

Astrobee ISS Free Flyers: Overview and Enabling Technologies

The Astrobee Team

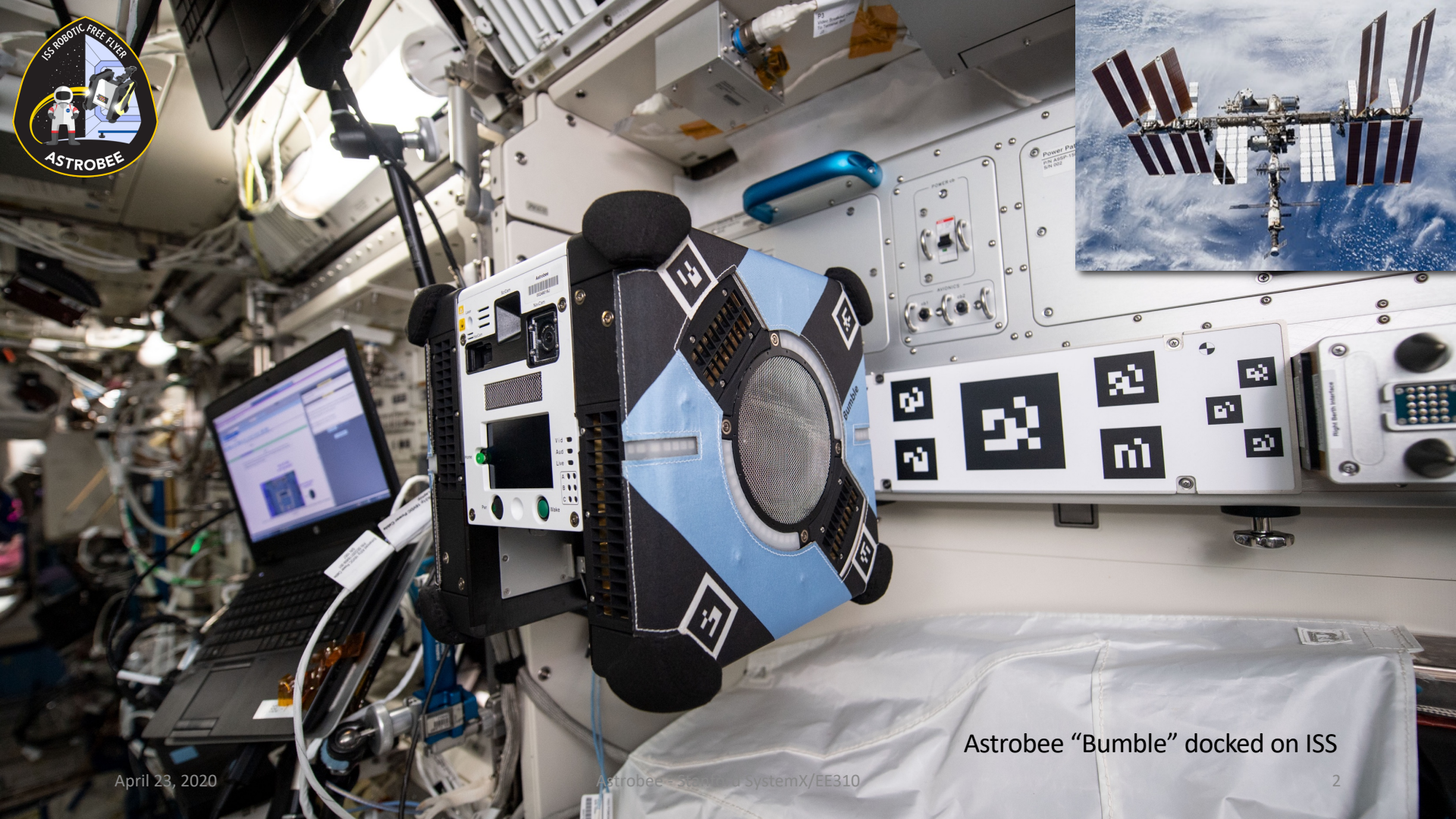
NASA Ames Research Center

Presented by Maria Bualat

Stanford SystemX/EE310 Seminar

April 23, 2020

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Astrobee “Bumble” docked on ISS

RELATED WORK



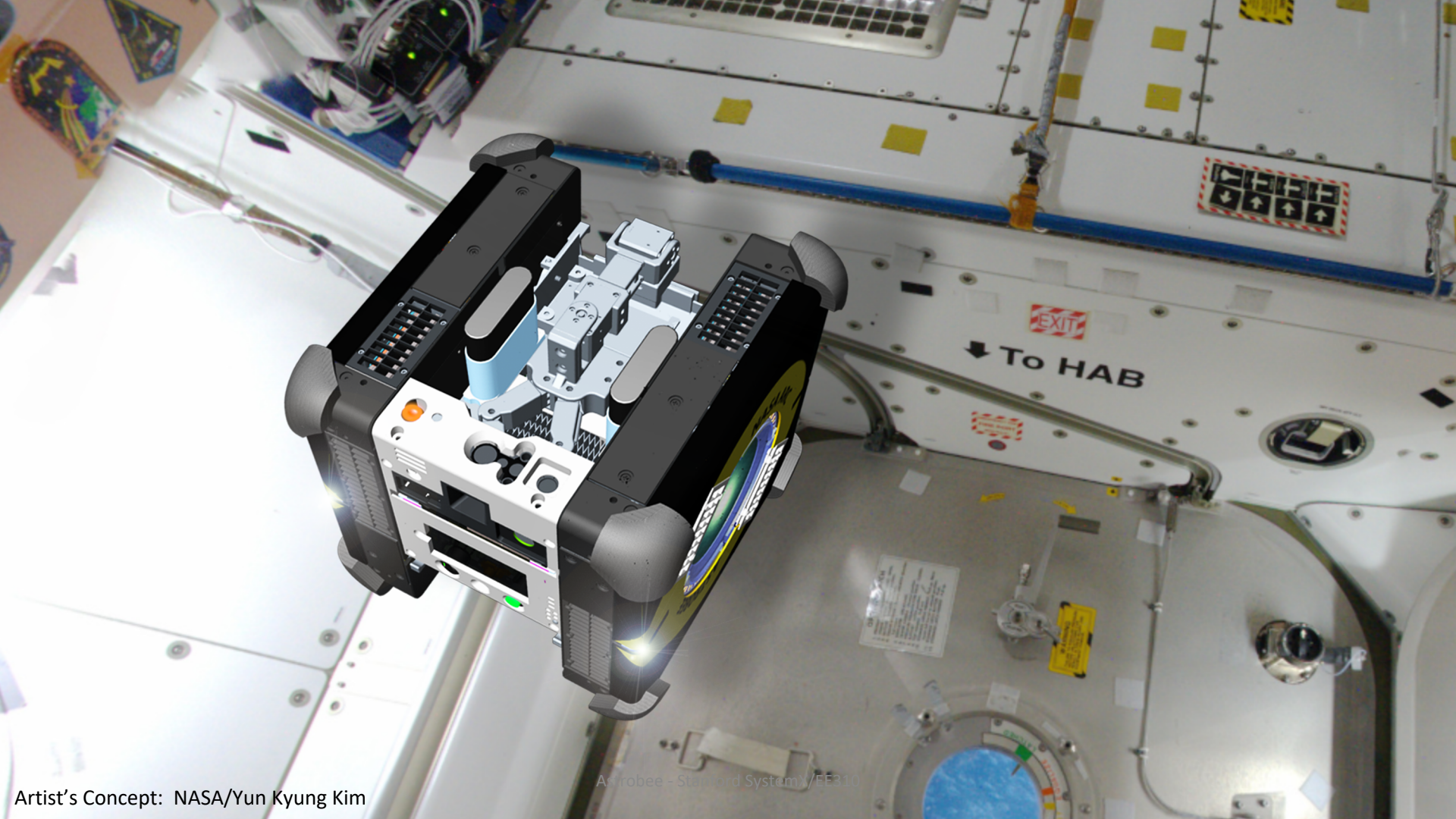



Slosh


VERTIGO


MIT
NASA ARC
AURORA DARPA
SPHERES


RINGS



Artist's Concept: NASA/Yun Kyung Kim

AERCam Sprint



Smart SPHERES



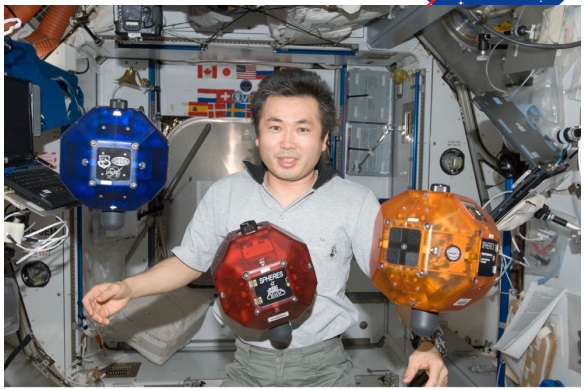


PSA

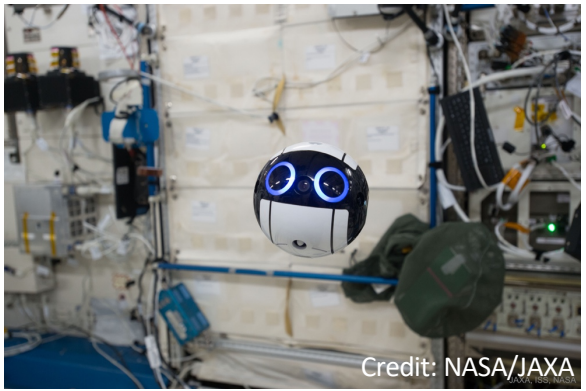


Current IVA Free Flyers

- SPHERES (NASA) – launched 2006
  - Highly successful research platform used for many guest science experiments
  - Astrobee will replace SPHERES, managed by the same facility team
- Int-Ball (JAXA) – launched 2017
  - Successful experiment in building an IVA free flyer with a rapid development cycle (18 months)
  - Small size (15 cm diameter, softball) enabled by JAXA's miniaturized all-in-one CPU / IMU / 3-axis reaction wheel module
  - Joint activities between Int-Ball and Astrobee are planned
- CIMON (DLR/Airbus) – launched June 2018
  - Enable research on AI for human-robot interaction
  - International cooperation – CIMON shares the pool of batteries that Astrobee qualified for ISS



SPHERES



Int-Ball

OBJECTIVES



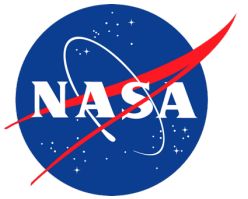
Goals

- Deliver 3 free flying robots and a docking station to the ISS
- Enable guest science (replace SPHERES)
- Provide capability for instrument surveys and mobile camera work



Astrobee flight equipment (free flyers, arms, batteries)

Technical Approach and Objectives

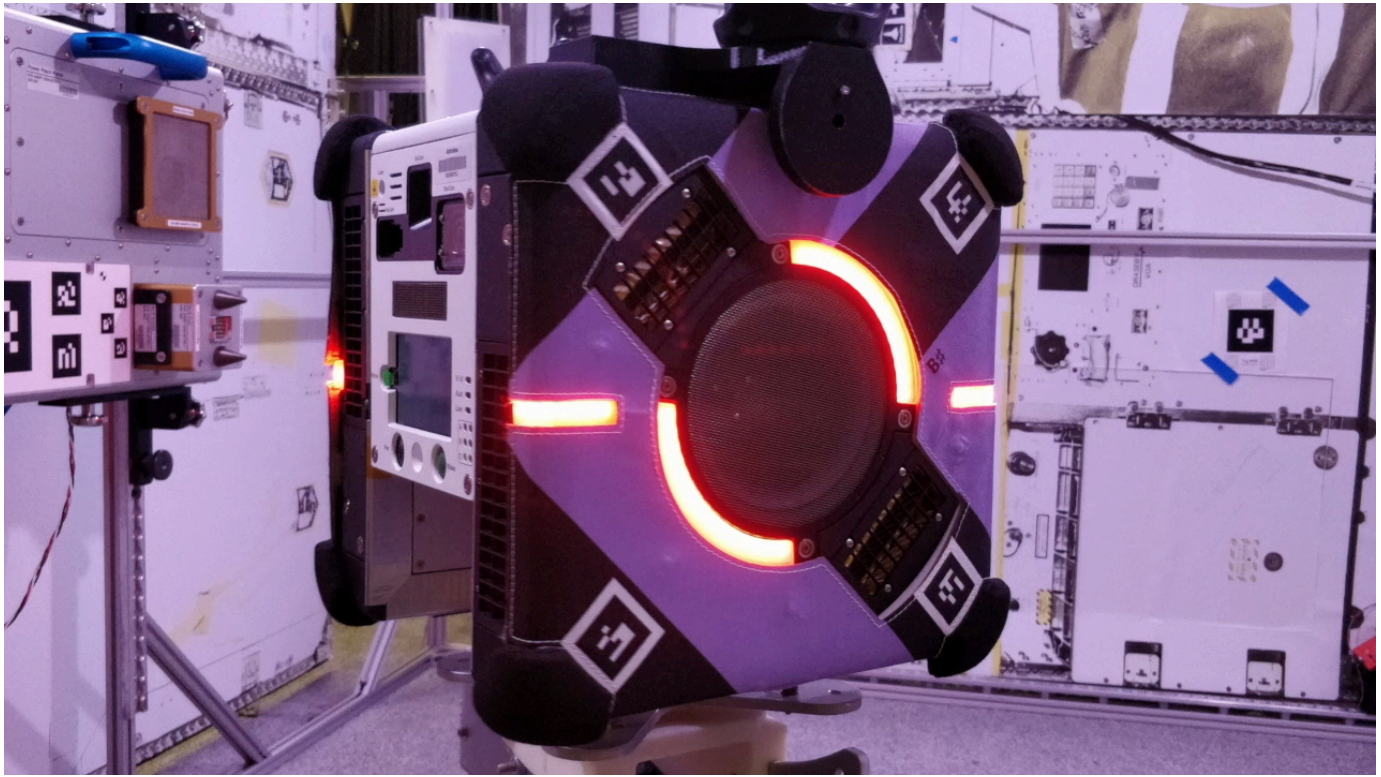


- Minimize burden on astronauts by executing most experiments fully **autonomously with ground supervision**
- Battery-powered propulsion and autonomous docking to recharge so **astronaut support is not required** to resupply consumables
- Incorporate **safety controls** such as collision mitigation and use of non-flammable materials
- Use a vision-based navigation system that **does not require any new infrastructure** in the ISS interior
  - Enables operation throughout the U.S. Orbital Segment (USOS) of the ISS

Development Process

- Developed incrementally over a **series of prototypes**. Earlier prototypes addressed trade studies and areas of risk. The later prototypes implemented system requirements and **incrementally matured the system design**. Testing validated system requirements and capabilities, and bought down risk.
- The **prototypes were not treated as flight** hardware. Prototyping allowed the team to make design changes at a rapid pace, without the overhead of flight hardware processes.
- The **Certification Units** were developed off the final prototype design, with modifications as a result of final prototype testing. These units were not only be used for **performance testing**, but also for **ISS interface requirement verification and certification**.
- Finally, 2 Dock and 4 Free Flyer **Flight Units** (1 flight spare each) were built following Ames Research Center (ARC) procedures and processes for flight hardware. They then shipped to Johnson Space Center (JSC) for final environmental tests and launch processing.

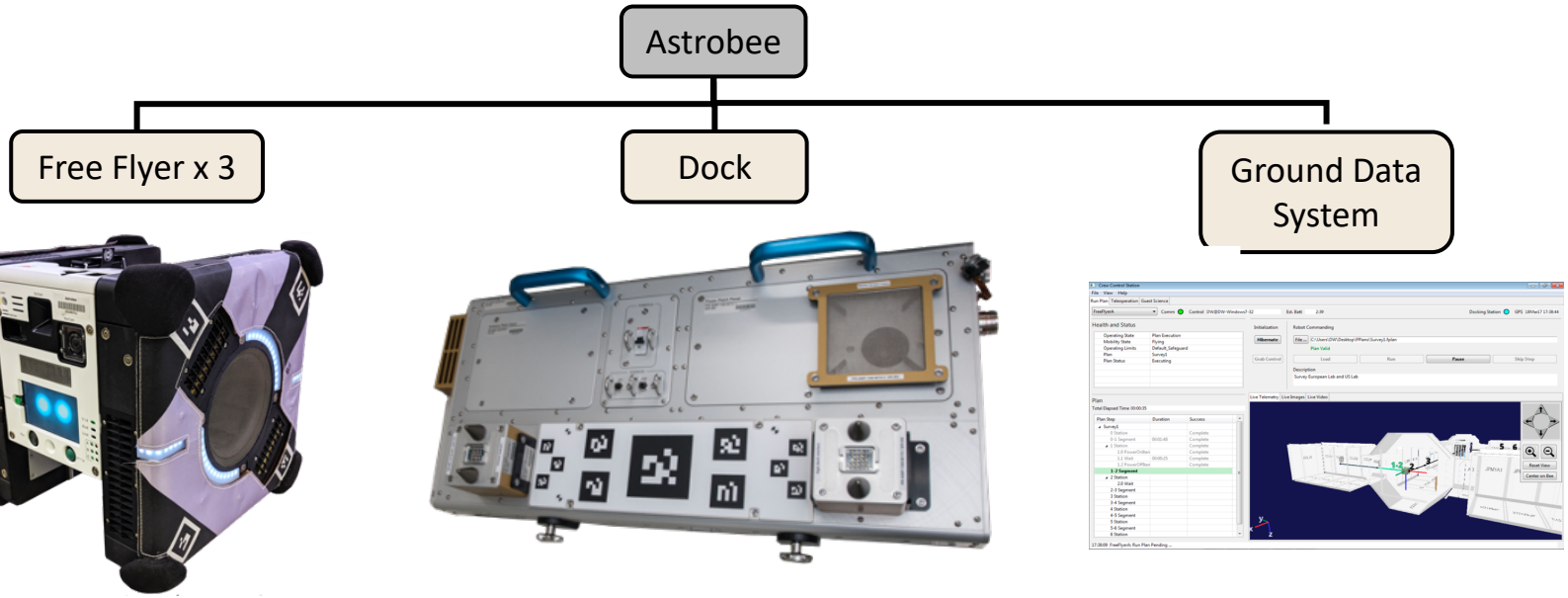
Video: Astrobee First 4 Years



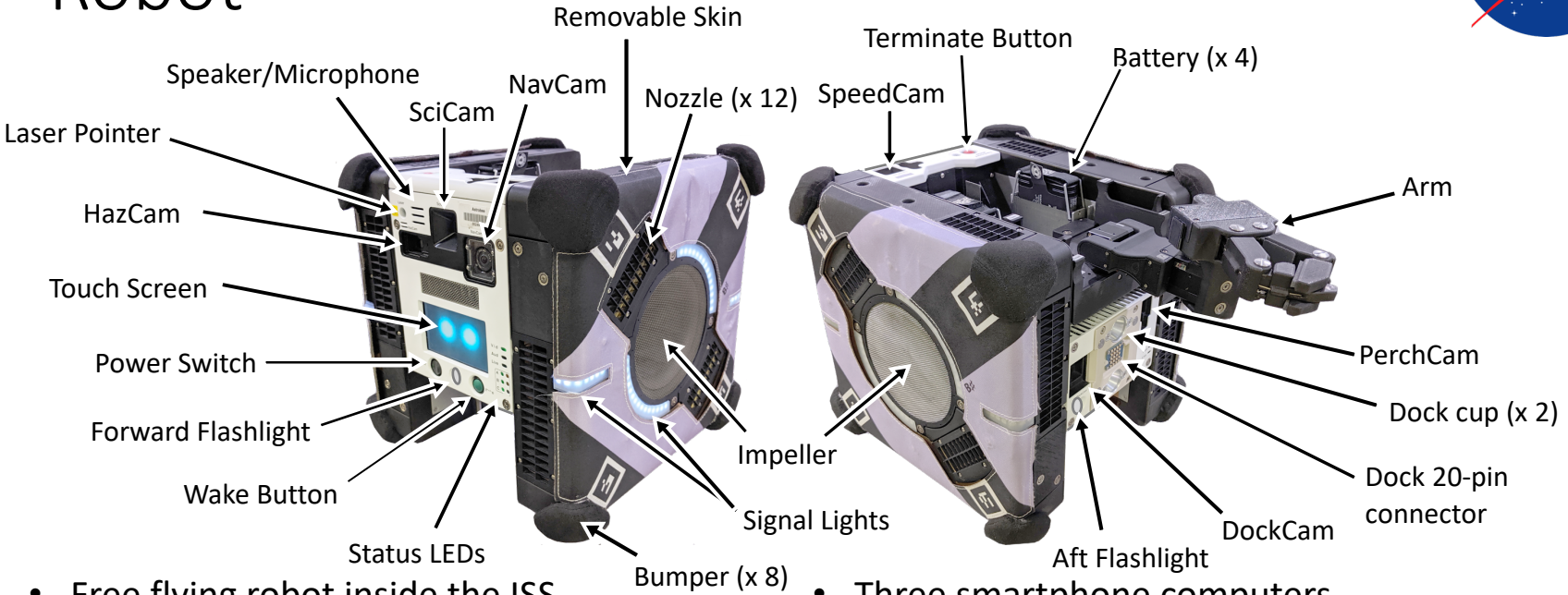
SYSTEM OVERVIEW



Astrobee Elements



Robot

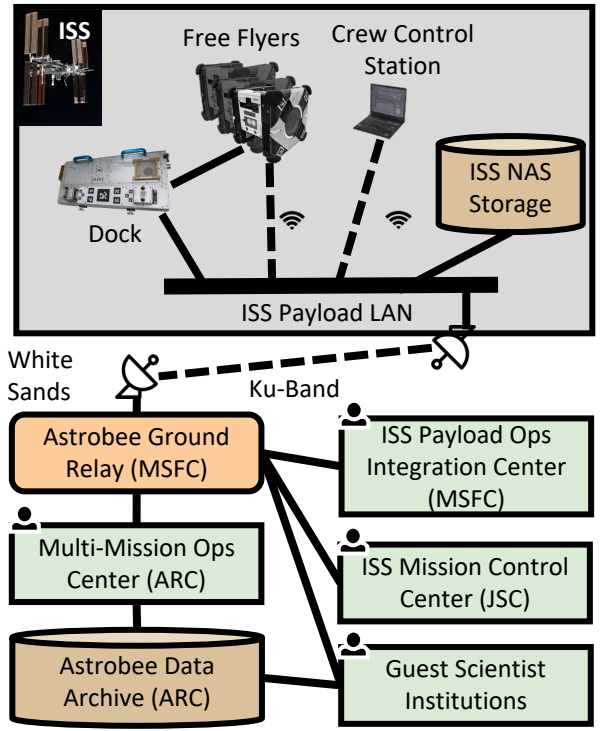


- Free flying robot inside the ISS
- 32 cm wide, ~9.1kg (2 batt., no arm)
- All electric + fan-based propulsion
- Robot arm for “perching”, ~1kg

- Three smartphone computers
- Three payload bays for expansion
- Microphone not currently enabled

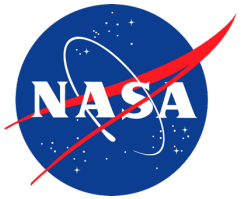
Communications

- Communicates through ISS WiFi when flying
- Single telemetry/video stream to ground
- Multiple ground stations can connect through server
- Large file transfers and software updates through Ethernet on the dock



Astrobee communications path

Computing and Software Architecture

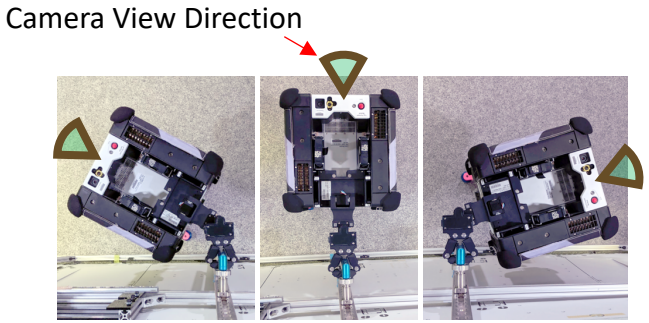


- Multiple processors isolate software to provide robustness
- Flight software uses service-oriented architecture, built on Robot Operating System (ROS) middleware

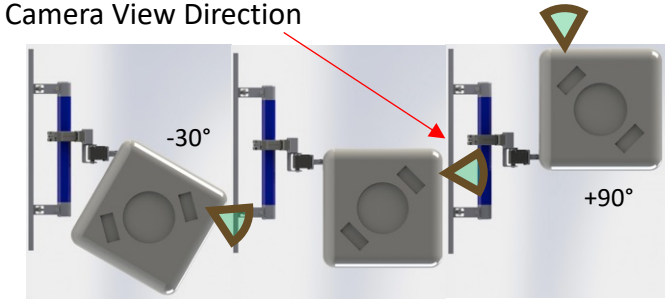
Processor	Purpose	Type	Comm	OS
Low-Level Processor (LLP)	High-rate control SW in isolation from the rest of the SW	Wandboard Dual, 1 GHz, 3W max power	Ethernet, USB 2.0, I^2C	Ubuntu Linux
Mid-Level Processor (MLP)	Most infrastructure SW (e.g. machine vision) in isolation from guest SW	InForce IFC6501, Snapdragon 805	Ethernet, USB 2.0, I^2C, WiFi	
High-Level Processor (HLP)	HD video compression, Touch screen interaction, Guest science	InForce IFC6601, Snapdragon 820		Android
Microcontrollers	Power management, Prop modules, Perching arm	PIC	USB 2.0 or I^2C	

Perching Arm

- Designed to grasp handrails
- Stows completely in payload bay
- Acts as a pan-tilt unit while perched
- Flexible and back-drivable
- May be perched manually

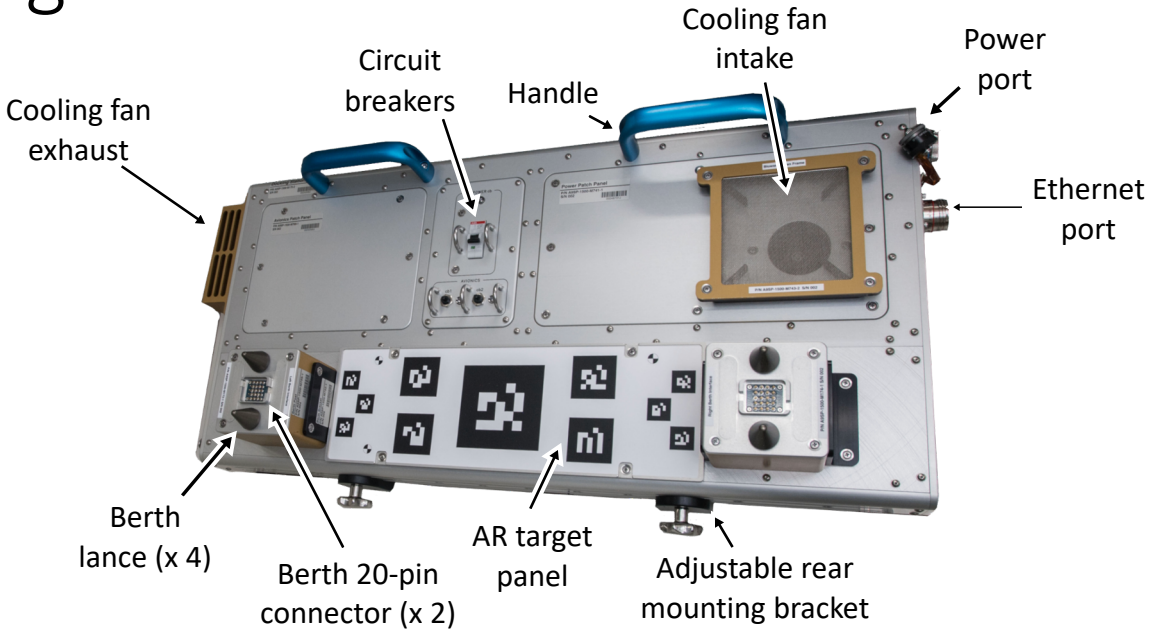


Astrobee Perching Arm pan motion



Astrobee Perching Arm tilt motion

Docking Station



- 85 cm x 38 cm x 28 cm
- Berths for 2 free flyers
- Provides power and Ethernet

- Fiducials used for visual servoing to autonomously dock
- Magnets provide retention force

Basic Conops

- When an Astrobee is idle, it charges in its dock
- Astrobees can execute complex plans with full autonomy and no astronauts present
  - Including undock, traverse multiple modules *(only Japanese Experiment Module (JEM) currently mapped)*, return to dock
- Astrobees run with ground operator oversight
  - When an anomaly occurs, an Astrobee generally stops and waits for operator intervention
  - It can continue operating during communication outages until it encounters an anomaly
- The operator can always take over and teleoperate
- Astronauts can also be operators, but this is will likely be a rare occurrence (objective to minimize crew time)

Hardware Status

- All planned on-orbit hardware is aboard the ISS
- Flight Spare Bee and Dock at JSC Bonded Stores

Date	Flight	Astrobee Cargo
2018-11-15	NG-10	Docking Station
2019-04-17	NG-11	Honey Bee, Bumble Bee, 16 batteries, Dock spare parts
2019-07-25	SpX-18	Queen Bee, 8 batteries, 3 perching arms
2019-11-02	NG-12	Astrobee spare parts

PROPULSION



Inside Only

- Intra-Vehicular (IV) vs. Extra-Vehicular (EV)
- For research, it would be ideal to operate in both environments
- Why does Astrobee only operate in IV environment?
  - **Safety:** Malfunctioning EV free flyer has room to build up a lot of speed and could damage station
  - **Utility:** EV-compatible propulsion would require reaction mass refueling and shorter max sortie duration
  - **Cost:** IV-only system can use cheap, capable COTS hardware components that are not EV-compatible

Design

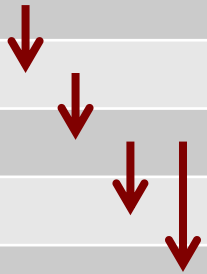
- All-electric propulsion simplifies recharge
- Two interchangeable modules
  - Each has a central impeller
  - Two impellers counter-rotate to cancel torque
- Max acceleration 10 cm/s^2
- Moving parts enclosed



Cert Unit propulsion module, skin not installed

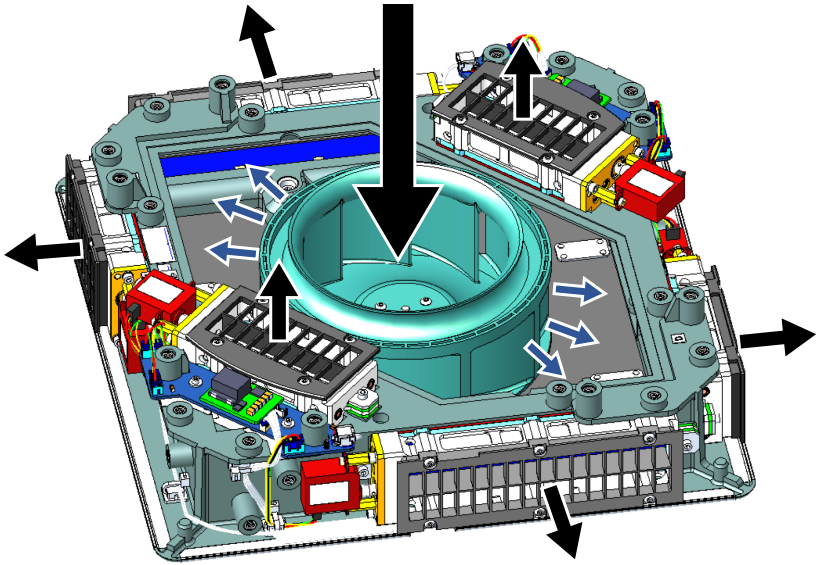
Propulsion Comparison

Topic	SPHERES	Astrobee
Mission	Research platform	Research platform + utility robot
Design drivers	As close as possible to EV-compatible	Low crew overhead, support longer sorties
Approach	Cold gas	Battery-powered fans
Refueling	Crew replaces battery packs and CO2 tank	Autonomous dock and recharge
Reaction mass	Limited (CO2 tank)	Unlimited (cabin air)
Performance challenge	Reaction mass efficiency	Power efficiency
Exhaust velocity	High (~250 m/s)	Low (~11 m/s)
Max pressure	High (~870 psi at CO2 tank)	Low (~0.1 psi in plenum)
Nozzle area	Low (~0.005 cm^2)	High (~40-65 cm^2), total ~10% of surface area



Air Flow

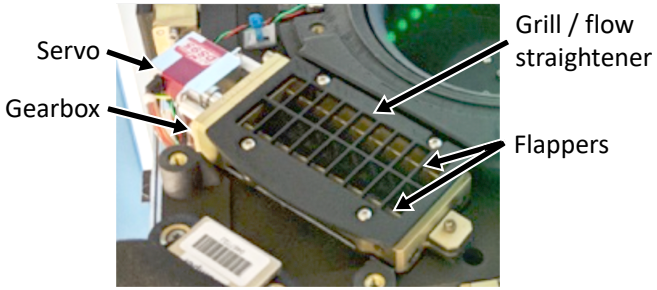
- Each propulsion module is built around a plenum
- Centrifugal impeller draws air in through an intake
- Lightly pressurizes plenum (~0.1 PSI over ambient)
- Air flows out through six nozzles
- 12 nozzles in all, sufficient to provide holonomic control
- Impellers rotate at the same speed in opposite directions, canceling gyroscopic moment and drag torque

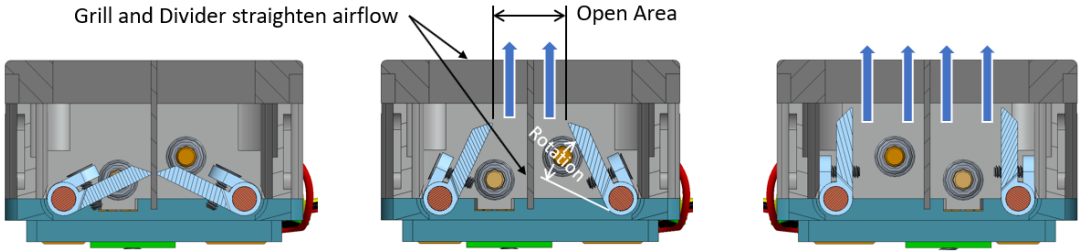


Air flow through an Astrobee propulsion module (cover removed to expose plenum cavity)

Nozzles and Efficiency

- Nozzles blow air in a fixed direction with an adjustable flow rate
- Propulsion efficiency:
  - For typical spacecraft, achievable Δv for propellant mass fraction scales linearly with the thruster exhaust velocity (v_e).
  - Astrobee has unlimited propellant, and focuses on power efficiency of thrust (W/N), which scales inversely with v_e
  - Astrobee operates efficiently with low plenum pressure (~0.1 psi) and exhaust velocity (~11 m/s)
  - SPHERES satellites use EV-analog cold gas thrusters that operate at ~25 psi with exhaust velocity ~250 m/s.





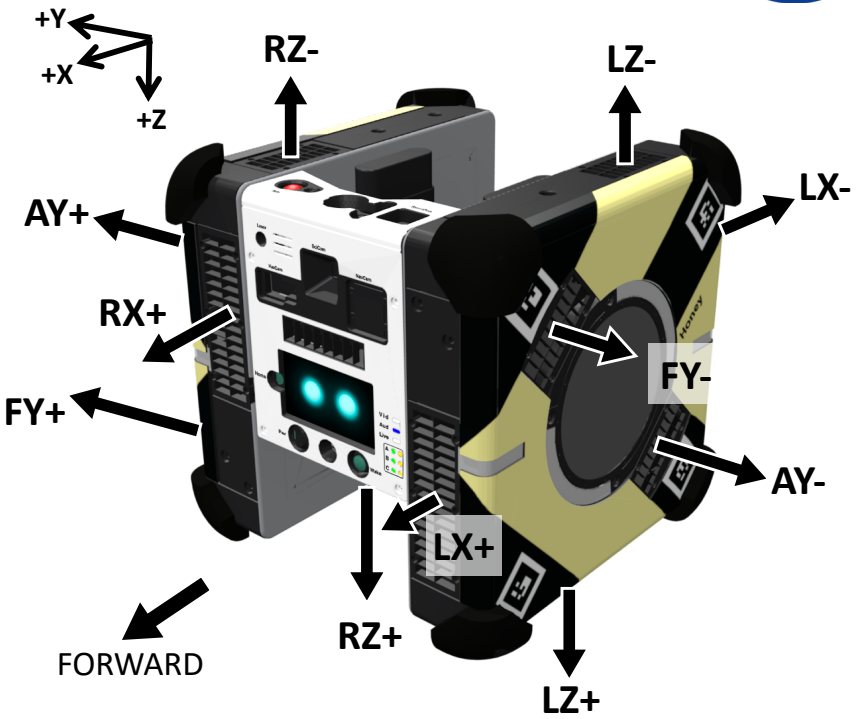
Closed
(no airflow, no thrust)

Opened
(airflow produces thrust)

Full Open
(maximum thrust)

Holonomic Control

- Thrust vectors do not pass through the robot's center of mass
- Matched pairs provide pure force along an axis or pure torque about an axis
- Non-symmetrical performance
  - Thrust performance greatest on the x-axis: largest nozzles
  - Weakest on the y-axis: uses two nozzles on the same propulsion module
  - Maximum torque in yaw
- Forward facing sensors make forward the preferred direction of flight

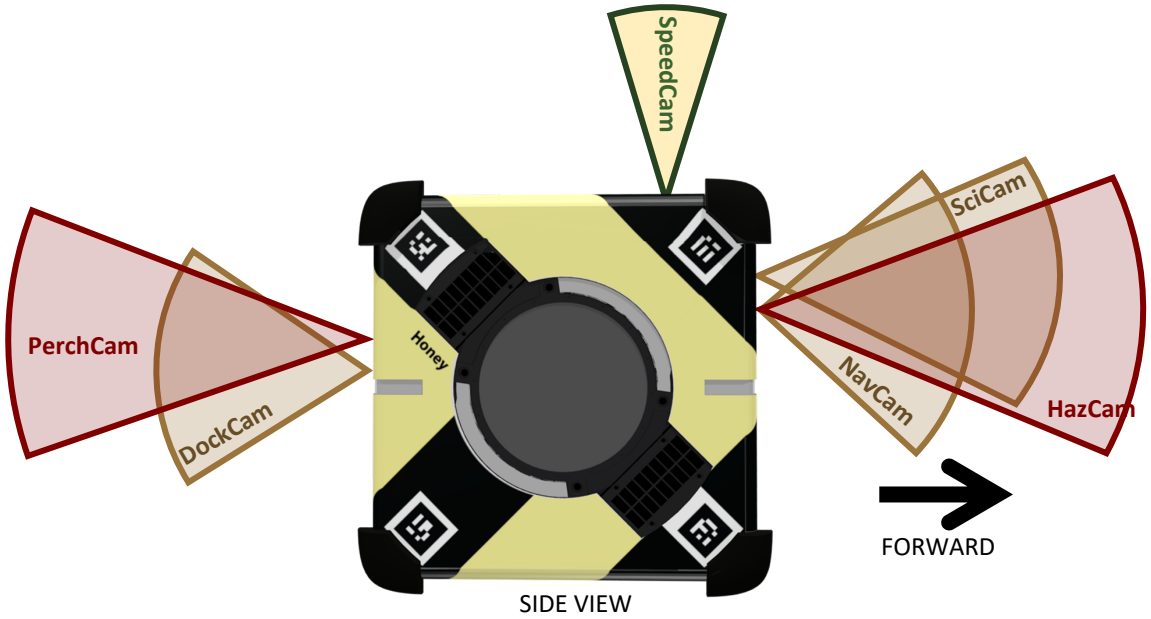


Thrust vectors of Astrobee nozzles

VISION-BASED NAVIGATION



External Sensors



Sensor	Purpose	Type
NavCam	Localization – General-purpose	Camera
DockCam	Localization – Fiducial-relative while docking	Camera
SciCam	HD video streaming and recording	Camera
SpeedCam	Redundant over-speed cutoff	Camera + Rangefinder , IMU
HazCam	Obstacle avoidance	Depth
PerchCam	Localization – Handrail-relative while perching	Depth

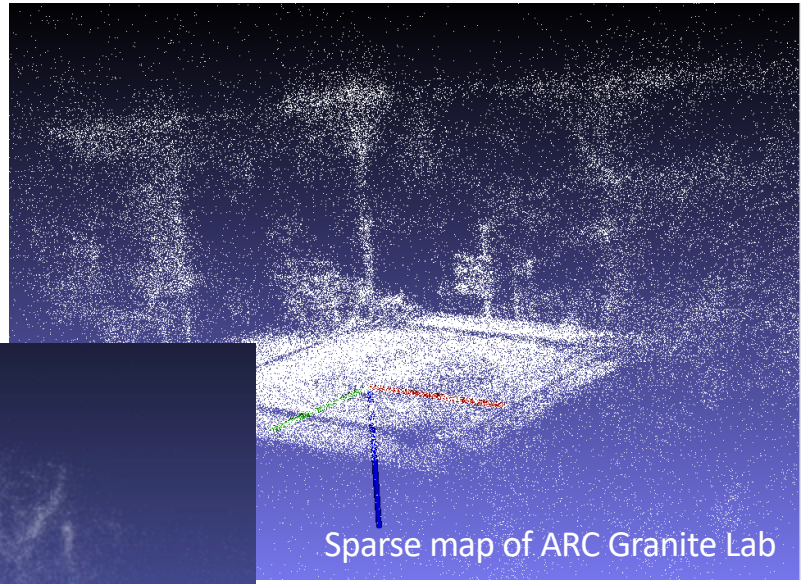
Position Estimation

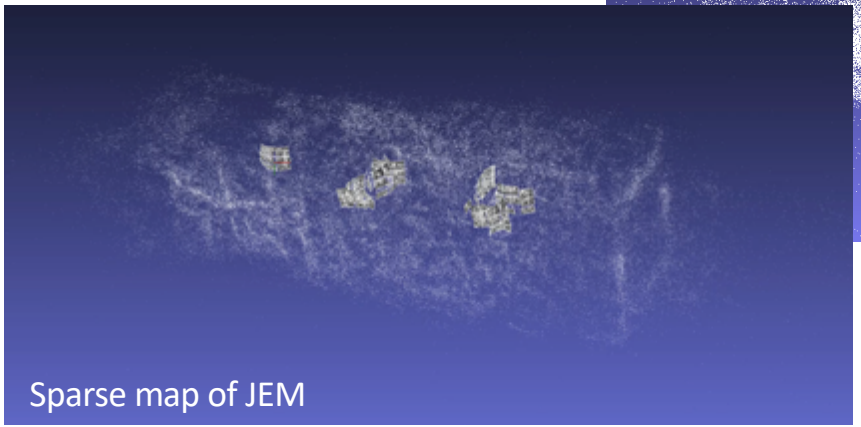
- All modes use augmented-state Extended Kalman Filter (EKF), and gyroscope and accelerometer from IMU

Mode	Operational Envelope	Additional EKF Inputs	Performance
General-purpose	Throughout ISS, with no infrastructure	2 Hz visual navigation, 6 Hz optical flow (NavCam)	~5 cm
Fiducial-relative	Vicinity of dock, Designated workspace with added fiducials	Fiducial tracking (DockCam)	~1 cm
Perch-relative	Vicinity of handrail	Perch estimator using PerchCam 3D point clouds	~2 cm

Offline Sparse Mapping

- Map built offline from images to localize the robot against interest points
- Map consists of:
  - Interest point descriptors
  - Interest point 3D location estimates





Sparse Map Building

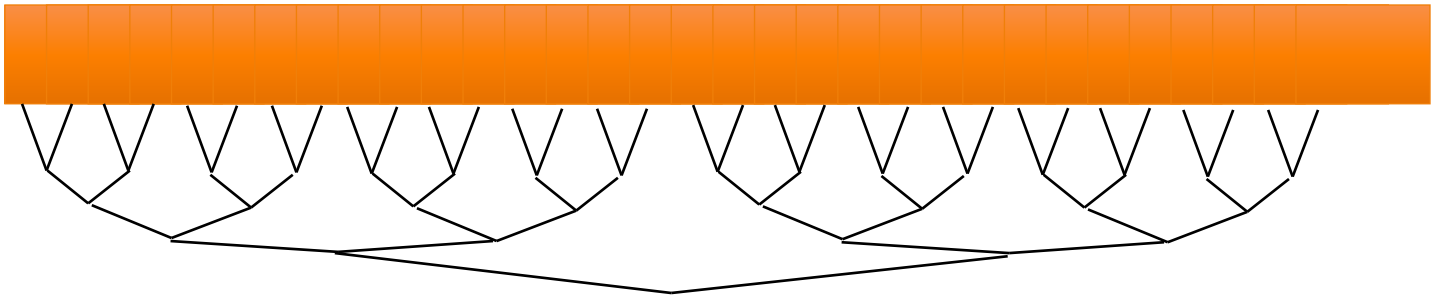
1. Collect images from different perspectives.
2. Detect SURF features on all images.
3. Match features between image pairs.
4. Form tracks of features that are seen in multiple images, triangulate initial camera pose and interest point location estimates.



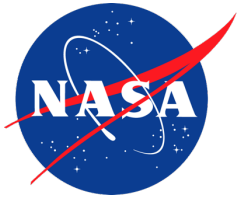
Visual features in ARC Granite Lab

Sparse Map Building (continued)

5. Simultaneously solve for 3D positions of tracked features and camera poses with incremental bundle adjustment on images in a tree structure.
6. Adjust map with global bundle adjustment, remove outlier interest points.
7. Rebuild map with known camera poses and faster BRISK features.
8. Register to fixed coordinate frame by manually selecting known locations on images.
9. Build bag of words database to quickly search for similar images.



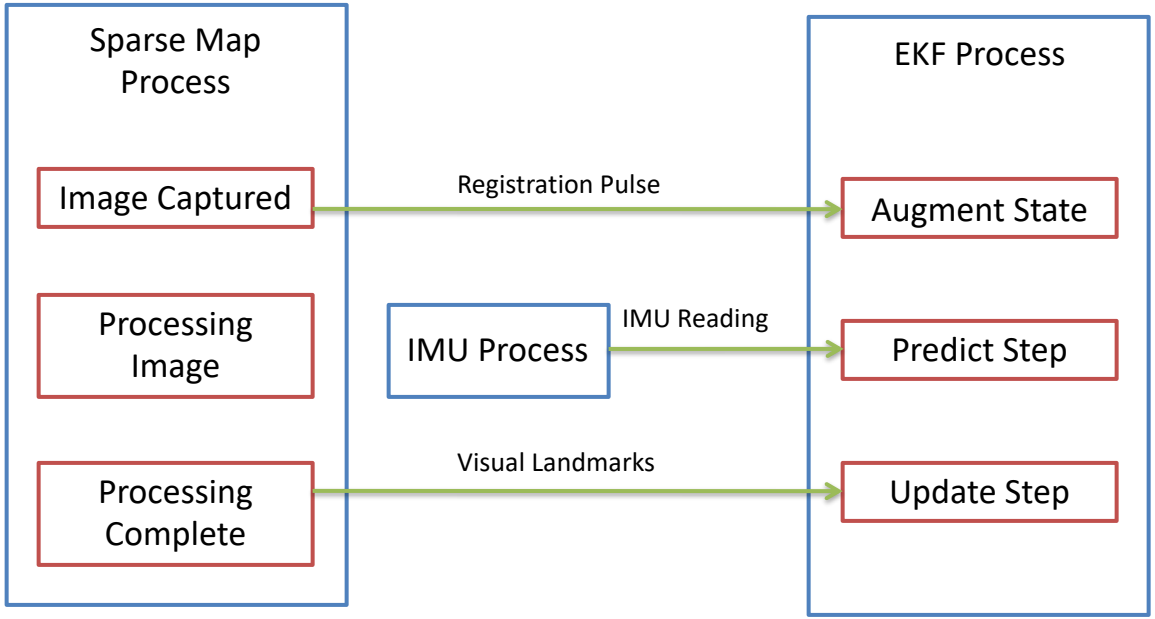
Visual Features for Localization



- Sparse Map Features:
  1. Detect BRISK features.
  2. Find similar images with bag of words database.
  3. Use RANSAC with P3P to find set of inlier matches.
  4. Send inlier pixel coordinates and 3D positions to EKF.
- AR Tags
  - Corners sent to EKF just like sparse map features.
- Handrails
  - Detected with time of flight depth sensor, points passed to EKF along with handrail axis.
- Optical Flow Features
  - Lucas-Kanade with Good Features to Track
  - Backwards tracking to remove outliers

EKF Position Tracking

- Approach based on augmented error state extended Kalman filter by Mourikis, Trawny, Roumeliotis, et.al.
  - Runs at 62.5 Hz
- Key idea: account for delay in image processing
  - Runs at 1-2 Hz
- Essentially allows EKF to rewind and apply each localizer update at correct time when it was captured

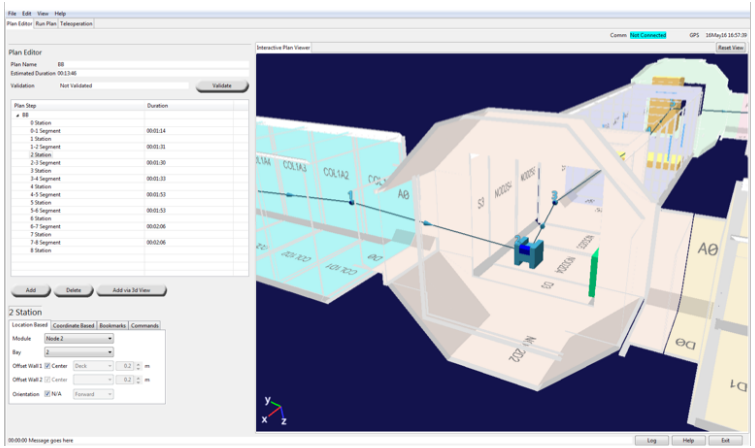


HUMAN INTERFACES



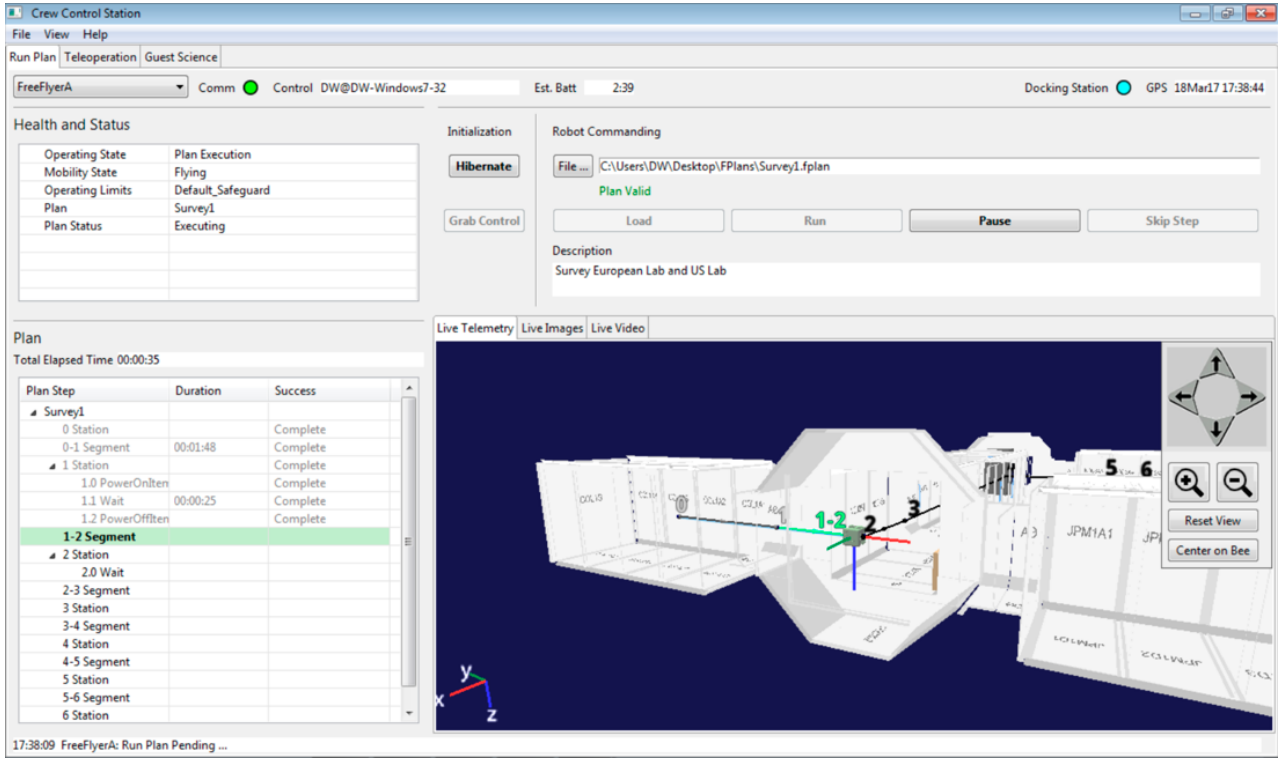
Ground Data System

- Astrobee Control Station
  - Sortie planning tool
  - Execution monitoring
    - Live telemetry
    - Image and video streams
    - 3D virtual display
  - Supervisory control (run plans or single commands)
  - 3D visualization + live video and status displays
  - Typically used by ground operators
- Crew Control Station (used rarely) runs on an EXPRESS Laptop Computer (ELC)
- Server for archiving and distributing Astrobee data
- Suite of engineering tools to support maintenance and software upgrades



Astrobee Control Station Plan Editor

See Crew Operator Training Video

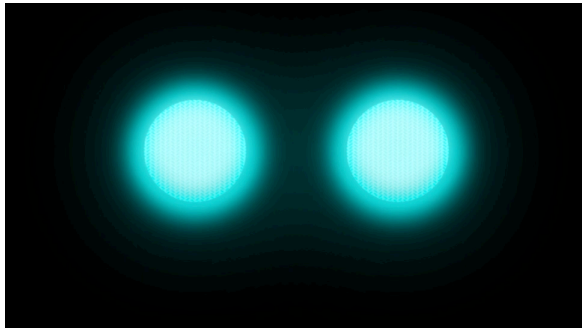


https://images.nasa.gov/details-ARC-20181114-Astrobee-OperatorTraining.html

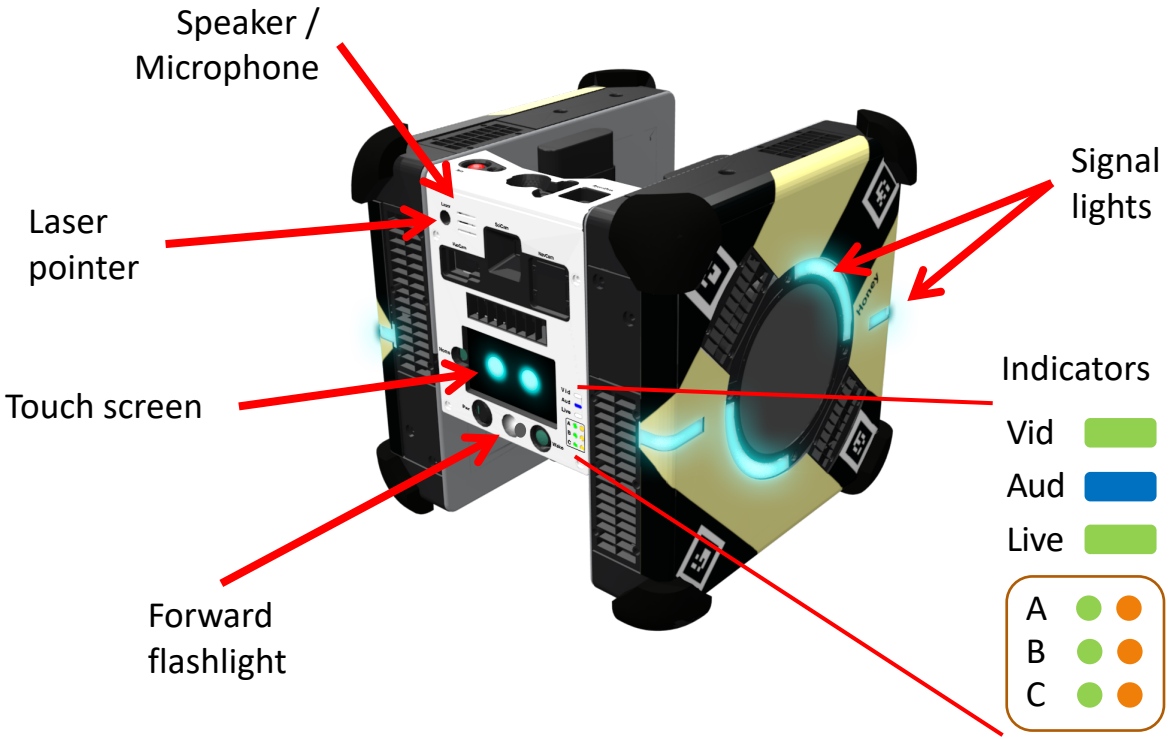
Control Centers

- Astrobee can be operated from almost anywhere
  - Flight controllers at Mission Control Center (JSC)
  - Payload controllers at Payload Operations Integration Center (MSFC)
  - Guest scientists at Multi-Mission Operations Center (ARC) or home institutions
- Provides flight controllers with a mobile camera for improved ground situation awareness during crew activities
  - Optimize viewing angles using the pan/tilt or by relocating Astrobee
- Supervisory control means 100% of operator's attention is not required

Human-Robot Interaction



Names, colors, and eye animations give the robots personalities.



Video: Astrobee Commissioning Highlights



Acknowledgments

- Astrobee is a team effort involving ~60 outstanding engineers
  - We have also been lucky to work with many excellent interns!
- Funded by:
  - NASA Game Changing Development Program (Space Technology Mission Directorate)
  - ISS SPHERES Facility (Human Exploration and Operations Mission Directorate)
- Thanks go to:
  - ISS SPHERES Team
  - ISS Payloads Office
  - JSC Flight Operations Directorate
  - ISS Avionics and Software
  - Advanced Exploration Systems Program

Questions?



Christina Koch and “Bumble”