Astrobee: A Stepping Stone to Caretaking Intra-Vehicular Robots

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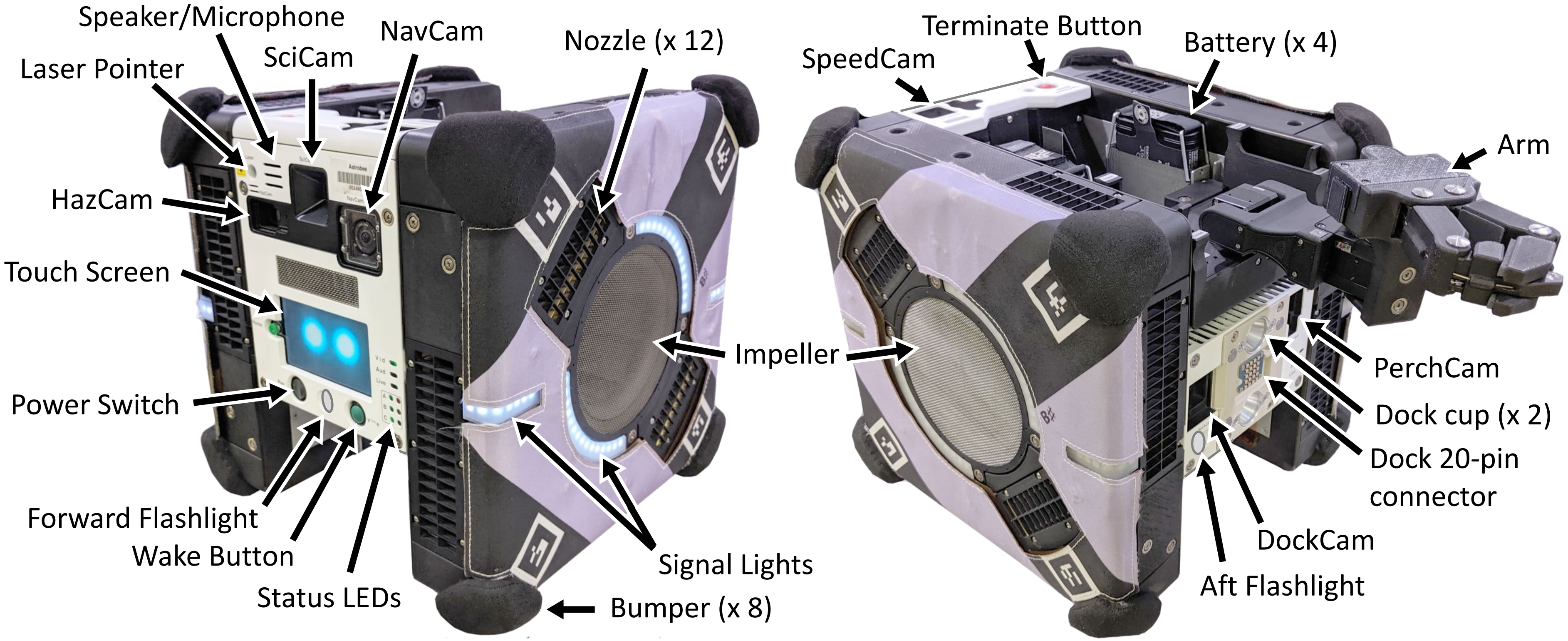
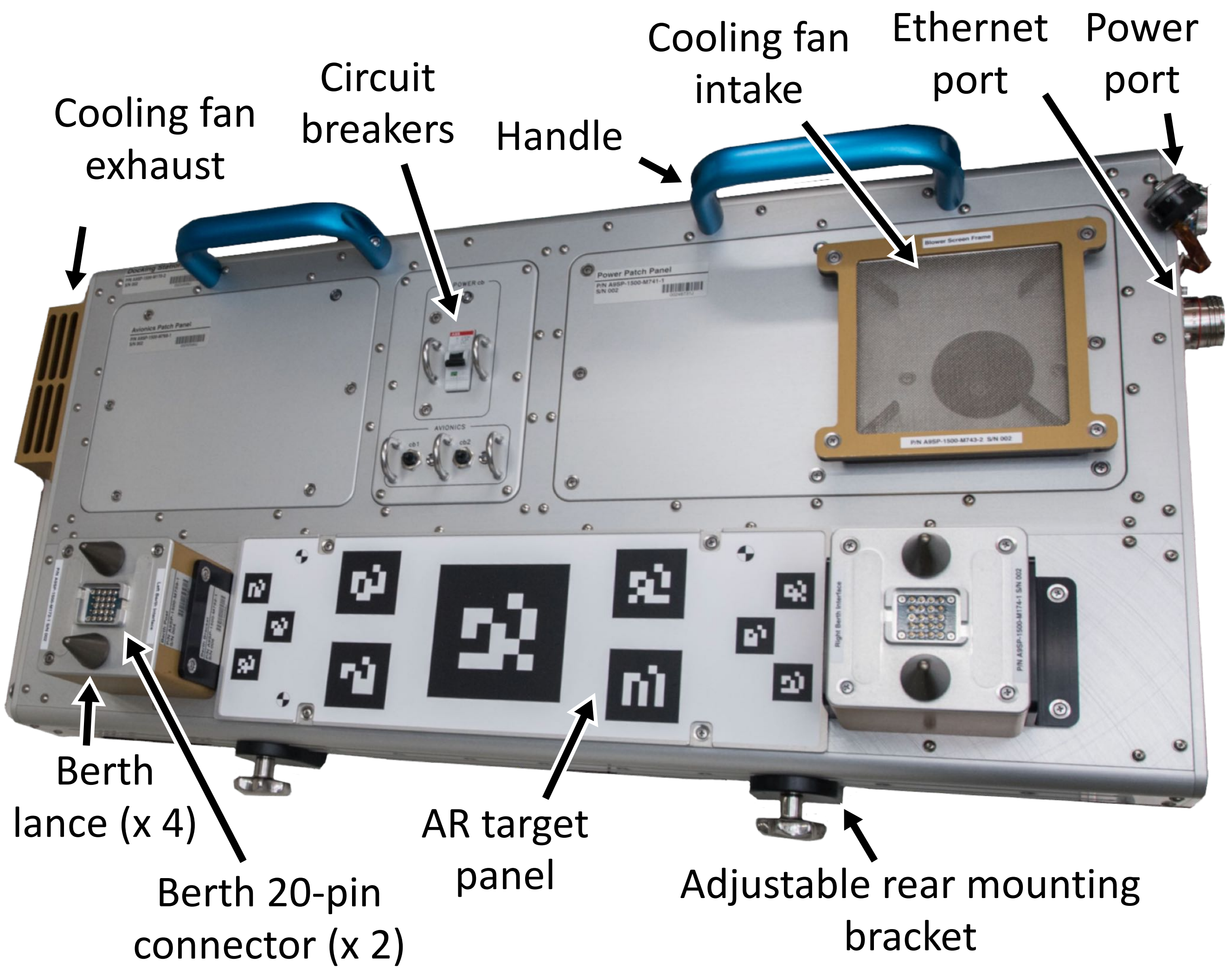
Astrobee Free Flyers

- 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



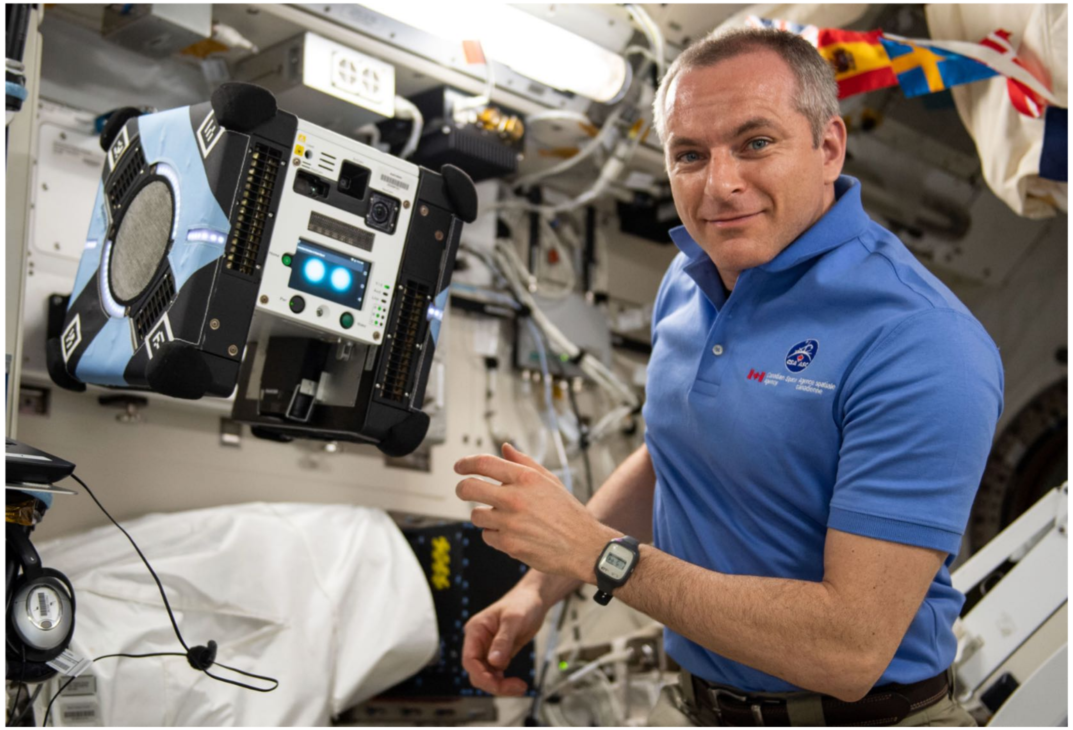
Astrobee Dock

- 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 will replace 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



Agenda

1. Introduction to Astrobee
2. Initial on-orbit results
3. Future caretaking of human exploration vehicles
4. Automating ISS operations

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2. **Initial on-orbit results**
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Launch Schedule

Launch	Date	Cargo
NG-10	**11/17/18**	 Dock
NG-11	**4/17/19**	 Honey  Bumble (Dock spare parts)
SpX-18	7/25/19	 Queen
NG-12	10/xx/19	(Astrobee spare parts)

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:
  - Runs from launch through the end of September 2019 (the end date of the technology development project)
  - 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
- After commissioning:
  - Astrobee will become available for guest science and ISS operational use
  - Astrobee is designed for sustainability (SPHERES ran for 13 years and counting on ISS)

Operational Readiness Testing

- The Astrobee ops team organizes multiple Operational Readiness Tests (ORTs) prior to each on-orbit activity, in order to:
  - Mature crew procedures and onboard training videos prior to formal ISS review
  - Build Astrobee ops team experience and mature ground procedures and tools to ensure smooth ground operations
- ORTs are a major investment, utilizing some or all of these resources:
  - Ops team: up to ~10 staff, depending on activity
  - Astrobee ground unit in Granite Lab (gravity offset environment)
  - Multi-Mission Operations Center (control room)
  - Payload Rack Checkout Unit (PRCU) at MSFC (emulator for communications to ISS)
- These ORTs are a big deal. We take them very seriously, but we can't catch everything!

Commissioning Activity Schedule

Activity	Robot	Date
Checkout	**Bumble**	**4/30/19**
Calibration & Mapping	**Bumble**	**5/13/19**
Additional Mapping	**Bumble**	**5/23/19**
Localization & Mobility	**Bumble**	**6/14/19**
Localization & Mobility	**Bumble**	**7/12/19**
Checkout & Calibration	Honey	7/25/19
Localization & Mobility	Bumble	7/30/19
Localization & Mobility	Honey	8/13/19
Checkout & Calibration	Queen	8/20/19
Localization & Mobility	Honey	8/27/19

Checkout Task

- Objective: Verify functionality of all major hardware components, post-launch
- Approach: Crew interacts with Astrobee as needed (switches, touch screen) and observes behavior; some components commanded from the ground
- Activity repeats: Once for Dock, once for each Astrobee
- Anomalies: None worth noting, so far
- Status:
  - Dock and Bumble checked out successfully, a huge relief!
  - Other Astrobees will be checked out later

Bumble Checkout

Calibration Task

- Objective: Collect updated intrinsic and extrinsic calibration parameters for Astrobee's cameras and IMU, post-launch
- Approach: Crew moves Astrobee in specified patterns with checkerboard calibration target in view of Astrobee cameras. Some motions call for vigorous shaking or spinning to stimulate IMU response.
- Activity repeats: Once for each Astrobee
- Anomalies: 1. IMU saturation
- Status:
  - Bumble calibration did not change since launch (this was a concern because we observed calibration changes in the certification unit after vibe testing)
  - Other Astrobees will be checked out later

IMU Calibration

IMU Saturation Anomaly

- During the calibration task, our procedure asked the crew to spin the Astrobee “as fast as possible” in order to maximize response from the IMU for calibrating the position of Astrobee’s center of mass
- Astronaut Anne McClain went above and beyond and unexpectedly managed to saturate the IMU angular velocity
- We repeated the task with updated instructions to limit the rotation to 360 degrees in 3 seconds.
- Lesson learned: Be careful when asking a former fighter pilot to do something as fast as possible :)

Mapping Task

- Objective: Build a map of an ISS module that will enable each Astrobee to localize itself and navigate to any target position in that module, specified using an ISS CAD model
- Approach: Crew carries Astrobee through specified motions so that it images all parts of the module interior from multiple angles. The imagery is downlinked and the map is stitched and registered to the ISS CAD model on the ground.
- Activity repeats: Once for each module
- Anomalies: 1. Imagery resolution, 2. Dock position
- Status:
  - JEM module map stitched and registered
  - Mapping of other ISS modules on hold for now pending other commissioning activities

Imagery Resolution Anomaly

- During the mapping task, we experienced degraded downlink bandwidth from the ISS
- The ground operator was monitoring image quality via live downlink; when the image stream got choppy, they responded by reducing image resolution
- That change unexpectedly affected not just the live downlink resolution, but also the images saved onboard
- As a result, the resolution of the saved images was insufficient for mapping, and the task had to be repeated later
- Lesson learned: If degraded bandwidth turns out to be a common problem, it should be simulated during ORTs in order to pick up and mitigate this kind of bad interaction.

Dock Position Anomaly

- During the mapping task, imagery was collected while Bumble was on the dock, allowing us to use Astrobee's localization system to estimate the installed position of the dock relative to the JEM CAD model
- However, when we visualized the estimated position, it was clearly significantly off; it appeared to actually overlap the rack hardware behind the dock. We're still debugging why this happened. One possibility is there may be dimensional errors in our JEM CAD model.
- Lesson learned: As usual in robotics, 3D maps and coordinate frames for a new environment are finicky and require iteration to get right.

Localization Task

- Objective: Verify each Astrobee's ability to track its 6-DOF pose using the map
- Approach: Crew carries Astrobee through specified motions with the localization system running. Ground operators monitor the quality of the localization fix.
- Activity repeats: Once for each Astrobee
- Anomalies: 1. Dock hanging, 2. Unreliable localization
- Status:
  - Bumble: Localization actually seemed to work well during the specified motions, but proved unreliable during later tasks; further testing is needed
  - Other Astrobees will be checked out later

Dock Hanging Anomaly

- At the beginning of the localization task, we could not contact the dock from the ground, although it was powered on.
- It responded normally after being power-cycled by crew.
- Presumably some kind of anomaly left it in a hanging state (during the preceding multi-day period when it was left on).
- Lesson learned: This type of anomaly is very typical for spaceflight systems, but we had not planned for it because the ISS rad environment is fairly benign and crew assistance is available; we may decide to add a watchdog timer to watch for a hanging condition and trigger a reset. (We have already added more onboard logging.)

Unreliable Navigation Anomaly

- This is the biggest and most complicated anomaly seen so far.
- Basically, the localization system does not reliably maintain its position fix, both from minute to minute and especially when the NavCam used for localization is pointed in certain directions
- We haven’t debugged this fully yet, but can report some factors that seem to be related:
  - Looking at places that were not imaged in as much detail during mapping
  - Looking at places from an unusual angle not captured during mapping
  - Looking at places that are not well-lit
  - Internal parameter tuning of localization components had been optimized for ground lab conditions rather than ISS conditions
- Lesson learned: This story is not over, but it has been a very good exercise for improving our live debugging tools and operational contingency planning.

Free Flying Task

- Objective: Verify each Astrobee's ability to respond to motion commands
- Approach: Crew releases Astrobee to fly freely, then ground sends a sequence of increasingly complicated motion commands. Crew helps in case of an anomaly.
- Activity repeats: Once for each Astrobee
- Anomalies: 1. Time sync
- Status:
  - Bumble: Motion control worked well when localization was functioning; testing could not be completed due to localization problems
  - Other Astrobees will be checked out later

1st Flight

Time Sync Anomaly

- Astrobee has multiple processors (LLP, MLP, HLP)
- The MLP continuously syncs to an ISS NTP time server, and the other processors sync to the MLP (using ntpd)
- If the time sync between LLP and MLP is off by more than ~0.5 seconds during ops, mobility commands start to fail
- We experienced a time sync failure on-orbit (~0.8 seconds off), having never seen one on the ground. Still not sure why it happened.
- However, we were able to diagnose the problem within about one hour, restore the sync manually, and continue testing later that day.
- Lesson learned: This is a case where having the right software experts in the operations center allowed us to recover quickly. That’s ideal if you can support that kind of staffing.

Flying Robustness Task

- Objective: Verify each Astrobee's ability to fly under various off-nominal conditions
- Approach: While Astrobee flies, crew introduces off-nominal conditions: 1. Crew nudges Astrobee to see if it can stop; 2. Crew partially occludes camera view to see if localization fix is lost; 3. Crew blocks Astrobee motion path to see if Astrobee stops before collision. Crew helps in case of an anomaly.
- Activity repeats: Once for each Astrobee
- Anomalies: Testing could not be completed due to localization problems
- Status:
  - Bumble: Motion control rejected nudges well when localization was functioning
  - Other Astrobees will be checked out later

Stopping Ability

Docking Activity

- Objective: Verify each Astrobee's ability to autonomously dock and undock
- Approach: Astrobee starts on dock, then autonomously undocks and returns to dock. Astronaut helps in case of an anomaly.
- Activity repeats: Once for each Astrobee
- Anomalies: Testing could not be completed due to localization problems
- Status:
    - Bumble: Autonomous undocking and docking both (surprisingly) succeeded at least once despite localization problems; further testing still needed
    - Other Astrobees will be checked out later

1st Autonomous Undocking

1st Autonomous Docking

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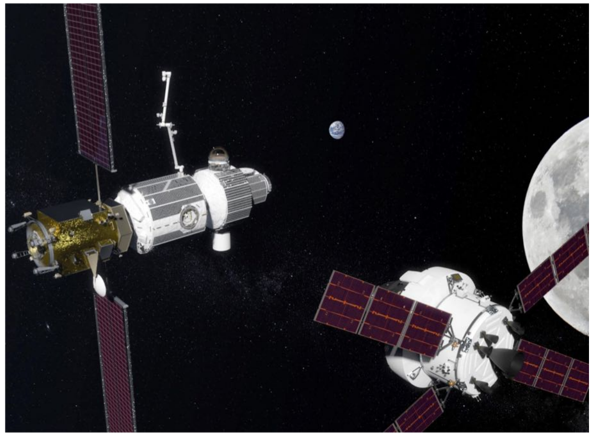
Caretaking of human exploration vehicles

- Future missions in NASA's Moon-to-Mars exploration architecture involve significant uncrewed periods
- For example, the Gateway space station in cislunar space is expected to be uncrewed >85% of the time
- **There is a critical need for intra-vehicular robotics (IVR) to maintain these systems when crew are not present**

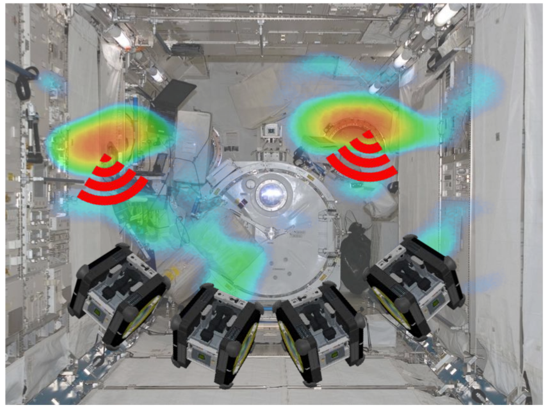


IVR Drivers

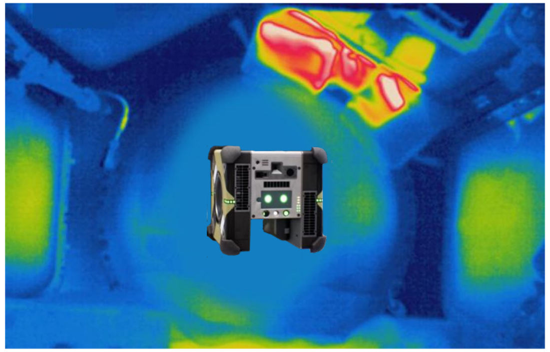
- **Reduce mission risk** through improved fault recovery during uncrewed phases
  - Example: Localize and patch leak
  - Example: Check if fire is a false alarm before committing to a major intervention like depressurization
- **Reduce mission cost** by enabling new design options
  - Example: Stock a spare part for IVR to swap in instead of redundancy, enabling simpler design
  - Example: Replace network of fixed sensors with a single mobile sensor
- **Free up crew time** spent on maintenance and logistics
  - Example: Transfer cargo from uncrewed visiting vehicle
  - Example: Perform routine inspections to detect problems
- **Enhance utilization** during uncrewed phases
  - Enable experiments that require manipulation support for >30 days (e.g. rodent research)
  - Enhance experiments that prefer to be isolated from crew (e.g. sterile lunar sample transfer)

Possible IVR use cases

Situation awareness

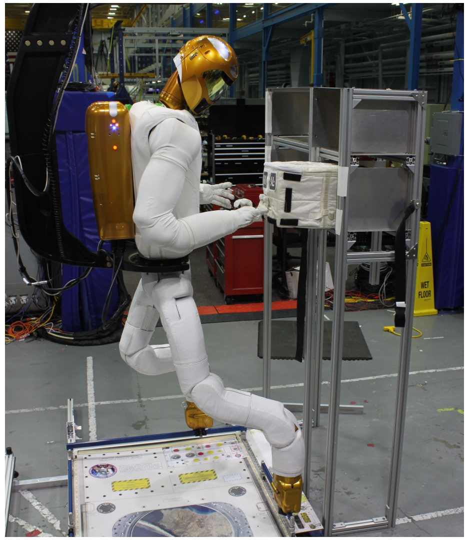


Localizing signal sources by analyzing signal strength variation



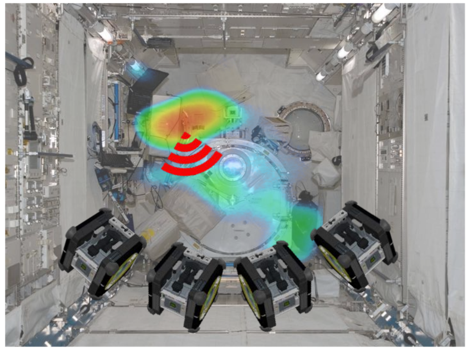
Habitat thermal mapping

Logistics management



Robotic cargo transfer

Fault management



Locate leak

Patch leak

Next steps

- The Gateway program has organized an IVR working group that is currently studying IVR use cases, architectures, and requirements
- ISS robots like Astrobee and Robonaut (headed back to ISS after repairs) will enable proof-of-concept work to flesh out IVR use cases for future missions

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Automating ISS operations

- Astrobee provides an opportunity for future automation of ISS operations
- The main objective is to save crew time on onerous recurring tasks so they can spend more time enhancing science
- However, on a case-by-case basis, we need to argue that automation will give positive return on investment within the lifetime of Astrobee and the ISS
- Current status is ISS operational divisions naturally want to see the results of Astrobee commissioning before investing in automating existing processes

ISS operations possible use cases

- Mobile camera
  - Remotely controllable camera for observing crew activities (save astronaut time on camera setup)
  - Can also perform spot inspections (“is that switch on?”)
- Sensor surveys
  - Move throughout the ISS collecting sensor samples
  - Crew regularly perform acoustic noise surveys and video surveys that are good candidates for automation
  - Some other data sets can be sampled with Astrobee’s existing sensors, or hardware already in development for ISS:
    - CO_2 concentration
    - Radiation
    - WiFi signal strength
  - Robot’s precise position knowledge enhances value of survey data

Conclusion

- Astrobee on-orbit commissioning is well underway
- Astrobee can enable proof-of-concept demonstrations of intra-vehicular robotics use cases for future exploration missions (such as Gateway)
- Astrobee provides an opportunity for future automation of certain ISS operations