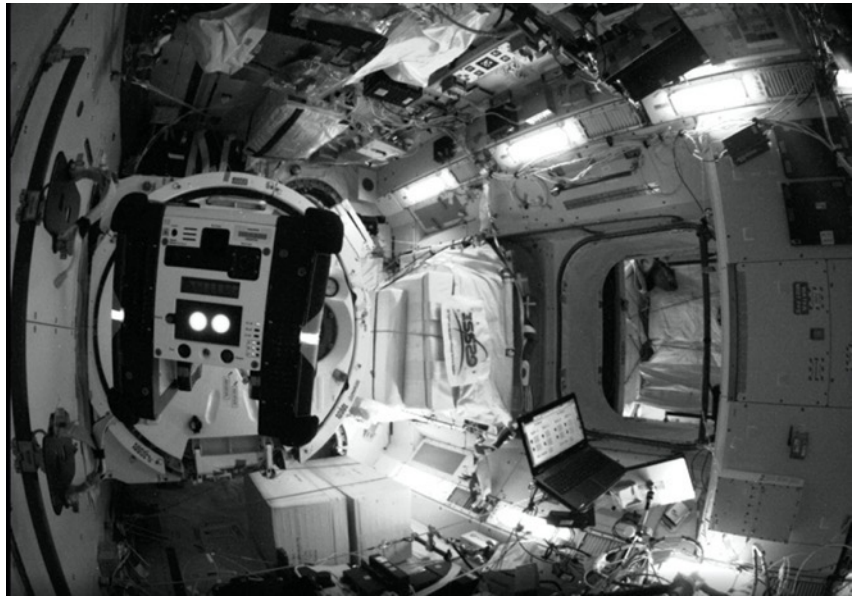




Perching Demonstration

- Honey perched autonomously on 07/26/2021
- Perch location was also useful to see how Bumble had become entangled.
- Operator was able to use the view from Honey to free Bumble.





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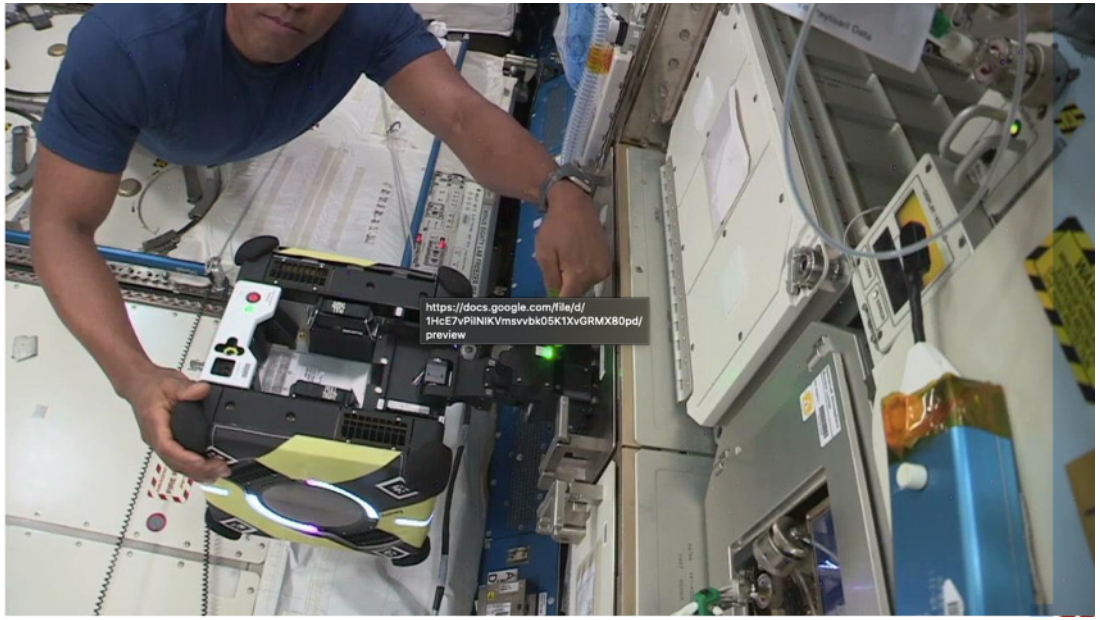
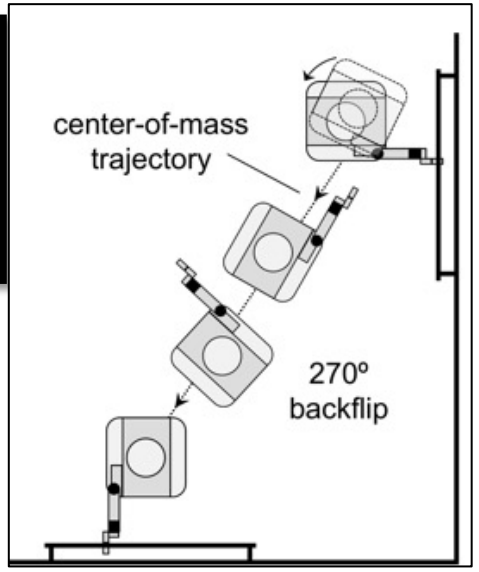
Completed Investigations

- Kibo Robotic Programming Competition – Year 1 – Completed 10/2020
- The REduced Gravity Gecko Adhesion docking Experiments (REGGAE) – Completed 01/2021
- Stanford Gecko – Phase 1 – Completed 04/2021



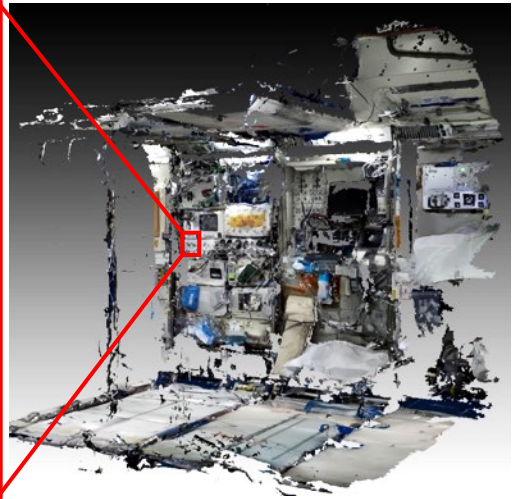
Ongoing Investigations

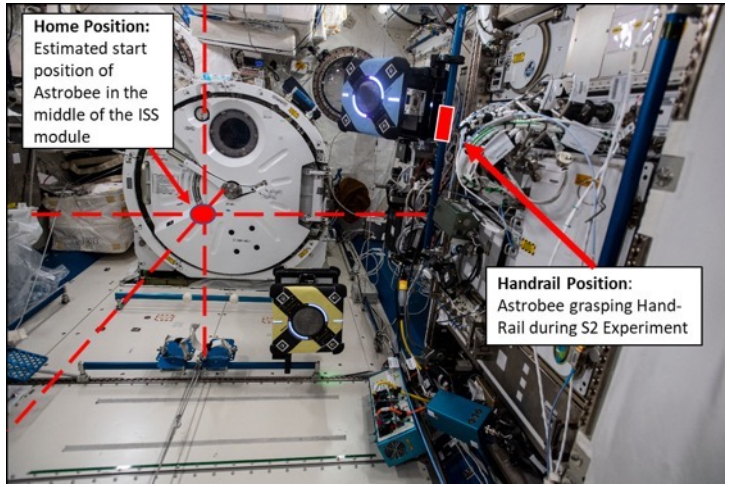
- Astrobatics (Naval Postgraduate School)
- SoundSee (Astrobotic/Bosch)
- Gecko (Stanford)
- RFID Recon (NASA AES/REALM-2)
- JAXA Kibo-RPC
- Astroporter (Tethers Unlimited)
- ISAAC (NASA STMD/GCD)
- ROAM (MIT/DLR)
- ReSWARM
- SVGS (FIT)
- SOARS (Zero-g Horizons)



Achievements

- 3 hours of continuous operation without crew intervention
- One Astrobee unit used to rescue a second
- 20 user sessions
- On-orbit repair of dock
- Autonomous Perching





(a)

(b)

(c)

(d)

So long SPHERES

- SPHERES investigations completed
- Satellites are being down-massed
- Work in progress to have them displayed in the Smithsonian

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Potential Future Investigations

- Planned Astrobee improvements include:
  - Robustness testing and refinement of autonomous perching.
  - Mapping and navigation in additional USOS modules.
  - Fault recovery software on the Dock
- Future payloads and users may include:
  - Zero Robotics, Middle-school and High-school programming competition previously hosted on SPHERES
  - Cargo manipulation and transfer
  - Free flyer and stationary robot collaboration
  - Microgravity fluid transfer
  - New docking mechanisms

Conclusion

- Astrobee on-orbit commissioning is completed, software updates and improvements will continue
- A few investigations have completed, with many ongoing
- Astrobee is ready for future users
- Astrobee improvements continue to enable more capabilities


QUESTIONS?