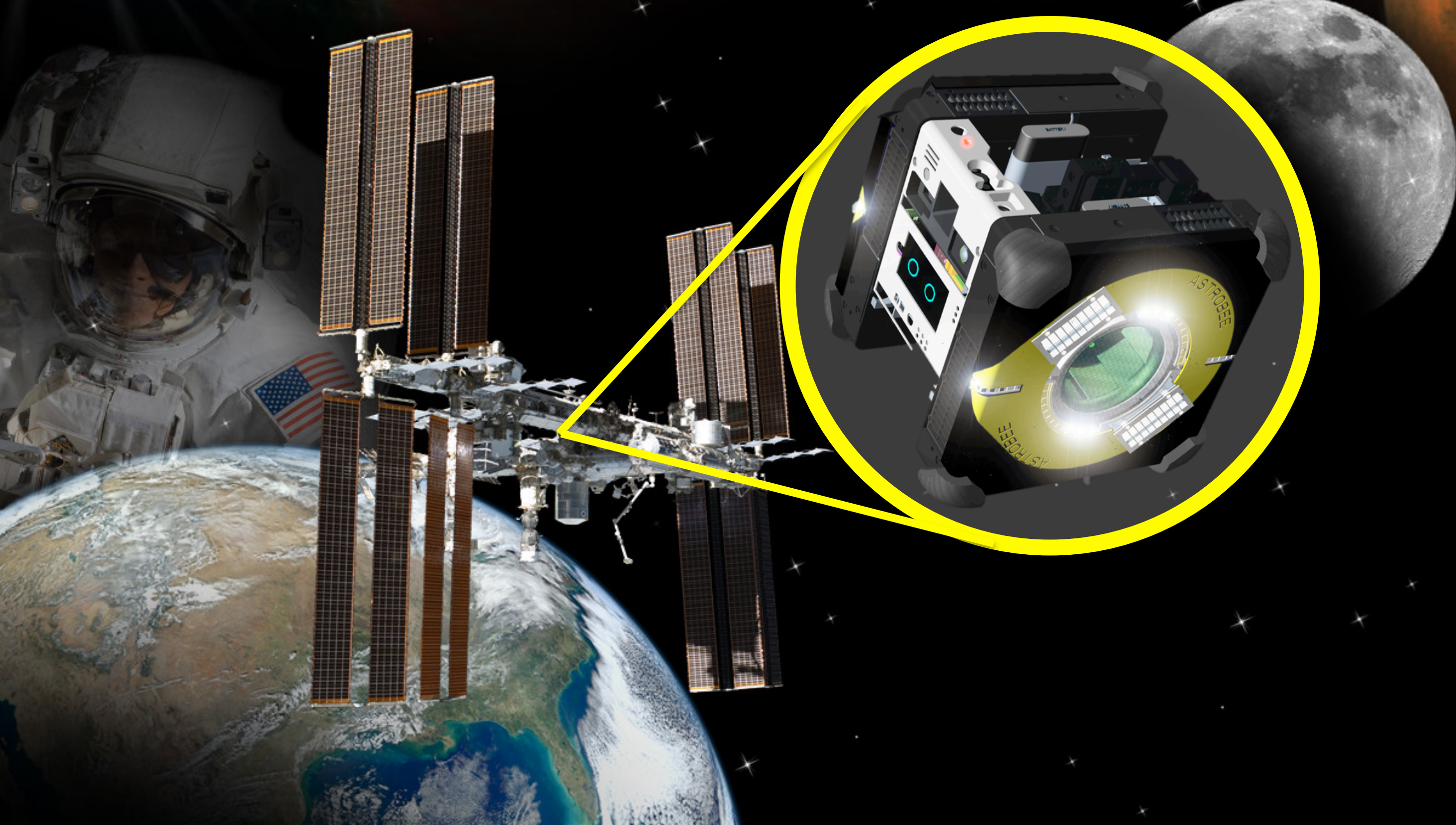
Telerobotics at NASA Ames

NESS Steering Committee Meeting



Terry Fong

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2019-09-25

Topics

1. **ISS Astrobee free-flying robot**
   Intra-Vehicular Robotics (IVR) research & development

2. **Integrated System for Autonomous and Adaptive Caretaking**
   Prototype software for Gateway internal caretaking

3. **Smart Deep Space Habitats**
   Multi-year research institutes funded by STMD

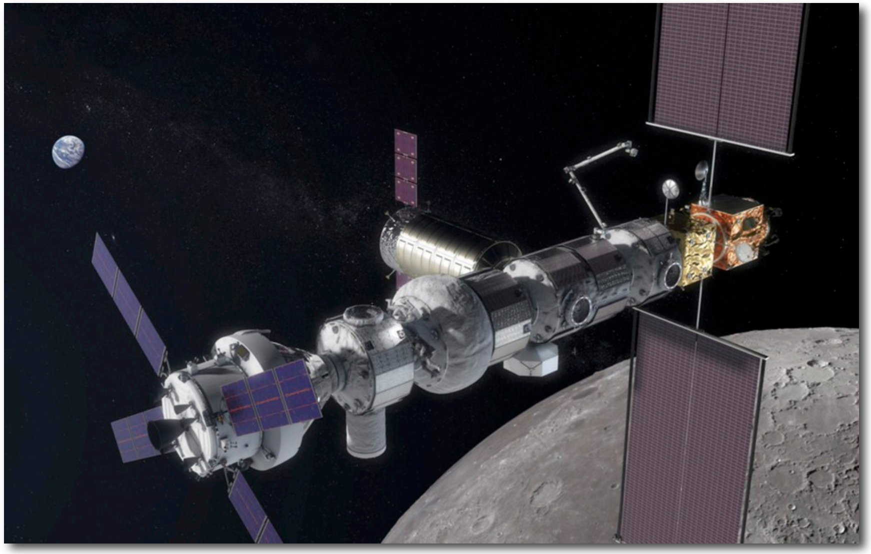
Intra-Vehicular Robotics

Motivation

- Intra-Vehicular Robotics (IVR) is the robotic system capability to perform IVA tasks in an **autonomous** or **remotely operated** manner
- Since Gateway will largely be uncrewed, IVR is **critical** and **essential** to maintain and protect the vehicle
- IVR services can be **utilized during all phases** (crewed, uncrewed, and transitions) to support operations and utilization

Benefits for Gateway

- Prepare & maintain Gateway during uncrewed phases
- Reduce crew time and effort needed for utilization and non-utilization tasks
- Enable science and other utilization tasks during uncrewed periods



IVA Free Flyers on the ISS

SPHERES (NASA) – 2006 to present

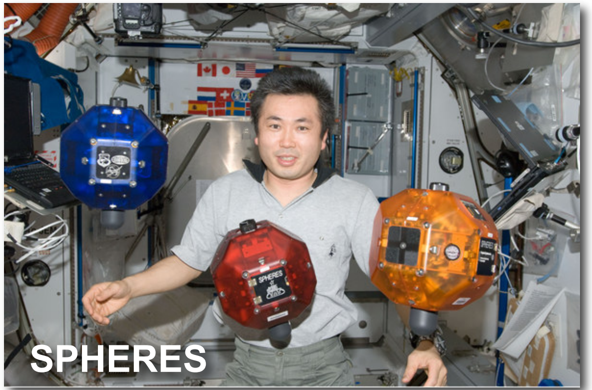
- ISS research facility used for many guest science experiments and outreach (ZeroRobotics activities)
- Astrobee will replace SPHERES, managed by the same facility team

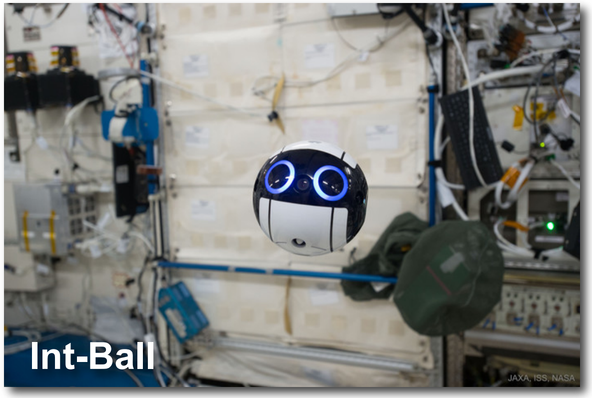
Int-Ball (JAXA) – 2017

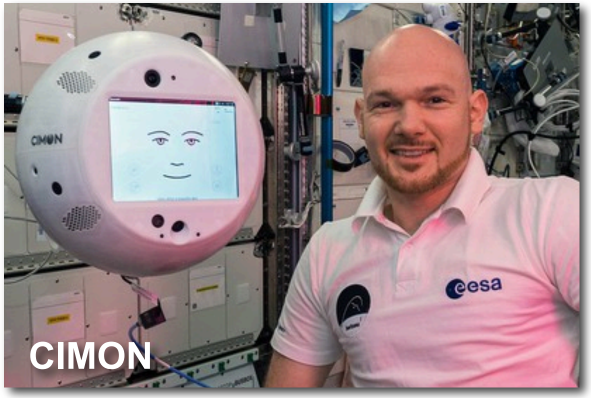
- Small size (15 cm diameter) enabled by JAXA's miniaturized all-in-one CPU / IMU / 3-axis reaction wheel module
- Joint outreach activities between Int-Ball and Astrobee in development

CIMON (DLR) – 2018

- Focus on human-robot interaction
- Uses the same batteries as Astrobee







Astrobee Project (2014 – present)

IVA Free-Flyer

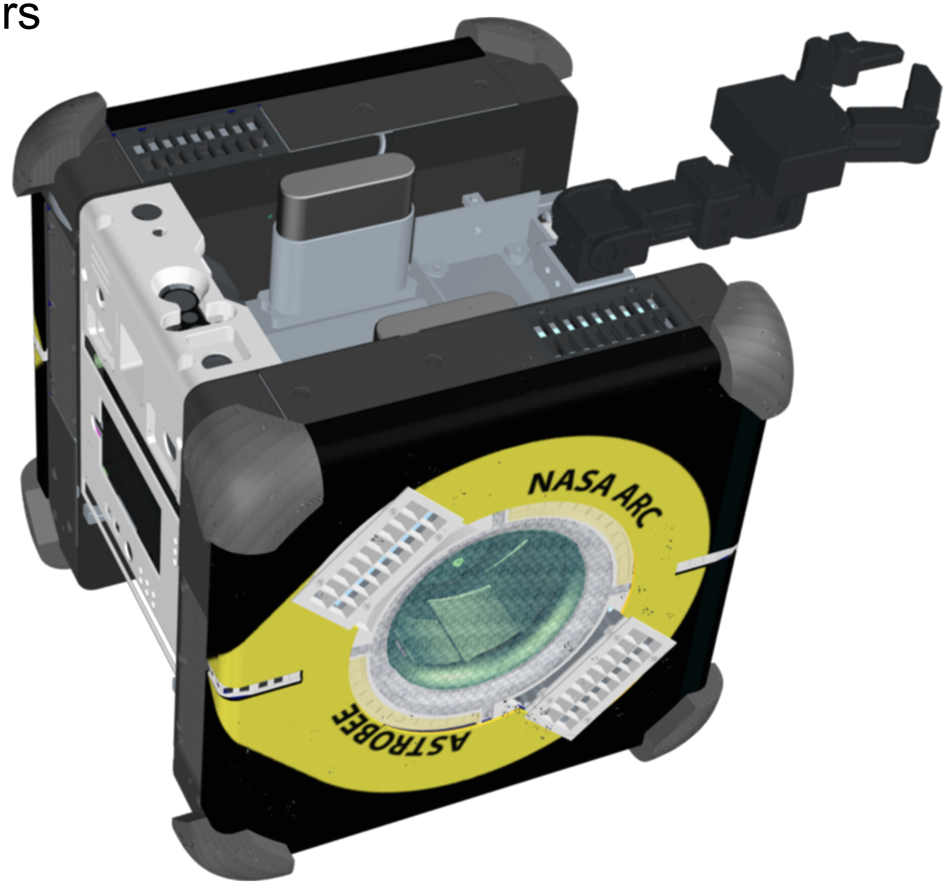
- International Space Station internal environment
- All electric with fan-based propulsion
- Three smartphone-class processors
- Expansion port for new payloads
- Open-source software
- ~32x32x32 cm, ~10 kg

Autonomy

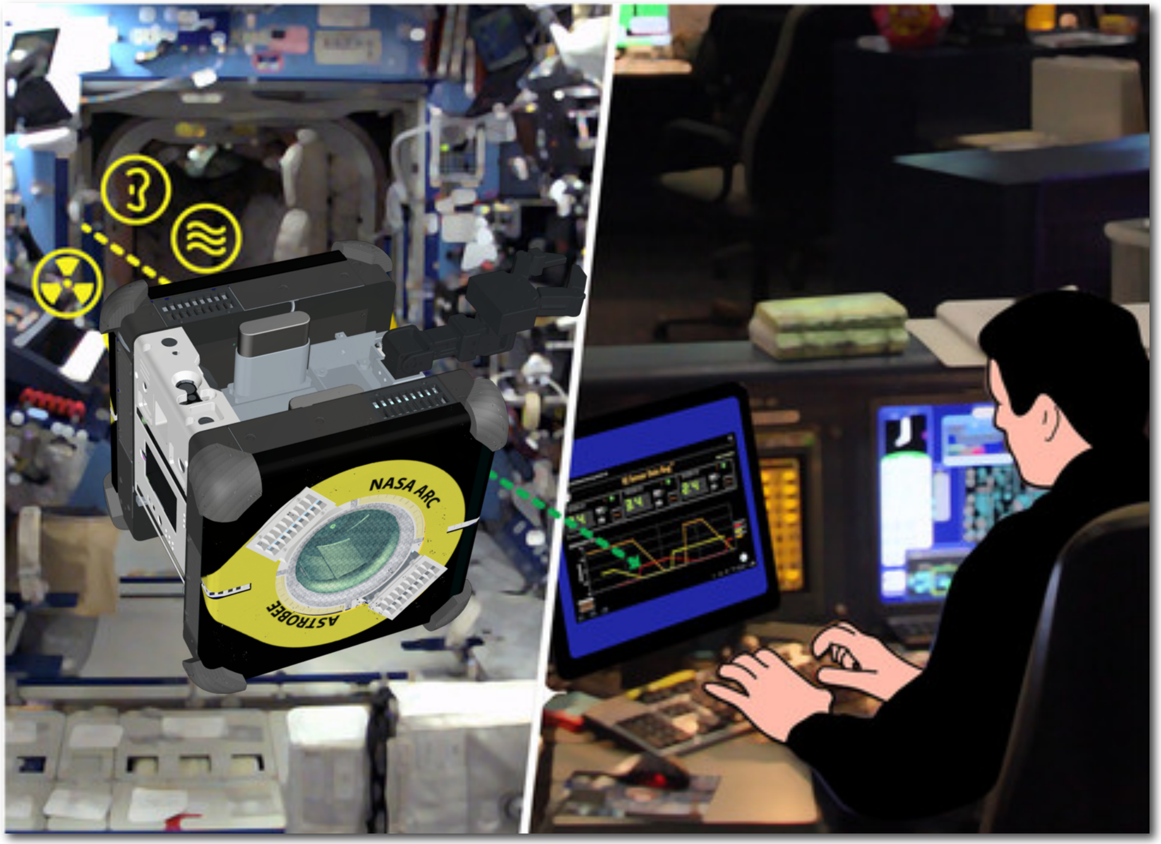
- Docking & recharge
- Perching on handrails
- Vision-based navigation

Use cases

- Mobile sensor
- Mobile camera
- Research facility



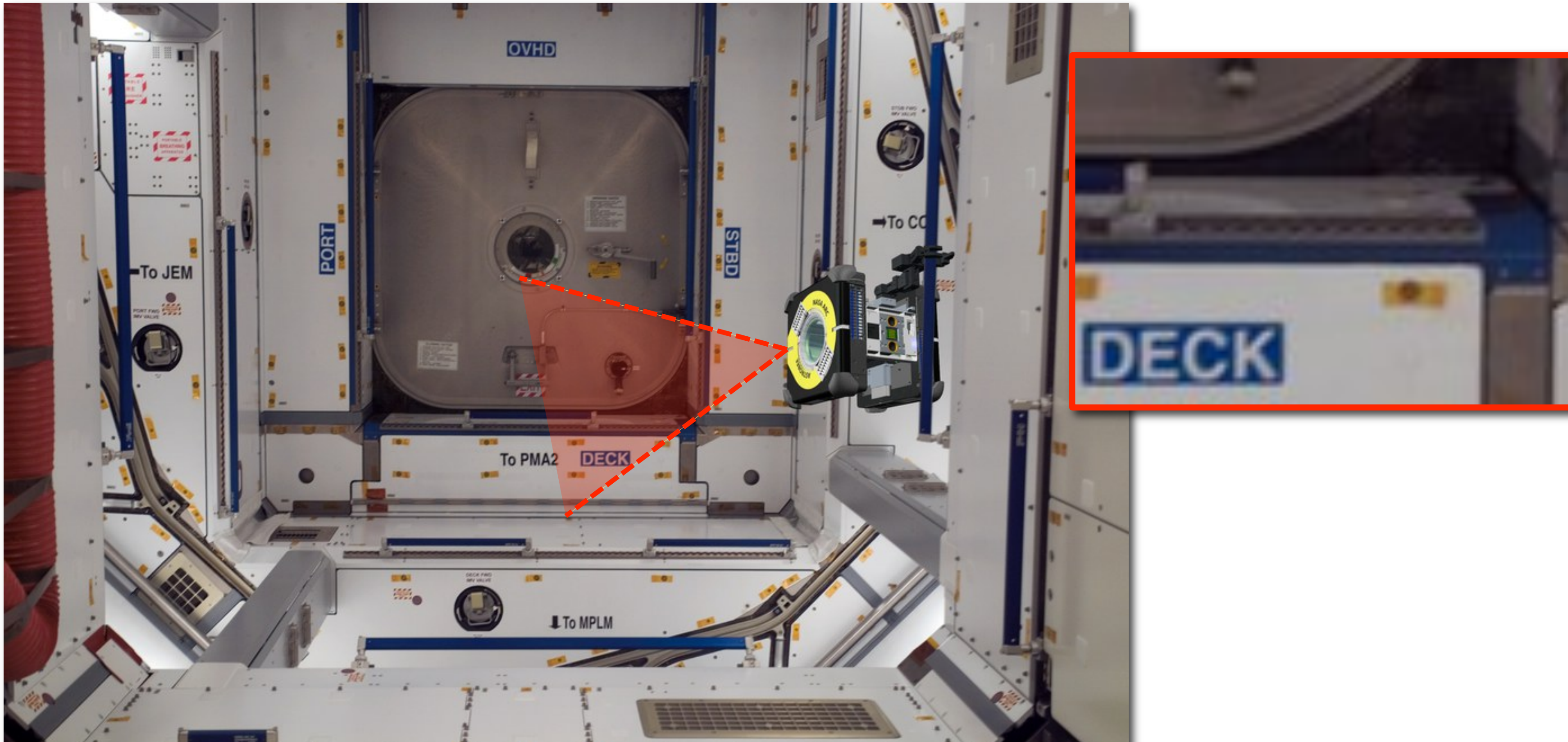
Mobile Sensor



Mission control remotely operates robot to perform IVA tasks

- Inventory (RFID tag scanning)
- Environment surveys (air quality, sound levels, etc)

Mobile Camera



Mission control remotely operates robot as a mobile camera

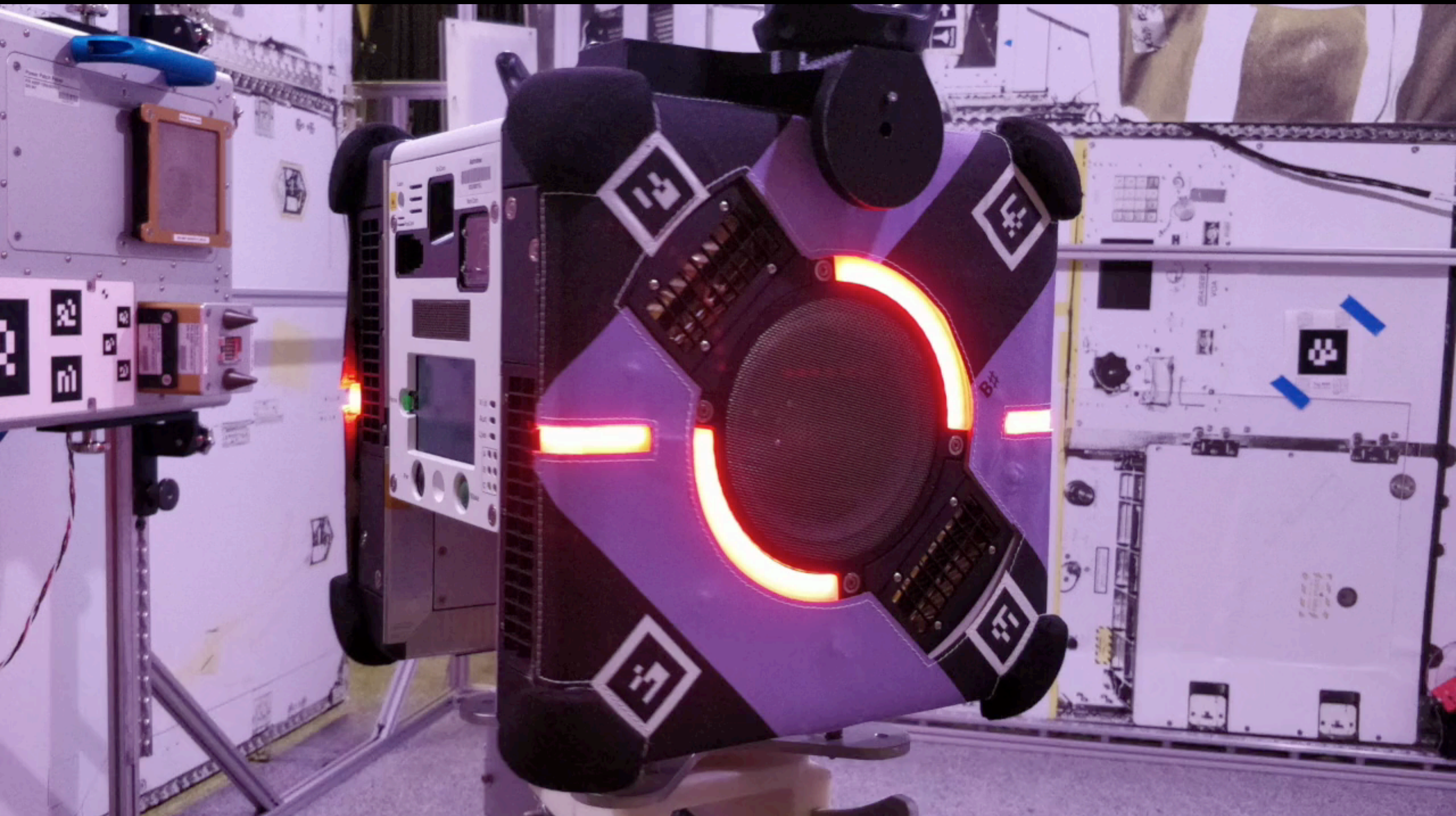
- Support astronaut work
- Better understand conditions inside the Space Station

Research Facility

Engineers, researchers, & students can use Astrobee for experiments

- New payloads – sensors, mechanisms, etc.
- New software – control, human-robot interaction, perception, etc.

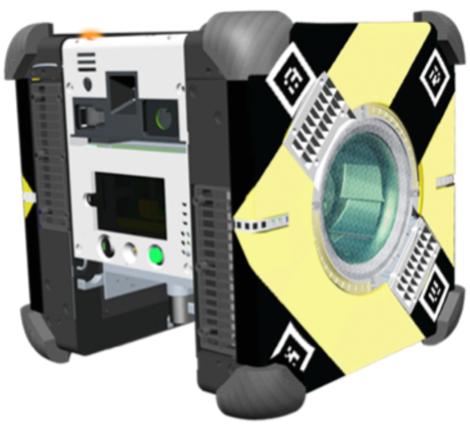

ISS ROBOTIC FREE FLYER
ASTROBEE

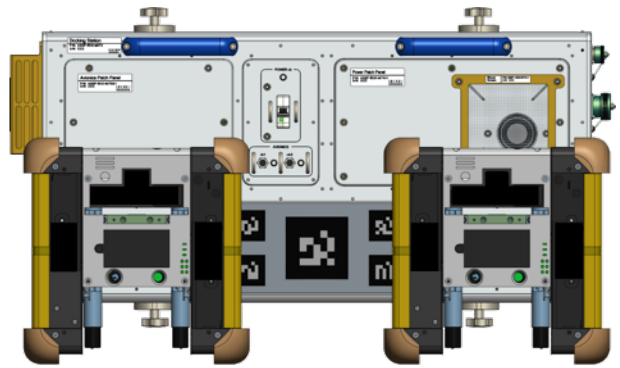


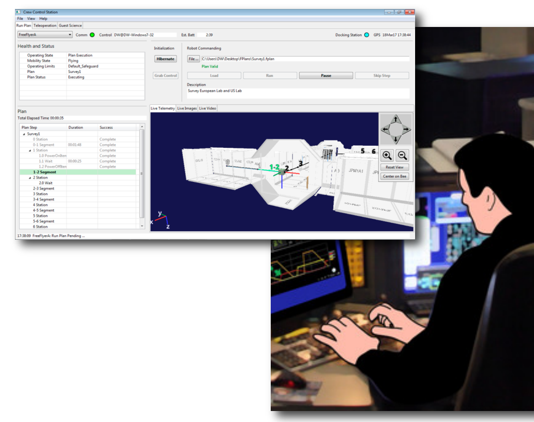
Astrobee System

Astrobee

- Robot (x3)
- Dock
- Ground Data System

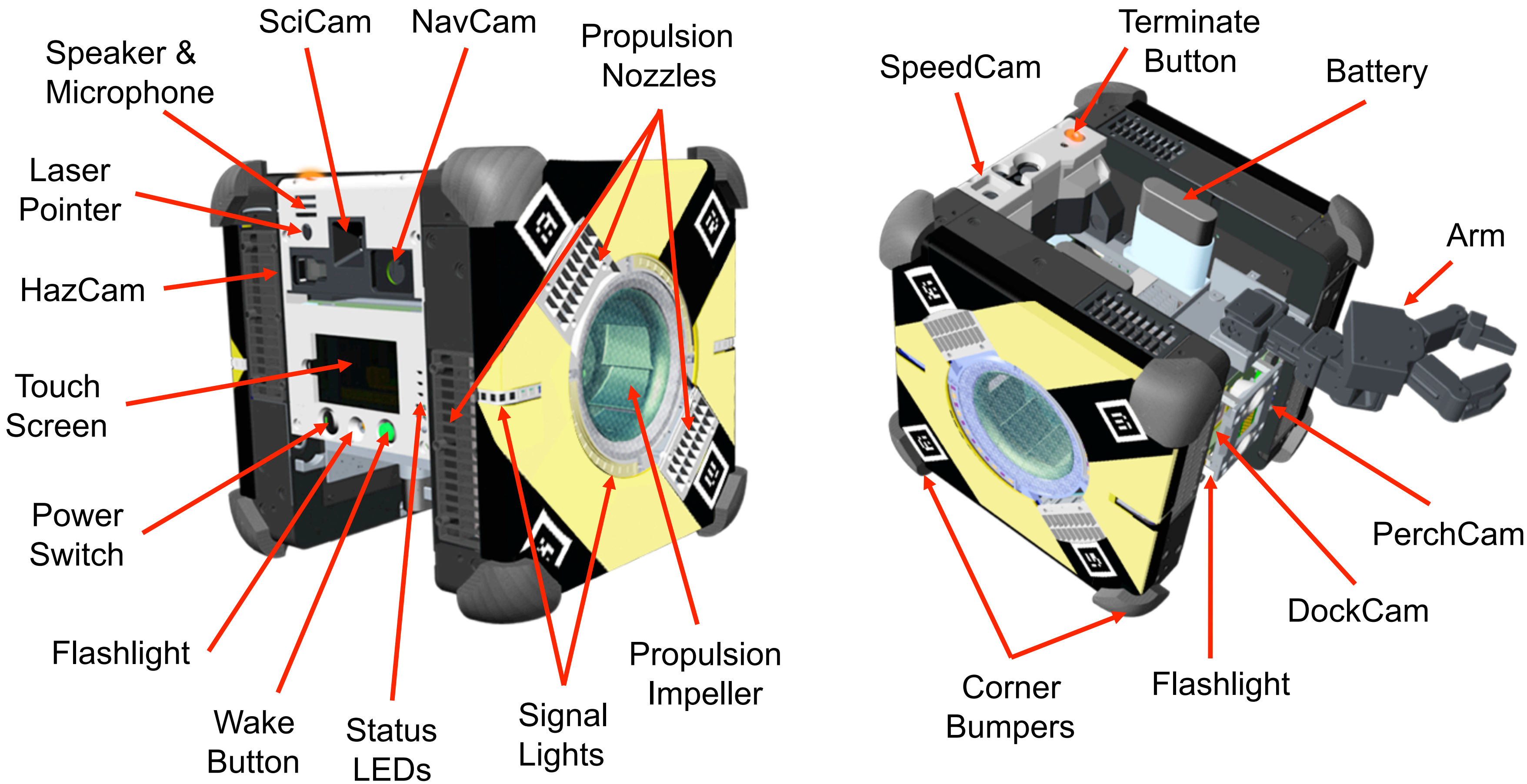






"Bumble Bee" (NG-11)
"Honey Bee" (NG-11)
"Queen Bee" (SpaceX-18)

Astrobee Robot



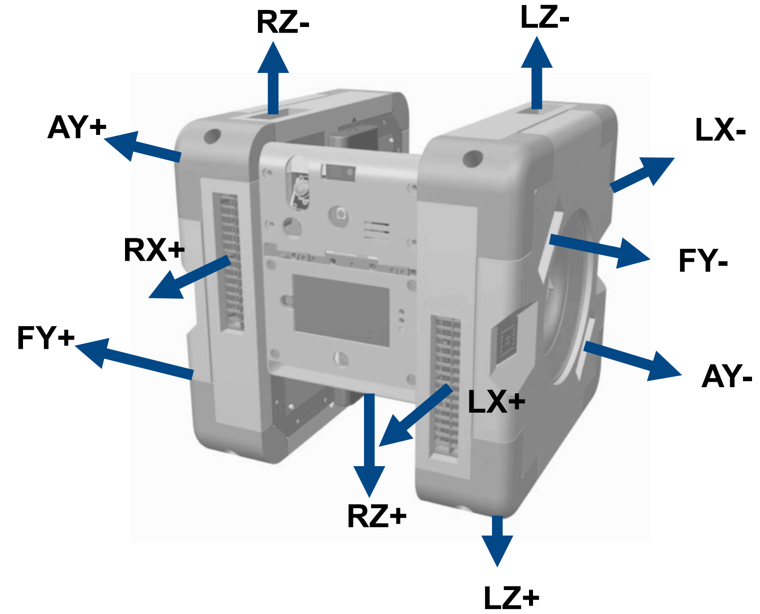
Propulsion

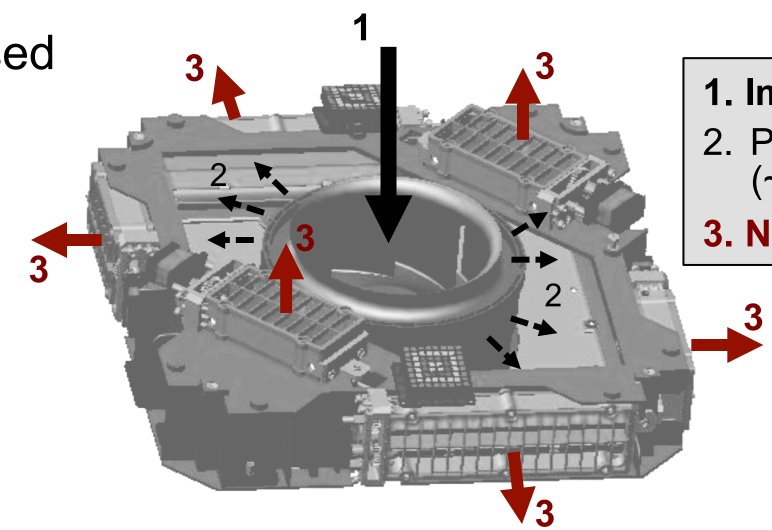
Key features

- All-electric + rechargeable
- Fully holonomic motion
- Max acceleration 10 cm/s^2
- IVA only using low-cost COTS

Two interchangeable modules

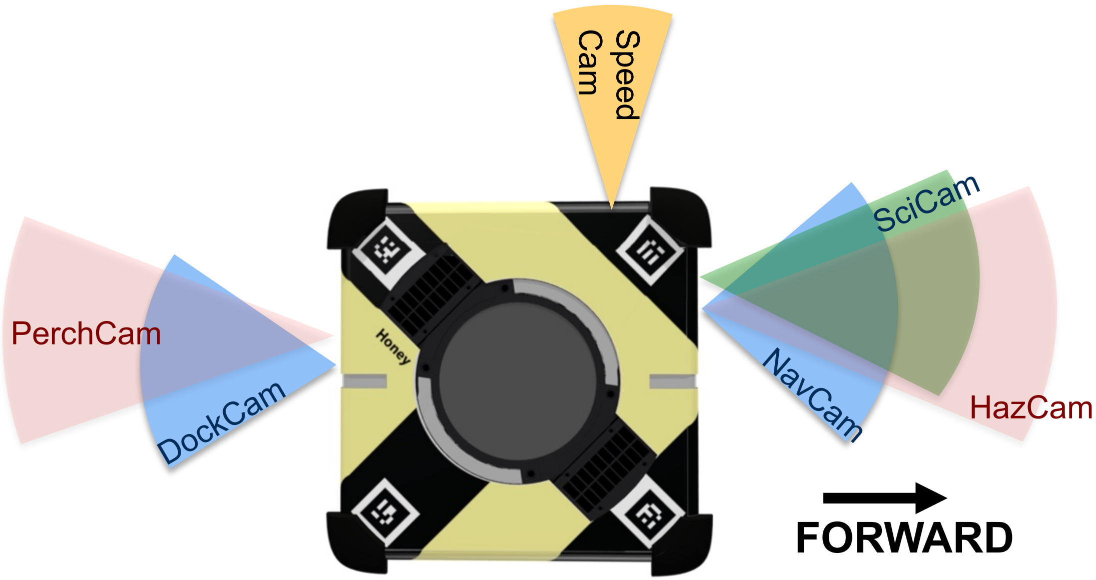
- Center impeller + plenum + nozzles (6 on each module)
- Proportional nozzle control
- All moving parts are enclosed





1. **Impeller intake**
2. Pressurize plenum (~0.1 psi)
3. **Nozzles exhaust**

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	Handrail-relative while perching	Depth

Localization

All modes use an augmented-state Extended Kalman Filter, inertial measurements, and external sensors

Mode	Operational Envelope	External sensors	Performance
General purpose	Throughout ISS (no nav. infrastructure required)	2 Hz visual navigation, 6 Hz optical flow (NavCam)	~20 cm
Fiducial relative	Vicinity of dock (designated workspace with fiducials – AR targets)	Fiducial tracking (DockCam)	~1 cm
Perch relative	Vicinity of handrail	3D point clouds (PerchCam)	~2 cm

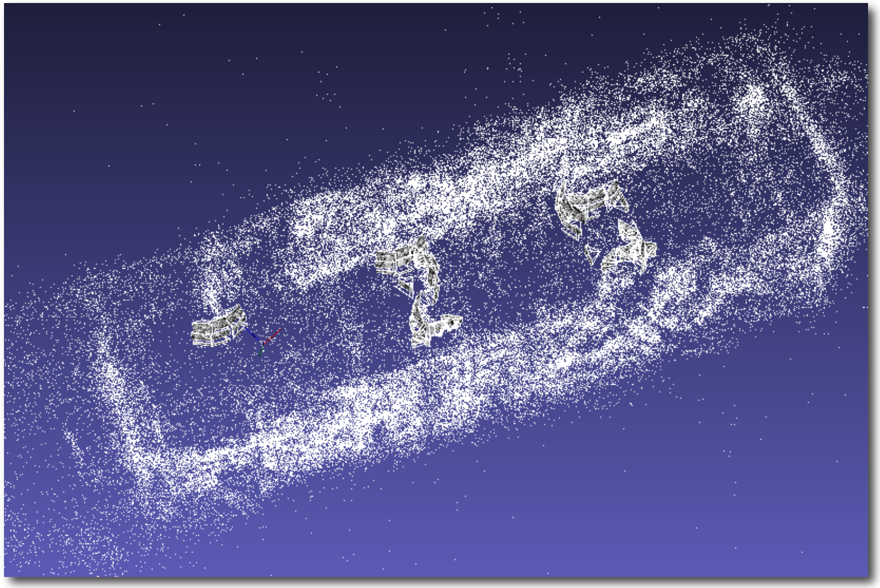
Visual Navigation

Primary mode

- Compares features with on-board map (created during non-real-time mapping phase)
- Incorporates inertial measurements during flight
- Visual odometry used when no map features are recognized
- ~20 cm accuracy

Augmented

- AR targets are used to achieve higher accuracy (~1 cm)
- Currently only used for docking
- Targets could be installed elsewhere in ISS if needed



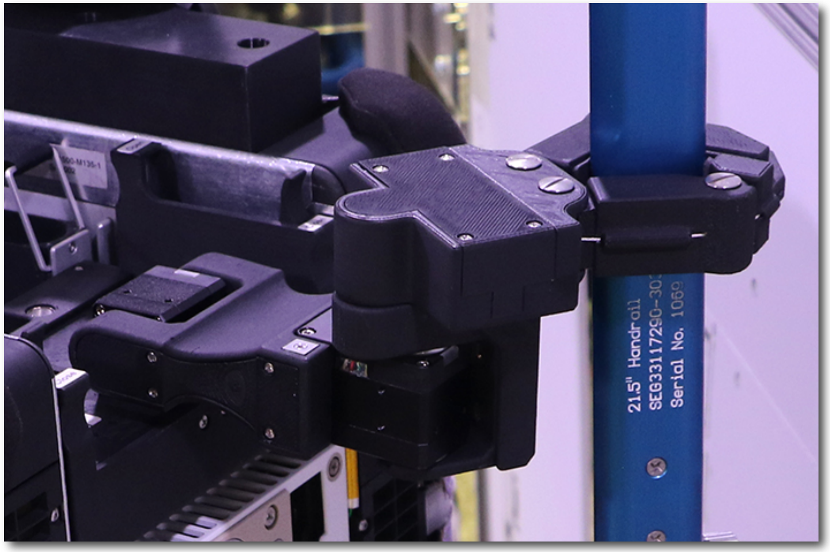
Feature map of the JEM

Coltin, B., Fusco, J., et al. (2016). Localization from visual landmarks on a free-flying robot. IEEE IROS.

Perching Arm

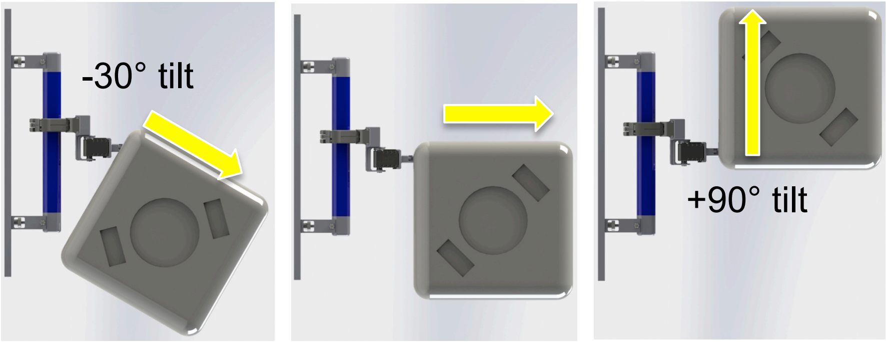
Specifications

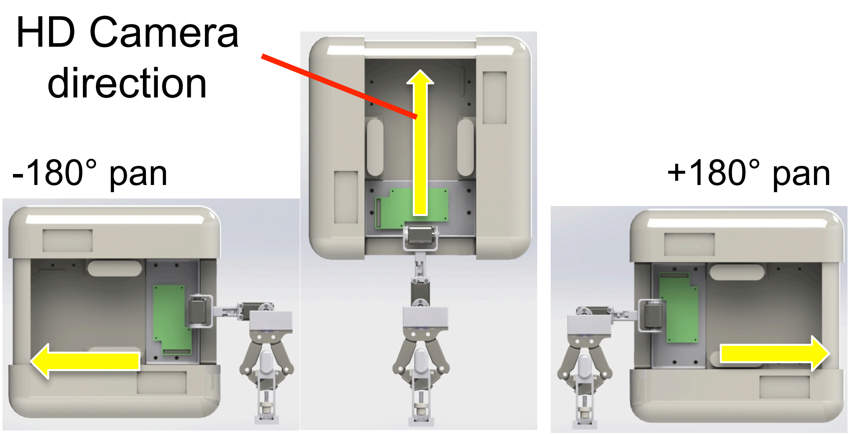
- ~0.5 kg, 23 cm reach
- Under-actuated, passively compliant, tendon-driven gripper
- Rotate Astrobee 90 deg in 15 sec



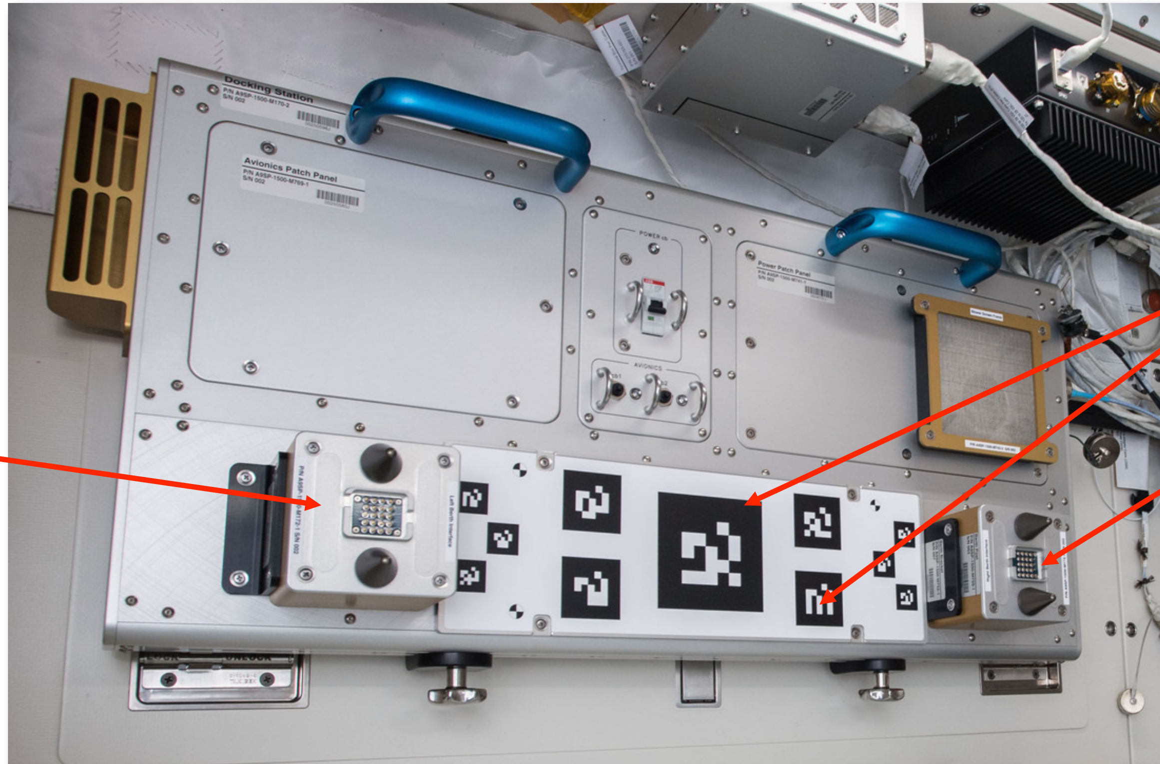
Use

- Designed to grasp handrails
- Pan/tilt Astrobee while perched
- Gripper can be manually opened





Docking Station



Installed in the Kibo Lab

Berths for 2 free flyers

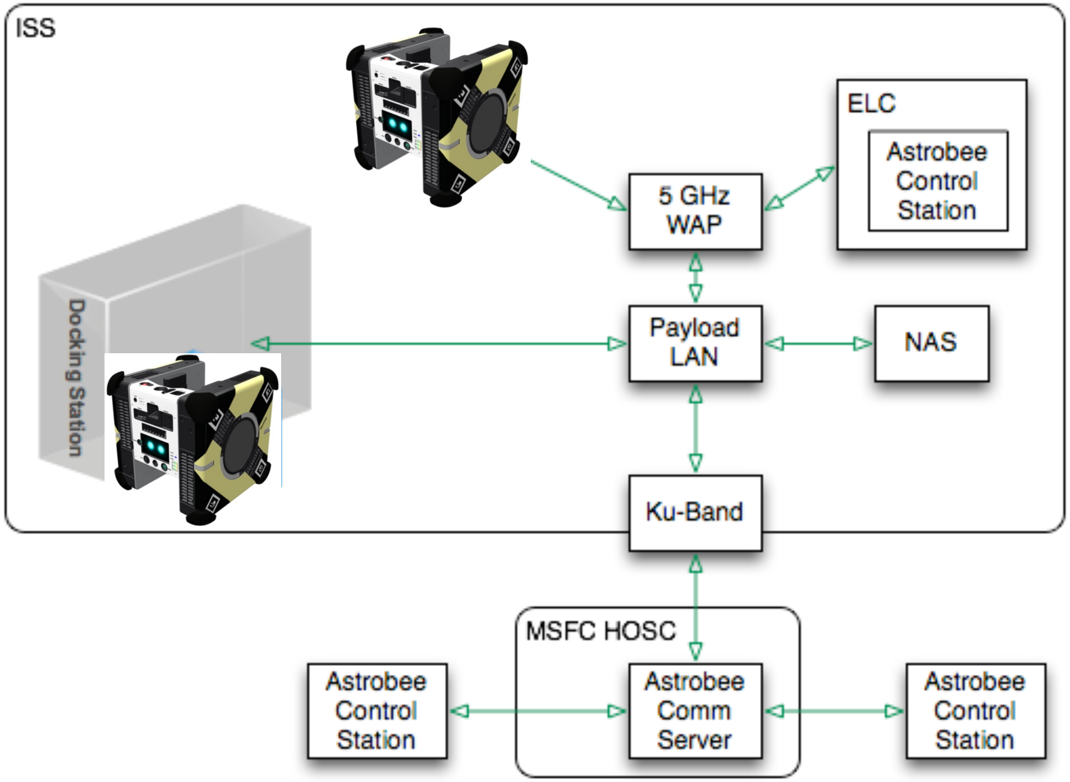
Provides power and Ethernet

Fiducials used during docking

Magnets provide retention force

Communications

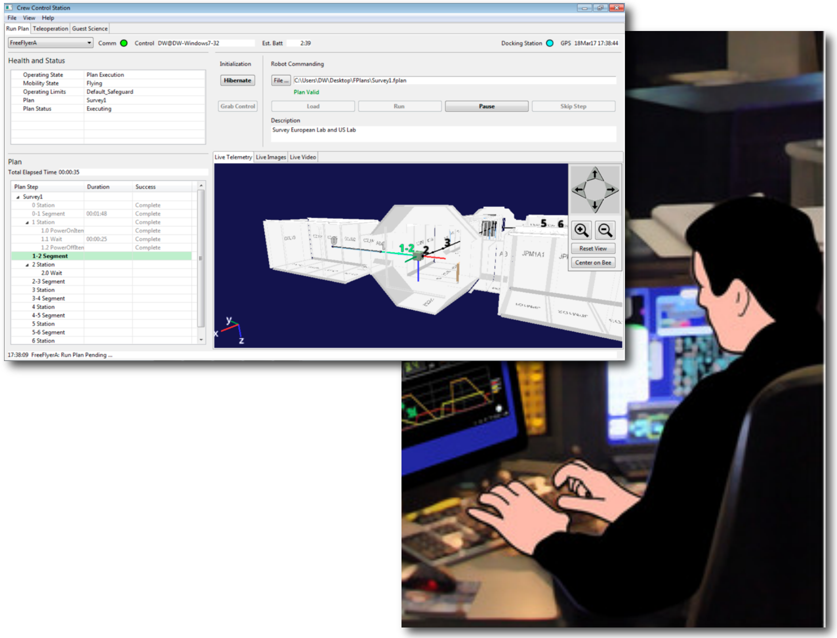
- Astrobee uses ISS Wi-Fi when flying
- Single telemetry + video stream to ground
- Multiple ground stations can connect through ground comm server
- Large file transfers and software updates performed via wired network (Ethernet) on the Docking Station



Ground Data System

Astrobee Control Station

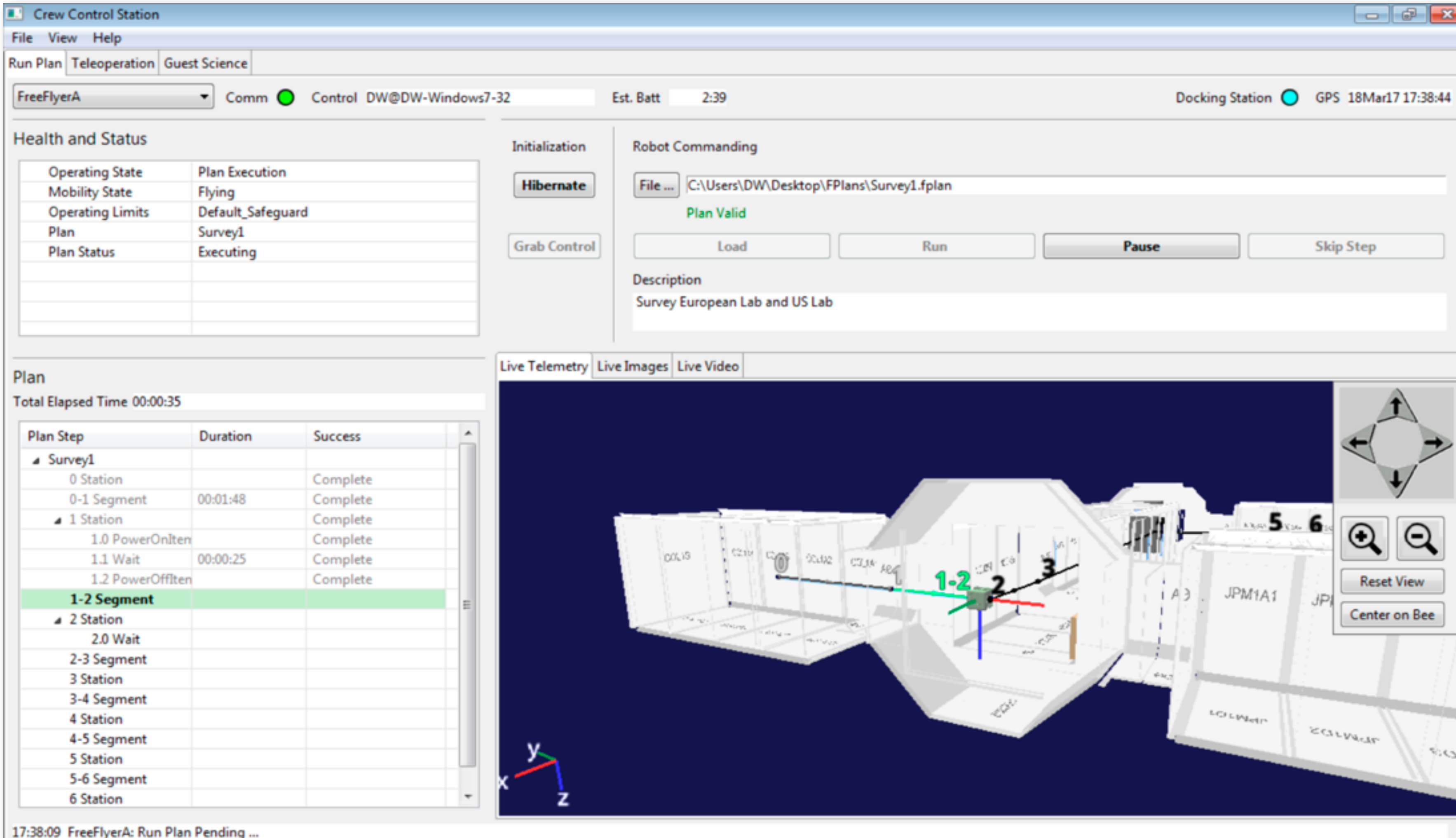
- Sortie planning tool
- Execution monitoring
  - Live telemetry
  - Image and video streams
  - 3D virtual display
- Supervisory control
- Typically used by ground operators
- Crew version (rarely used) runs on an EXPRESS Laptop Computer (ELC)



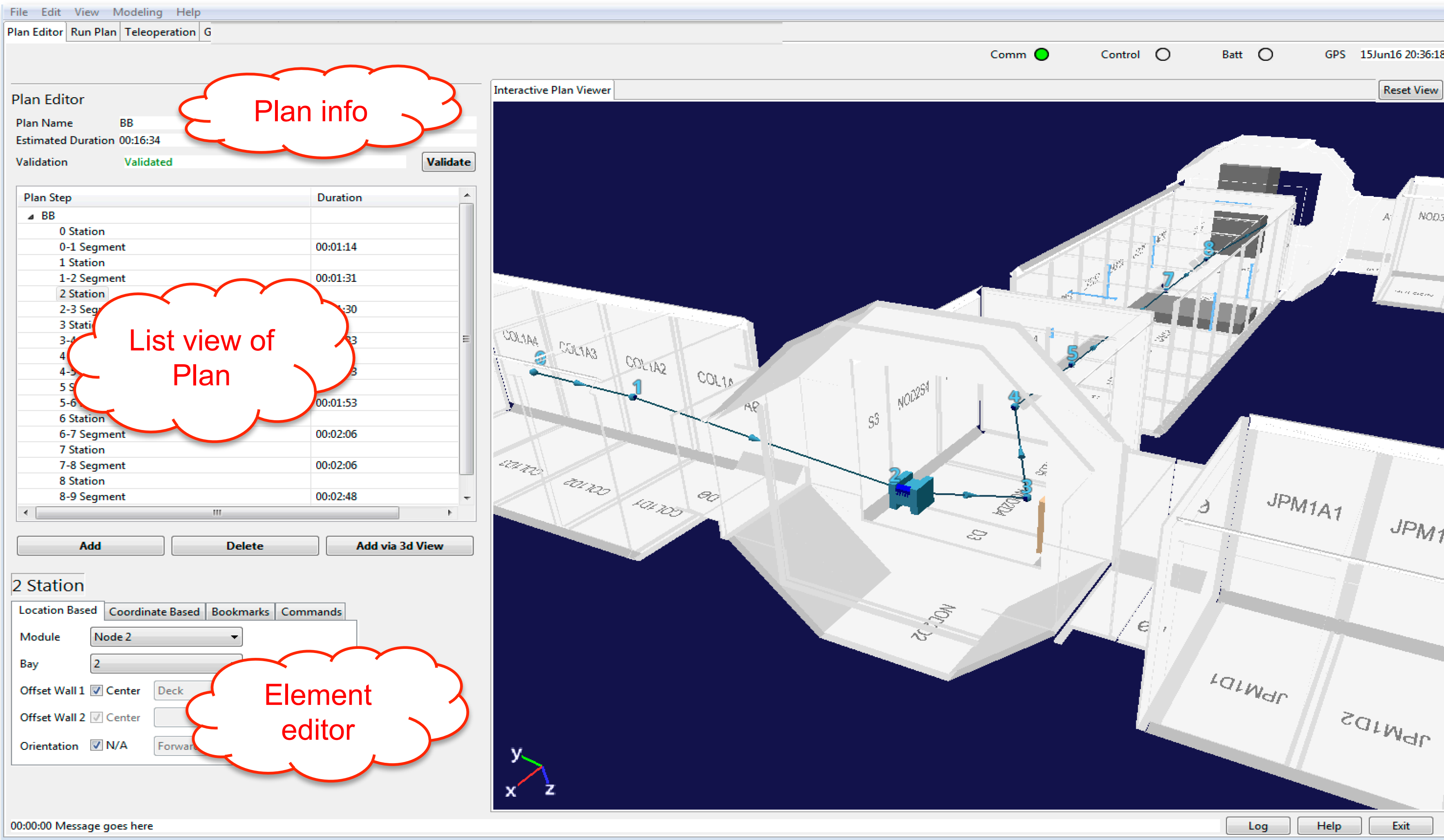
Server for archiving and distributing Astrobee data

Suite of engineering tools to support maintenance and software upgrades

Astrobee Control Station

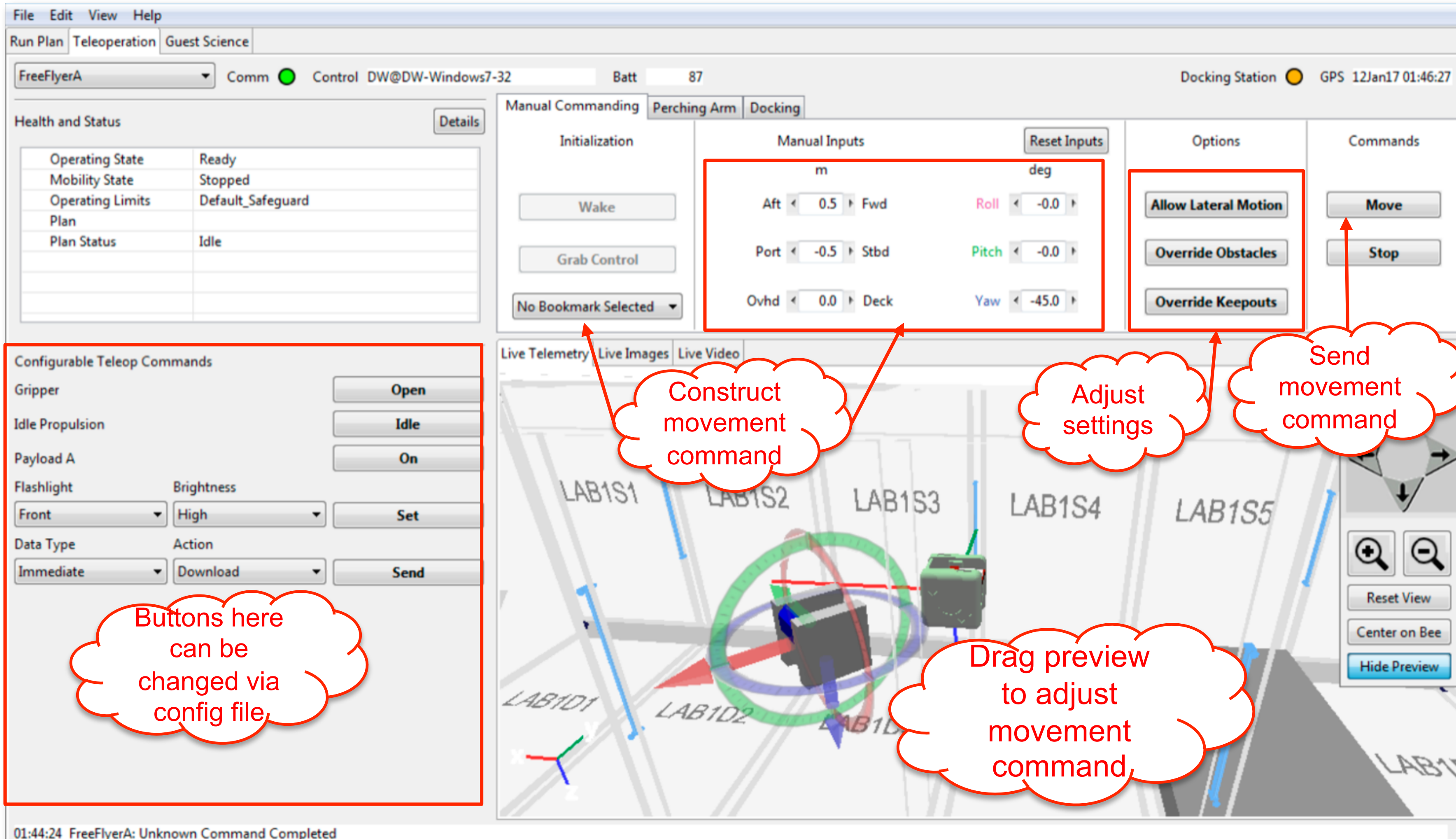


Plan Editor



File Edit View Modeling Help
Plan Editor Run Plan Teleoperation G
Comm Control Batt GPS 15Jun16 20:36:18
Plan Editor
Plan Name BB
Estimated Duration 00:16:34
Validation Validated
Validate
Plan info
Plan Step Duration
BB
0 Station
0-1 Segment 00:01:14
1 Station
1-2 Segment 00:01:31
2 Station
6 Station
6-7 Segment 00:02:06
7 Station
7-8 Segment 00:02:06
8 Station
8-9 Segment 00:02:48
List view of Plan
Add
Delete
Add via 3d View
2 Station
Location Based Coordinate Based Bookmarks Commands
Module Node 2
Bay 2
Offset Wall 1 Center Deck
Offset Wall 2 Center
Orientation N/A
Element editor
Interactive Plan Viewer
Reset View
JPM1A1
00:00:00 Message goes here
Log Help Exit

Teleoperation



Astrobee "Bumble Bee"
1st On-Orbit Activities

Astronauts Anne McClain,
David Saint-Jacques, & Christina Koch

Gateway Relevant Tests (2019-2020)

Logistics (Inventory) Use Case

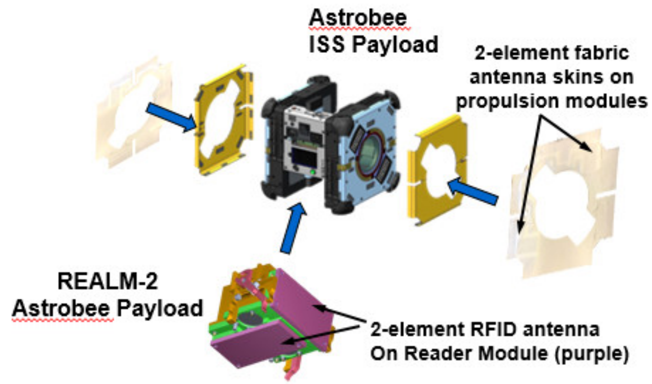
- Joint with NASA Logistics Reduction project (HEOMD AES)
- Determine how to effectively use mobile RFID for inventory

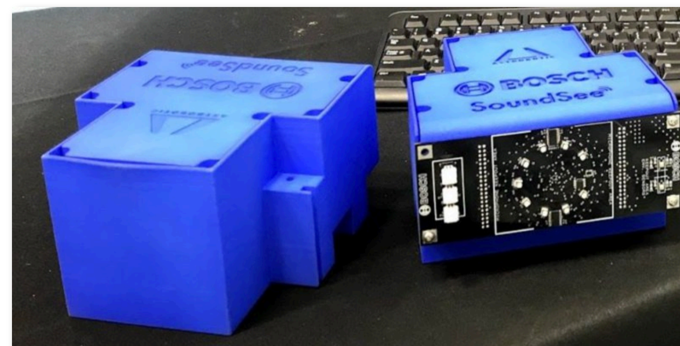
Inspection Use Case

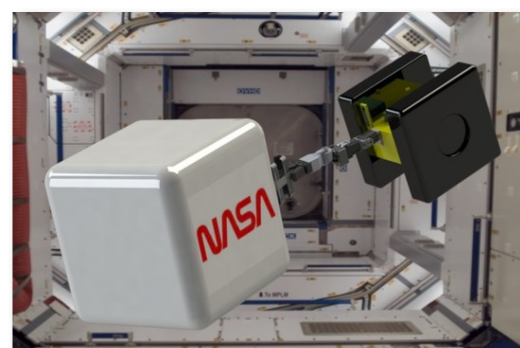
- Joint with Astrobotic/Bosch
- Determine use of acoustic monitoring for maintenance

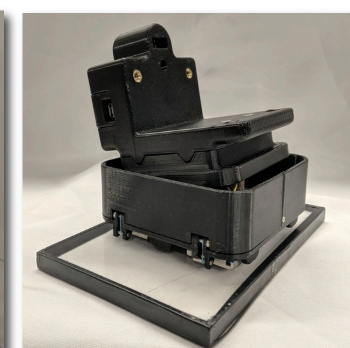
Logistics (Stowage) Use Case

- Joint with Stanford University (STMD ESI)
- Determine how a gecko gripper enables a free-flyer to work with a broad range of objects / surfaces
- Launched on SpaceX-18









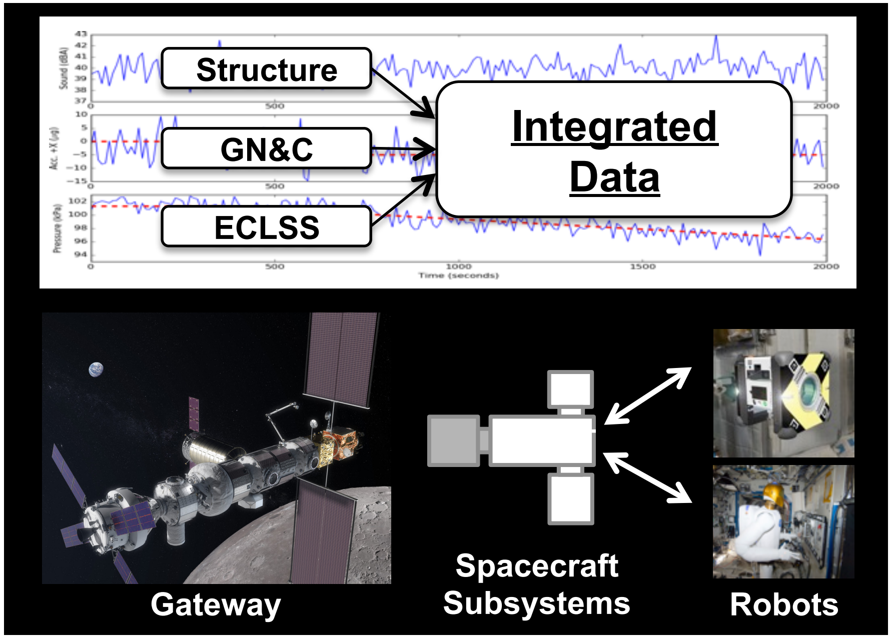
ISAAC

Integrated System for Autonomous and Adaptive Caretaking

- Develop autonomous caretaking technology for uncrewed spacecraft
- Integrate autonomous robots, spacecraft infrastructure (avionics, sensors, network), & ground control

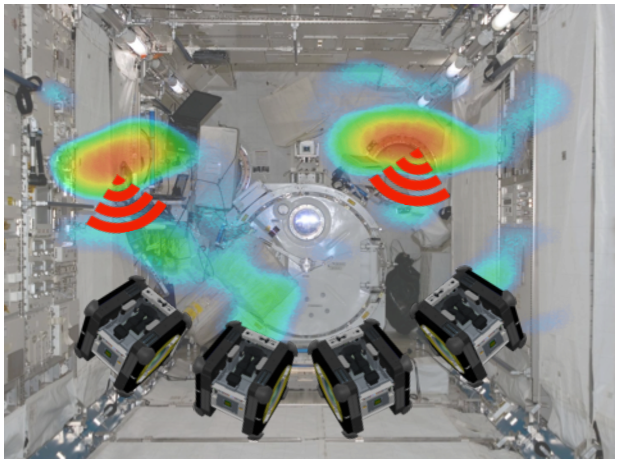
Technical approach

- Focus on capabilities required for Gateway (uncrewed periods)
- Assess feasibility and relevance for future deep space spacecraft
- Use ground labs (JSC iPAS) and the ISS for demonstration and testing

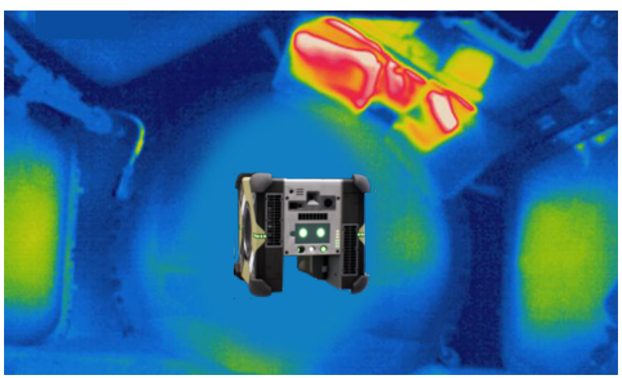


ISAAC Capability Areas

Autonomous State Assessment

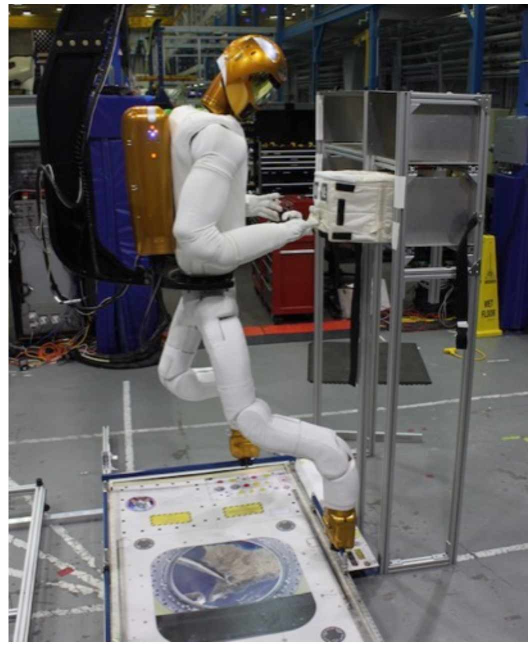


Localizing signal sources by analyzing signal strength variation



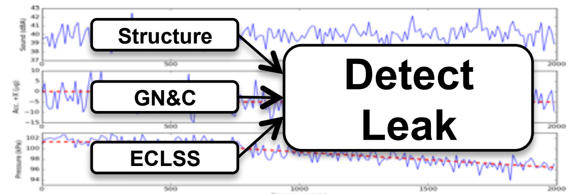
Habitat thermal mapping

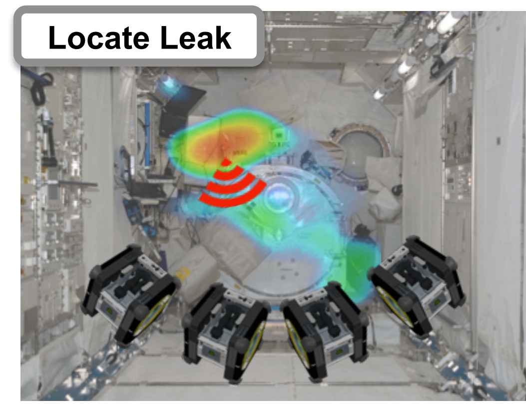
Autonomous Logistics Management



Robotic cargo transfer

Integrated Fault Management

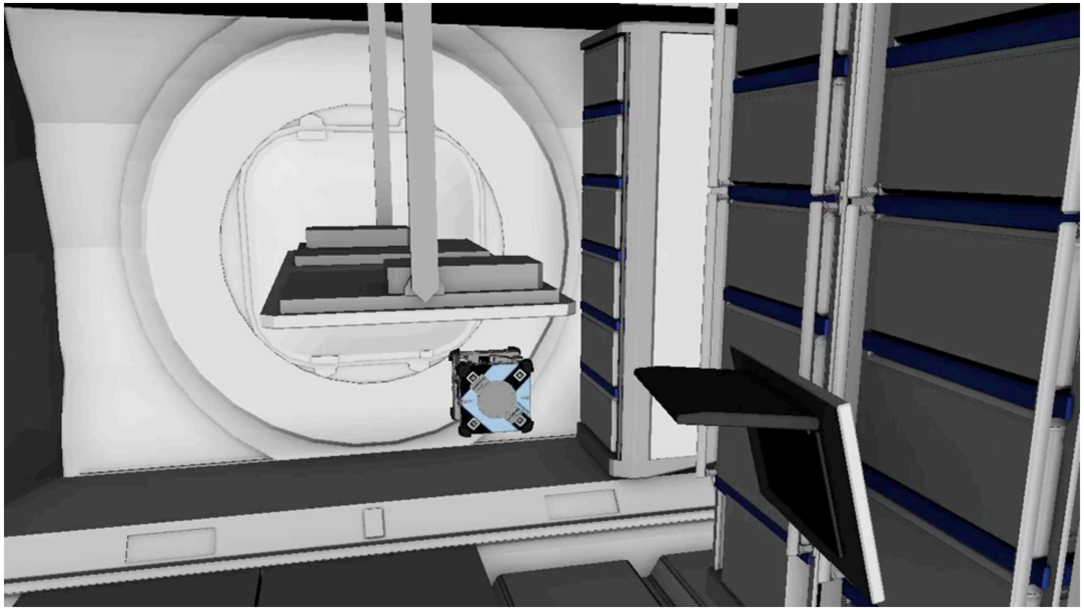




ISAAC Technology Development (2019)

Acoustic mapping with a free flyer

- Astrobee simulator
- Gateway 3D VR model
- Low fidelity ultrasonic noise sources
- Low fidelity ultrasonic microphone model
- Astrobee flies a fixed coverage pattern
- Map ultrasound intensity vs. location



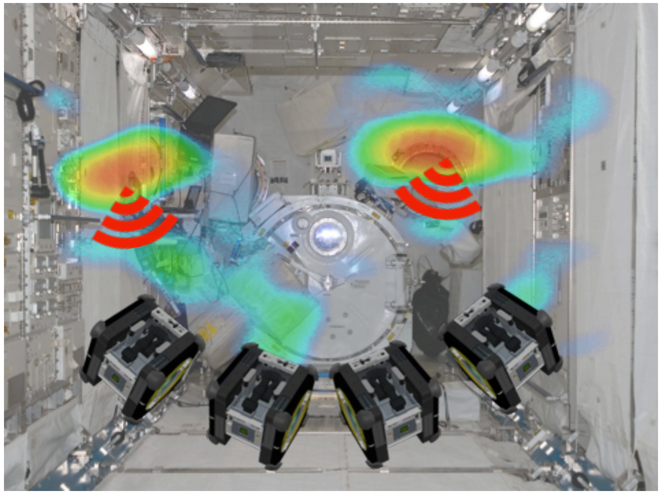
Low fidelity sound and sensor models are the starting point

- Focus on integrating spacecraft & robot commanding / telemetry
- Future work will improve sound and microphone model
- Possible tests on ISS using Astrobee and Astrobotic/Bosch acoustic monitoring payload

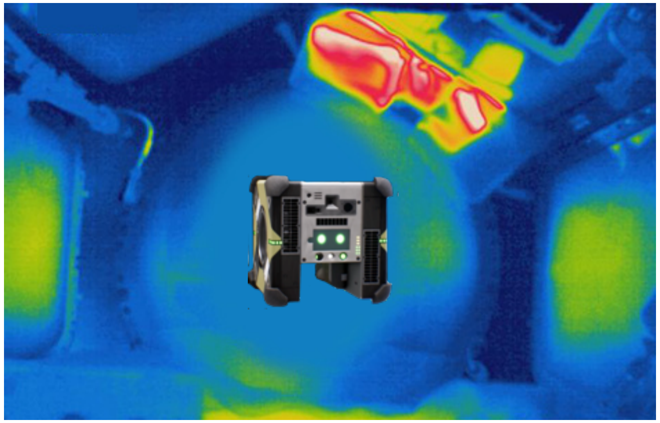
Autonomous State Assessment (2020)

Goals

- Build a 3D model of the ISS interior with co-registered data from multiple sensors. Possible map/sensor types:
  - Point: RFID reader
  - Area: Visual, depth, or thermal IR camera
  - Volume: Sound level, CO_2 level, wifi signal strength
- Map visual texture at 1mm – 0.2mm
  - Full map "base layer" is visual texture draped over 3D geometry. Texture will likely have higher spatial resolution than geometry.
- Anomaly detection for 3 types of anomalies using integrated data from robots and vehicle subsystems
  - e.g. hatch open/closed, temperature outside nominal range, item moved, cable disconnected, motor noise



Localizing signal sources by analyzing RSS spatial variation

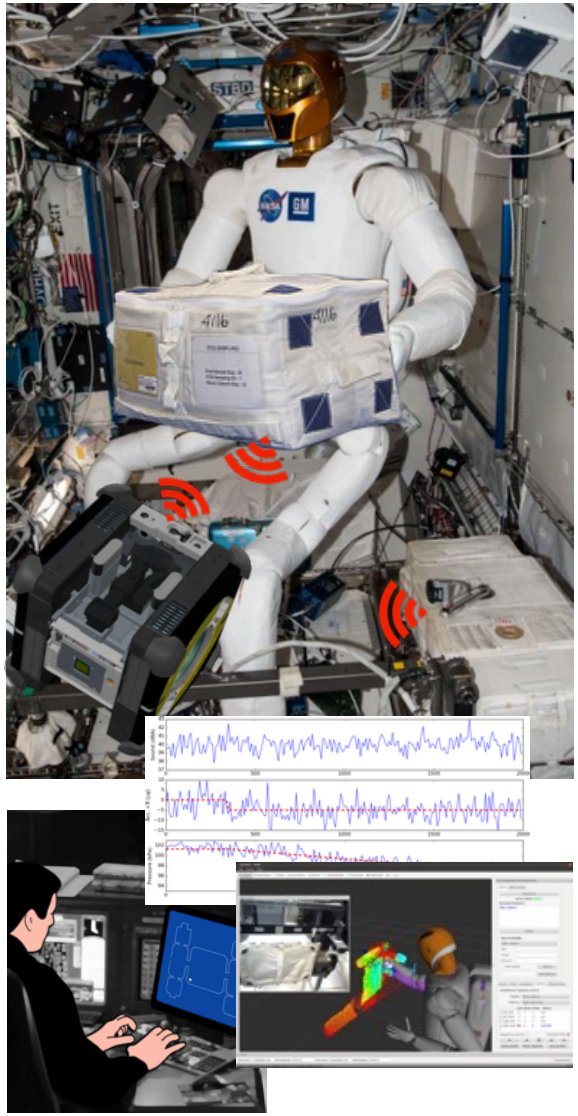


Habitat thermal mapping

Autonomous Logistics Management (2021)

Goals:

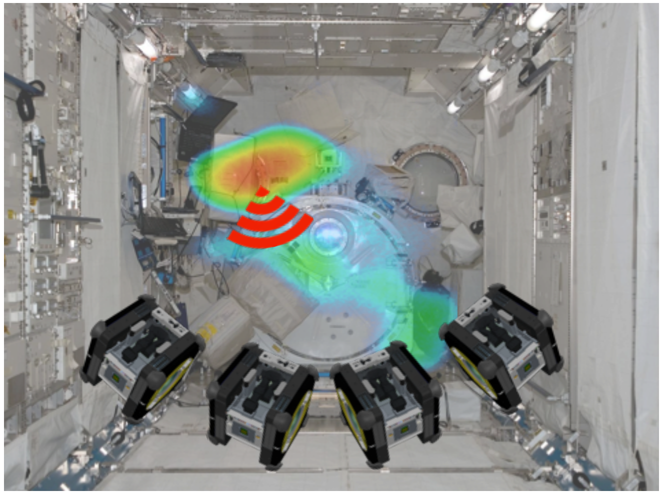
- Enhance cargo transport from FY20 LR-AL demo with new operator interface
  - Enhance user experience, make ops more effective
- Improve situation awareness:
  - Vehicle subsystems and robots in one 3D environment
  - Plot telemetry from vehicle and robots in one view
  - Geometry, status, progress, steps of current plan
- Unify remote commanding:
  - Enable at least one command type for each of three vehicle component types and two robots
  - Enable basic execution control for each robot: Execute single commands, run/pause/abort plan



Integrated Fault Management (2022)

Goals:

- Demonstrate finding and patching a simulated leak ("recovery scenario")
  - Detect: Repeat FY19 iPAS leak detection demo with improved fidelity (e.g. updated details of Gateway design, latest version of MAST, improved filtering)
  - Isolate: Astrobee with a microphone payload, "leak" ultrasound source, 3D volumetric mapping
  - Recover: Robonaut2 close a hatch or patch the leak
- Coordinated execution:
  - Automated generation of plans with actions for multiple agents and coordination between them
  - Distributed execution system capable of running multi-asset plans, including coordination



Locate leak

Patch leak

Smart Deep Space Habitats (Smart Habs)

2018 Space Technology Research Institutes (STMD)

- University led, multi-disciplinary, multi-institution
- Low to mid TRL research and development
- $15M awards ($3M / year for 5 years)

Focus

- Enable a **resilient** space habitat through the **pervasive** use of **autonomy**
- Novel analytical methods, decision making techniques & experimental proof-of-concepts

Three research areas

- Smart habitat intervention – maintenance & failure handling
- Smart architecture and analysis – combine heterogeneous systems
- Smart context and situation awareness – ensure seamless integration and interoperability between humans and habitat systems

HOME (UC-Davis)

UC DAVIS UNIVERSITY OF CALIFORNIA · Georgia Tech · Carnegie Mellon University · University of Colorado Boulder

The HOME Space Technology Research Institute for Deep Space Habitat Design
Habitats Optimized for Missions of Exploration (HOME)

HOWARD UNIVERSITY · USC University of Southern California · TEXAS A&M UNIVERSITY

Vision Statement

The HOME research team integrates proven engineering, groundbreaking research, and diverse team-member expertise in systems automation, machine learning, artificial intelligence, predictive analytics, robotics, and human crewed spacecraft design to develop new paradigms for the design of NASA's deep-space habitats.

Research Objectives

1) Develop Design Reference Mission functional-driven requirements and concepts of operation to serve as a context for autonomous system technology research.

2) Design evolvable sensor systems and data-driven analytics to assess, model, and predict system and infrastructure state, performance, and maintenance needs.

3) Develop and test methods to autonomously maintain spacecraft, utilizing subsystem redundancy, engineered graceful degradation, and robotic repair, with intermittent human assistance/supervision.

4) Develop a software tool for logistics-plan design that includes swap-over spares, performance de-rating, resupply, and onboard manufacturing of parts and sensors.

5) Develop novel interfaces, training, and performance measures for teaming of the SmartHab crew and the onboard robotics and autonomous systems to take maximum advantage of humans' capabilities when they are resident.

Team – Key Personnel and Organizations

Director/Co-PI	Dr. Stephen Robinson (UC Davis)
Executive Advisor/Co-PI	Dr. Bobby Braun (CU Boulder)
Deputy Director/Co-I	Dr. David Klaus (CU Boulder)

University of California, Davis (UC Davis)
Stephen Robinson, Bahram Ravani, Xinfan Lin, Sanjay Joshi, Zhaodan Kong

University of Colorado, Boulder (CU Boulder)
Bobby Braun, David Klaus, Allison Anderson, Torin Clark, James Nabity

Carnegie Mellon University
Mario Berges, Burcu Akinci, Stephen Smith, Artur Dubrawski

Georgia Institute of Technology
Nagi Gebraeel, Eric Truitt, Stephen Balakirsky, Thom Orlando

Howard University
Hazel Edwards

University of Southern California (USC)
Garrett Reisman

Texas A&M
Alaa Elwany

Benefits – Potential Impact

1) The deliverables of the STRI research will lead to highly autonomous, self-aware, resilient deep-space habitats for human exploration of space.

2) Enable improvements in crew safety and spacecraft resilience to reach practical criteria for developing vehicle and subsystem design requirements.

3) Reduced risk through research and testing of integrating new technology for large-sensor systems, data analytics that learn, predict, and correct, and decision methodologies to optimize logistics, resupply, and maintenance.

4) Significant technology spinoff to benefit Earth-based smart structures, robotic/human teaming, senor/data systems, and autonomous vehicles.

5) Diverse, well-educated student pipeline to the aerospace industry.

homestri.ucdavis.edu

RETHi (Purdue)

Resilient ExtraTerrestrial Habitats research institute (RETHi) (Version 2)

Vision: Develop and demonstrate transformative smart autonomous technologies that will adapt, absorb and rapidly recover from expected and unexpected disruptions to deep space habitat systems without fundamental changes in function or sacrifices in safety.

Research Objectives:

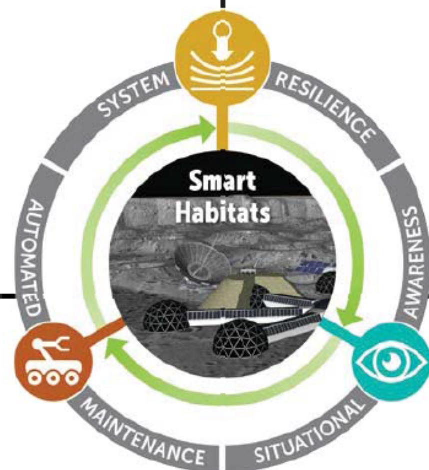
- Establish a *comprehensive systems resilience framework* to support design, operation, and management of efficient and effective long-term deep space habitats
- Develop smart habitats that *autonomously sense, anticipate, respond* to and *learn* from disruptions
- Develop *decision-making techniques* for complex interconnected, interdependent habitat systems
- *Educate* the next generation of engineers and scientists

Leadership Team: Shirley Dyke (PU), PI
Karen Marais (PU), Lead Thrust 1
James Braun (PU), Lead, Thrust 2
Justin Werfel (HU), Lead, Thrust 3
Ramesh Malla (UC), Lead, Industrial Partnerships

Lead Organization: Purdue University (PU)

Participant Organizations: University of Connecticut (UC), Harvard University (HU), University of Texas San Antonio (UTSA)

Additional Key Personnel: Ilias Bilionis (PU), Antonio Bobet (PU), David Cappelleri (PU), George Chiu (PU), Ashwin Dani (UC), Elena Glassman (HU), Song Han (UC), Chuck Hoberman (HU), Mohammad Jahanshahi (PU), Arturo Montoya (UTSA), Krishna Pattipati (UC), Julio Ramirez (PU), Jiong Tan (UC), Dawn Whitaker (PU), Robert Wood (HU)



Benefits:

- Methods to achieve intelligent and resilient design of complex systems' accelerated recovery.
- Autonomous robotic capabilities for wide-ranging use in space or to work alongside humans on the Earth.
- Advances in active learning to characterize the temporal evolution of complex systems of systems.
- Techniques to model and simulate human decision-making and act cooperatively, especially in extreme situations.
- Training the next generation of graduates to lead the U.S. into the future.
- Strengthened partnerships between academic institutions and the US space industry.

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Questions?

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