Astrobee On-Orbit Commissioning

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NASA Ames Research Center

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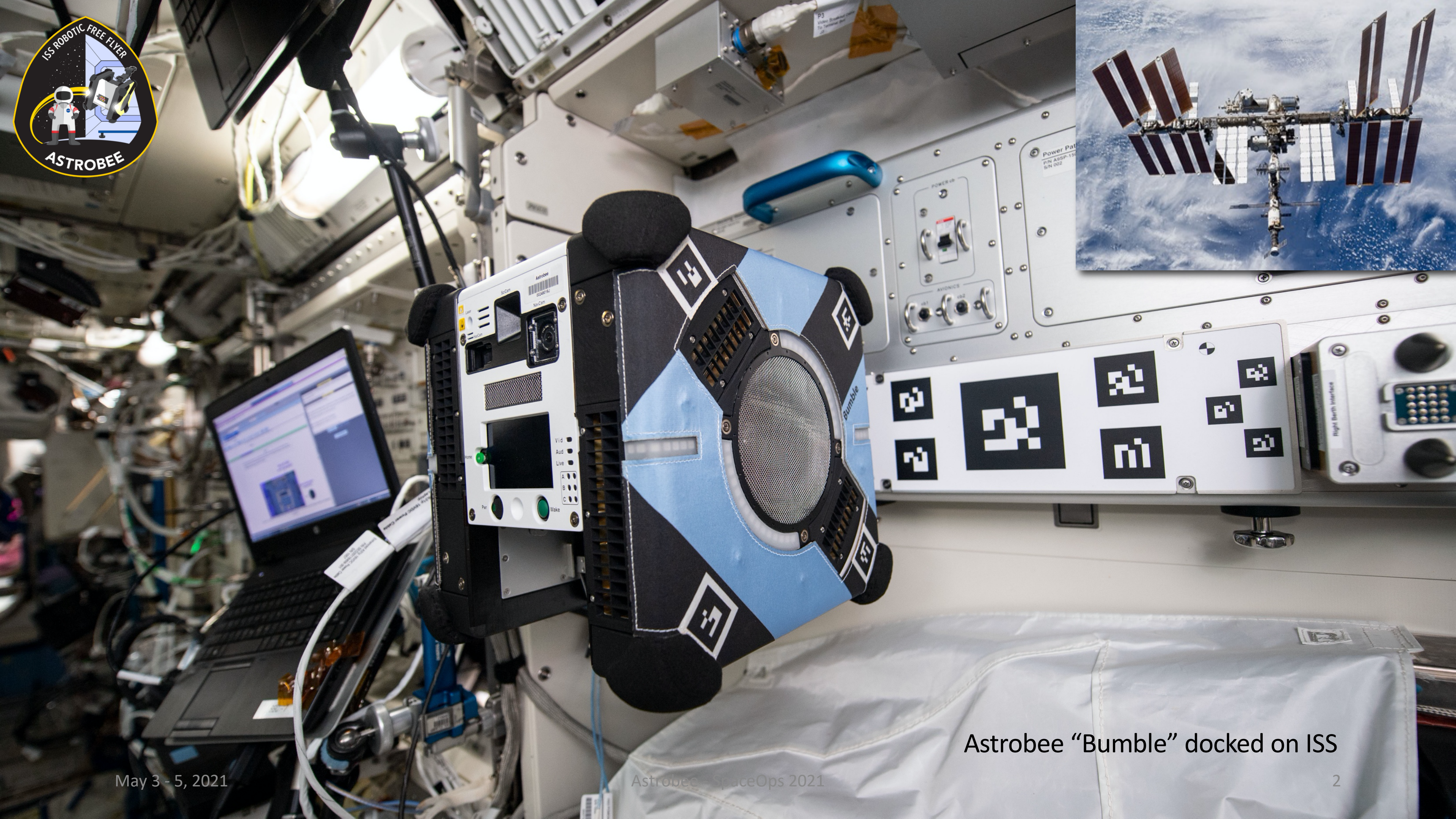


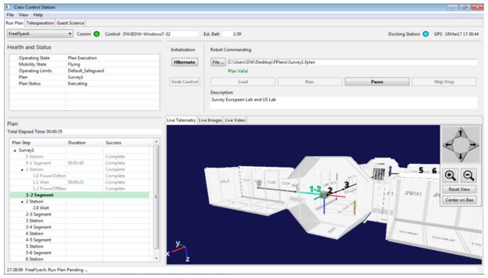
Astrobee “Bumble” docked on ISS

Project Objectives

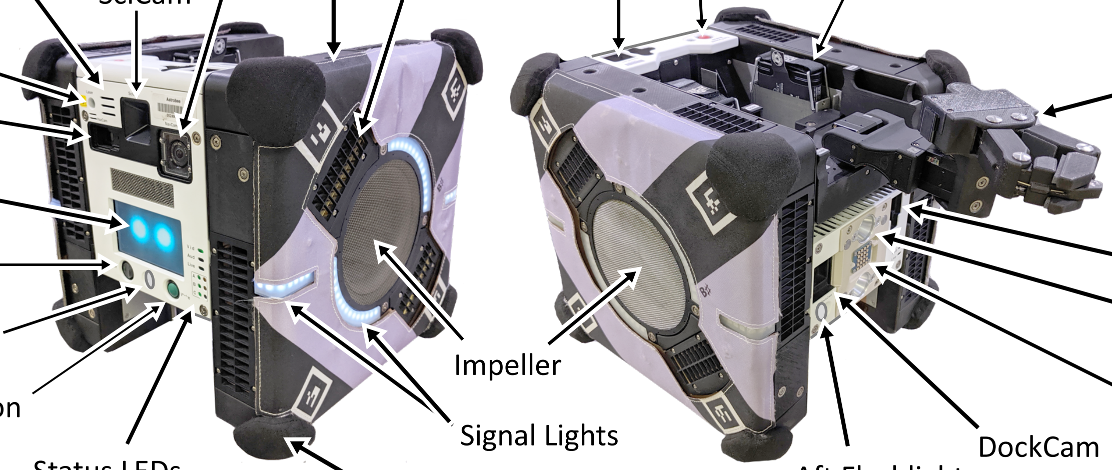
- Provide a microgravity robotic research facility in the ISS US Orbital Segment (USOS), which will replace the SPHERES facility
- Provide remotely operated mobile camera views of the ISS USOS to enhance the situation awareness of mission control
- Perform mobile sensor tasks in the ISS USOS

Astrobee Elements

- Astrobee
  - Free Flyer x 3
  - Dock
  - Ground Data System



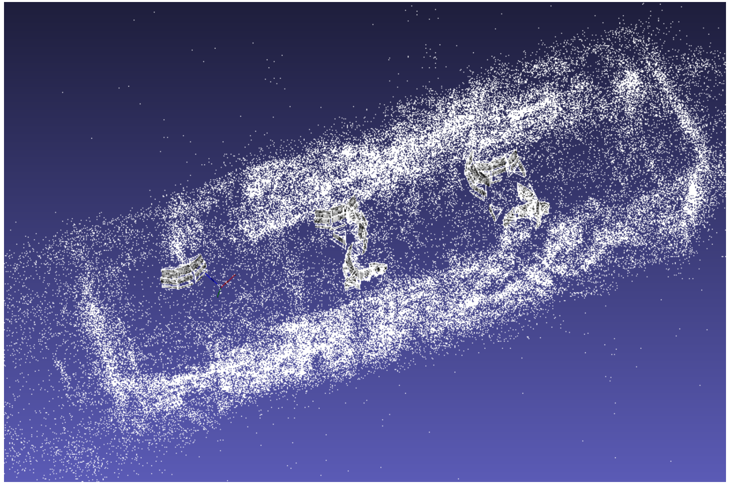
Robot



- 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
- 6 cameras
- Three payload bays for expansion
- Microphone not currently enabled

System Description: Localization

- Vision-based navigation
  - Compares features with on-board a priori map
  - Incorporates inertial measurements
- Fiducials used for autonomous docking
  - Requires approximately 1 cm position accuracy

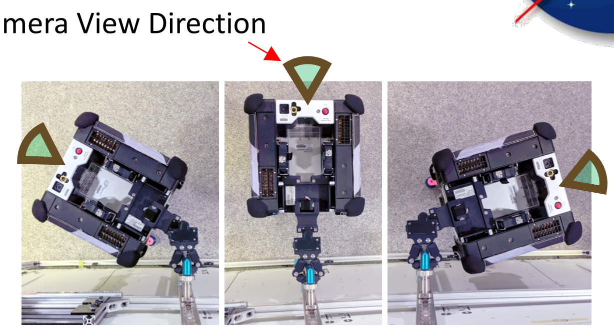


Feature map of the JEM-PM

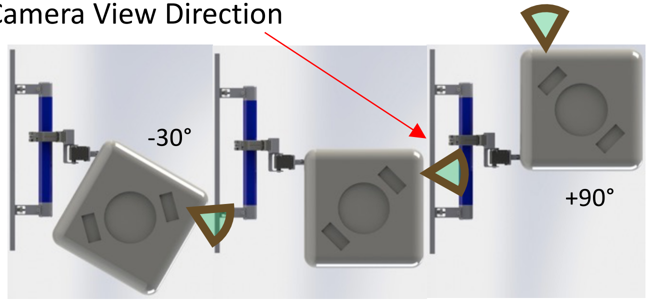
- Visual odometry
  - Robot can continue to navigate where no map features are recognized

System Description: 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

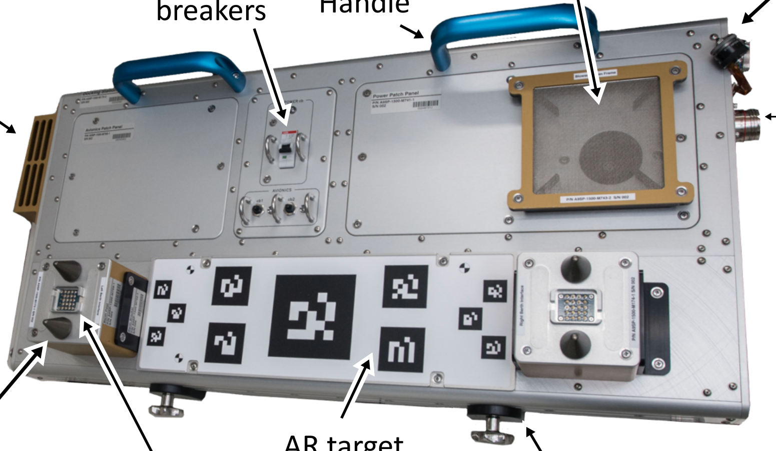


Astrobee Perching Arm pan motion



Astrobee Perching Arm tilt motion

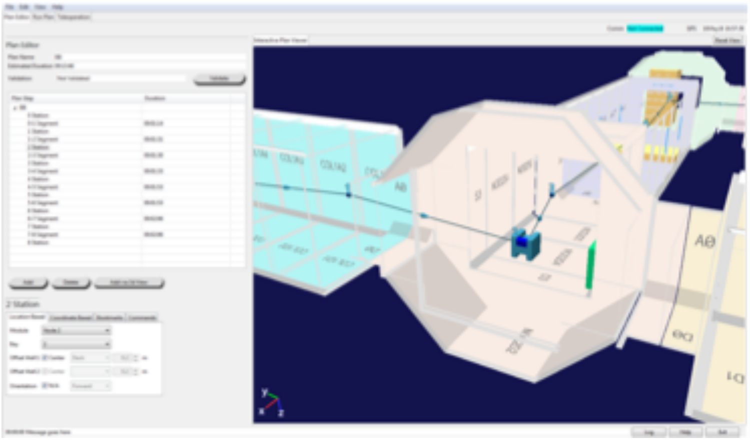
System Description: Docking Station



- 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

System Description: 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

Basic Conops

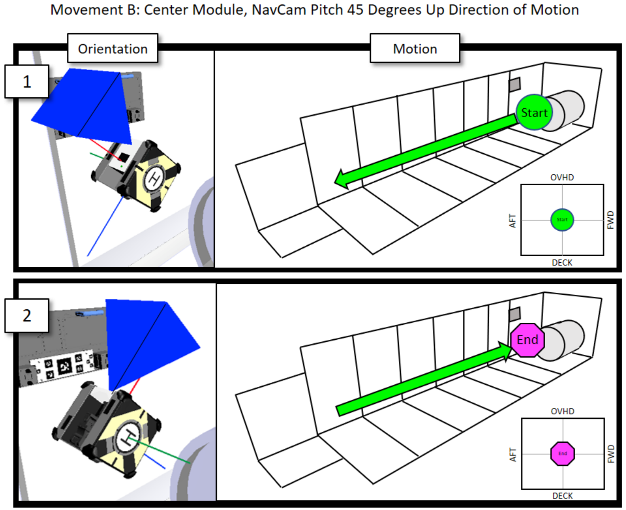
- When an Astrobee is idle, it charges in its dock
- Astrobees can execute complex plans with full autonomy and no astronauts present
  - Including undock, traverse multiple modules *(only Japanese Experiment Module (JEM) currently mapped)*, return to dock
- Astrobees run with ground operator oversight
  - 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)

Commissioning Approach

- Gradually demonstrate increasing capability
- Plan to repeat activities
- Hardware checkout and calibration of each robot is independent
- Software improvements on one, improves all
  - Concentrate on one robot before moving on to others
- Gradually incorporate payloads

Types of Activities

1. Checkout
   - Crew unpacks and inspects hardware
   - Functional tests of all hardware
2. Calibration
   - Astrobee collects sensor data while crew provides motion
   - Cameras use a calibration target (checkerboard or dock fiducials)
3. Mapping
   - Crew "flies" the robot while Astrobee collects NavCam imagery
4. Localization & Mobility (LoMo)
   - Verify robot localization within module
   - Robot performs increasingly complex motions to test mobility system
5. Crew Interface
   - Crew controls the Astrobee using the Crew Control Station



Example crew mapping motion

Types of Activities (cont.)

6. Ops Demo
   - Demonstrate an operational mission scenario (e.g. visual inspection)
7. Payload Installation
   - Crew installs payload (e.g. perching arm)
   - Functional tests of payload
8. Payload Demo
   - Operational demonstration of payload
   - e.g. Perching Arm
     - Autonomous perching/unperching
     - Panning and tilting while perched
9. SPHERES/Astrobee Hand-off
   - Symbolic passing of the torch from SPHERES to Astrobee

2019 Commissioning Activities

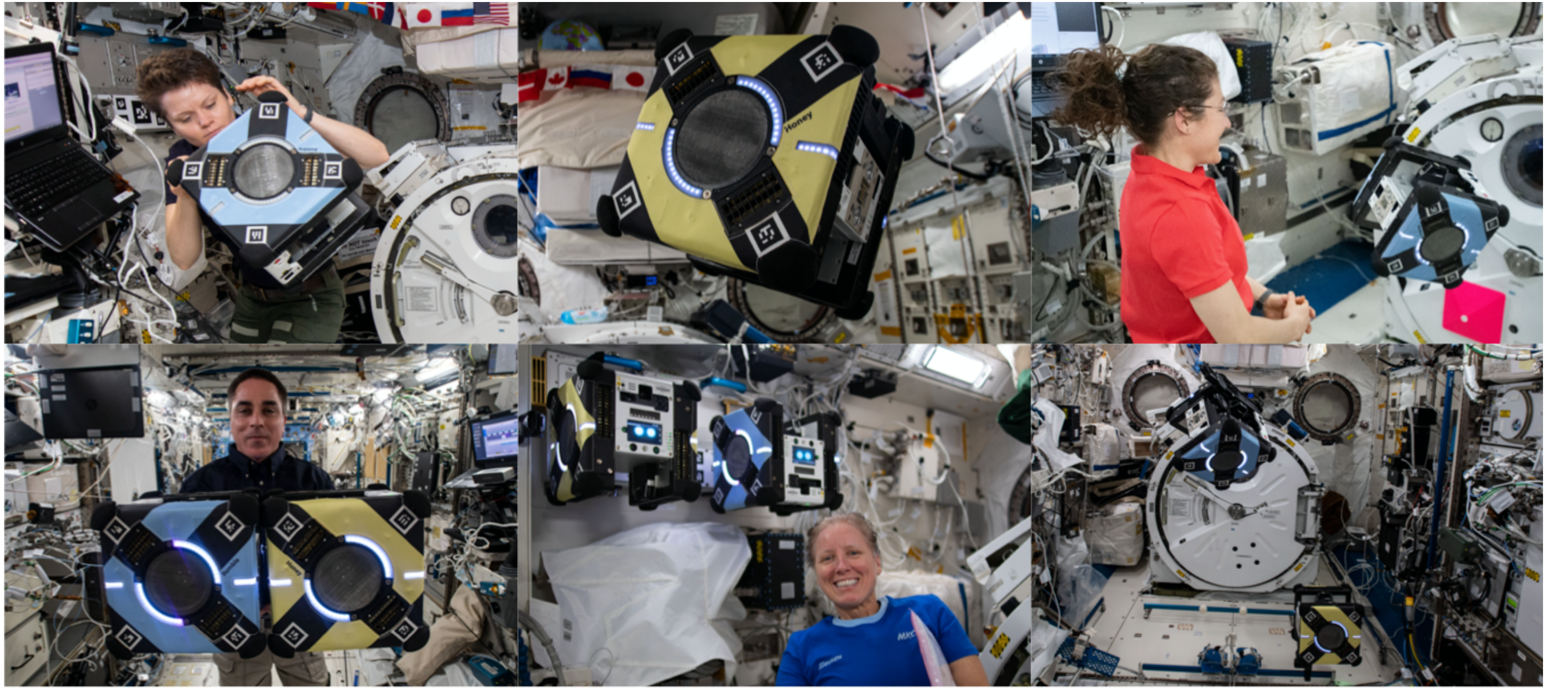
Date	Activity	Robot	Crew Member
15 Feb 2019	Docking Station installation and checkout		David Saint-Jacques
30 Apr 2019	Checkout	Bumble	Anne McClain
13 May 2019	Calibration and JEM mapping	Bumble	Anne McClain
23 May 2019	JEM mapping	Bumble	David Saint-Jacques
14 Jun 2019	Localization and mobility 1	Bumble	David Saint-Jacques
12 Jul 2019	Localization and mobility 2	Bumble	Christina Koch
24 Jul 2019	Localization and mobility 3a	Bumble	Christina Koch
28 Aug 2019	Localization and mobility 3b	Bumble	Christina Koch
30 Oct 2019	Checkout and calibration	Honey	Luca Parmitano
01 Nov 2019	Localization and mobility 4	Bumble	Luca Parmitano
31 Dec 2019	Astrobee/SPHERES Photo Op	Honey, Bumble	Andrew Morgan

2020 - Present Commissioning Activities

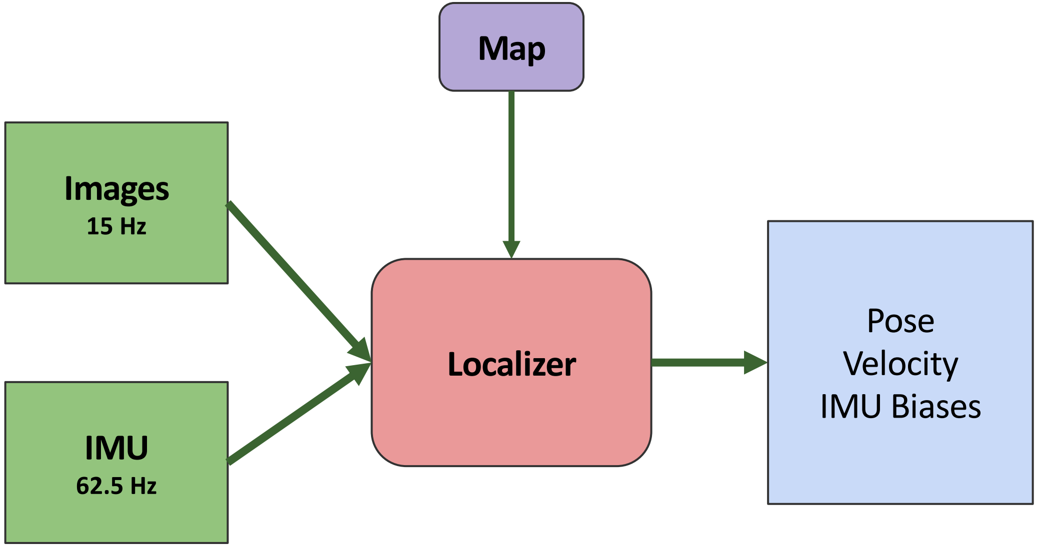
Date	Activity	Robot	Crew Member
30 Apr 2020	Localization and mobility 5	Honey	Chris Cassidy
13 May 2020	Localization and mobility 6	Bumble	Chris Cassidy
02 Jul 2020	Crew Minimal: Validate SciCam streaming	Bumble	
04 Sep 2020	Localization and mobility 7	Bumble	Chris Cassidy
14 Dec 2020	Crew Minimal: Validate Honey localization	Honey	
21 Dec 2020	SoundSee checkout – First powered Astrobee payload	Honey, Bumble	Shannon Walker
04 Feb 2021	Arm installation and checkout	Honey, Bumble	Kate Rubins
12 Feb 2021	Crew Minimal: Test new localization software	Bumble	
10 Mar 2021	Crew Minimal: Test updated localization software	Bumble	

Video: Highlights

Astrobees and Astronauts



Baseline Astrobee Localization

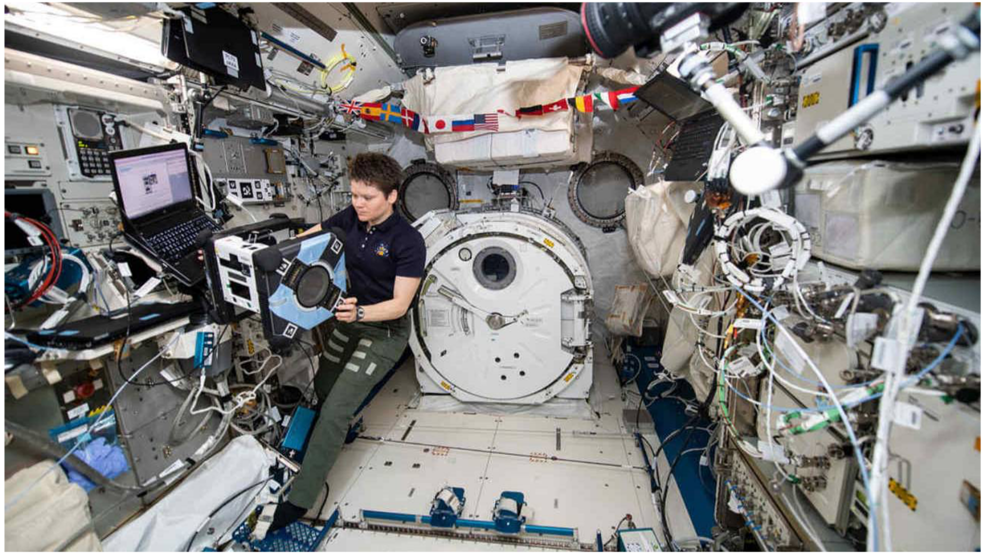


- Feature-based map matching
  - Using BRISK features
- Optical flow feature tracking
  - Independent of map
  - Ids and tracks local features
  - Used for visual odometry
- EKF (Extended Kalman Filter) Localization
  - Based on MSCKF
  - Mourikis AI, Roumeliotis SI. "A multi-state constraint Kalman filter for vision-aided inertial navigation."

B. Coltin, J. Fusco, Z. Moratto, O. Alexandrov, R. Nakamura, "Localization from Visual Landmarks on a Free- flying Robot," Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2016.

Shortcomings

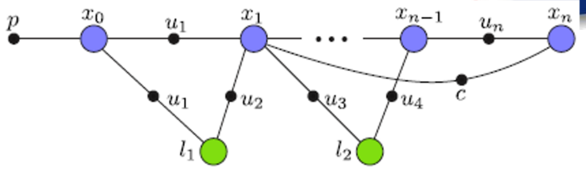
- Map Changes
  - Lighting, cargo bags, new equipment cause errors in map matching, requires frequent map updates
- EKF Localization accumulates drift
  - When images aren’t successfully matched to the map, relies on visual odometry which is prone to drift



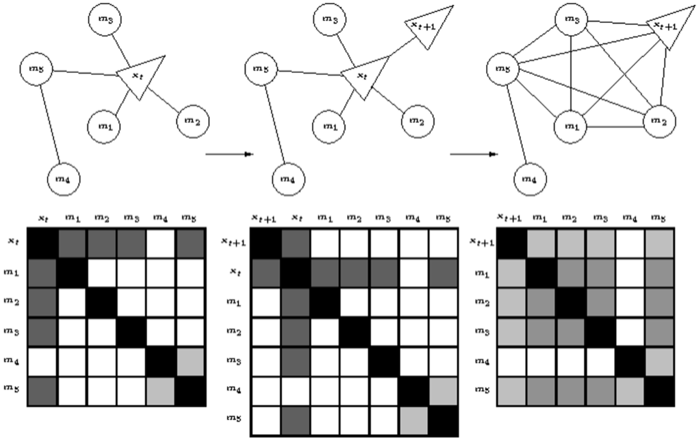
Astronaut Anne McClain inspects Bumble

Solution: More Accurate Localization Estimate Using Graph-based Methods

- Graph-based methods have become quite popular over the last couple of years and graph-based solvers have become efficient enough to run as live localizers
- Use open-sourced gtsam library
- Graphs are more computationally expensive, but do multiple iterations of optimization to more accurately calculate localization estimate
- EKF can be thought of as doing a single iteration which is faster and more efficient but more error prone
- Graph optimizes a history of poses and other estimates to improve accuracy



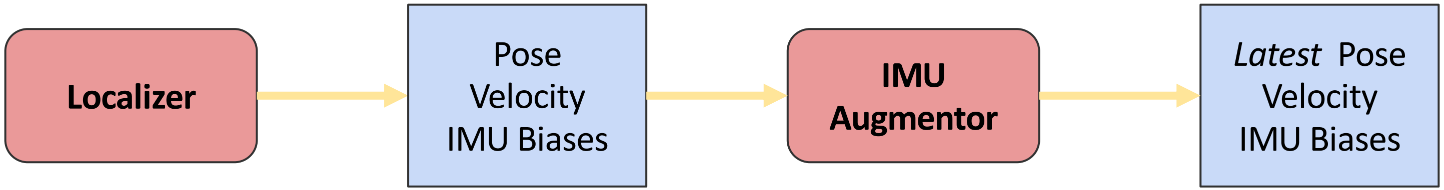
"iSAM in Depth" Tutorial by Kaess



Walter, Matthew R. et al. "A Provably Consistent Method for Imposing Sparsity in Feature-Based SLAM Information Filters."

New Localization Architecture

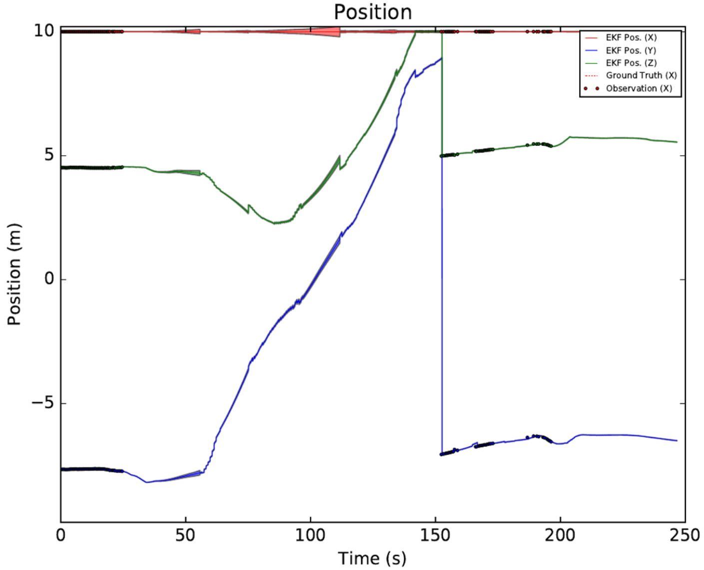
- Account for increase in computation time by adding latest imu measurements to latest graph-based localization estimate
- Tunable limit for number of optimization iterations and duration of history to optimize over to tailor graph-based method to available computing resources



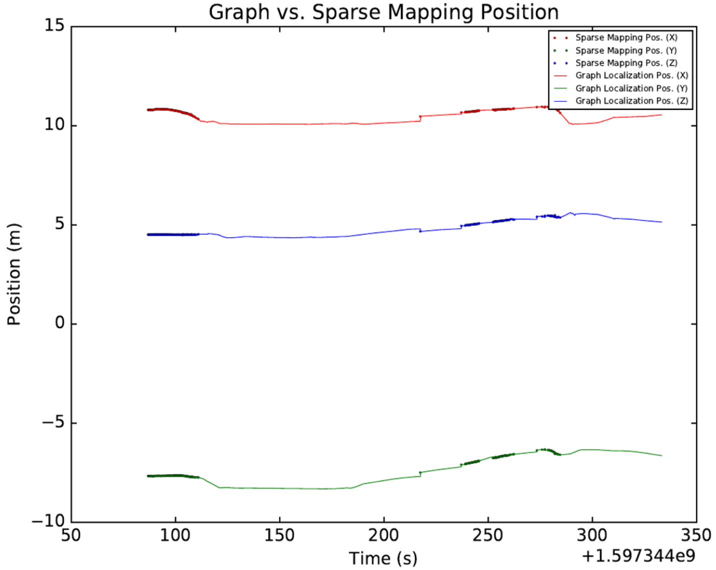
R. Soussan, B. Coltin, V. Kumar, T. Smith, “AstroLoc: An Efficient and Robust Localizer for a Free-flying Robot,” Manuscript submitted for publication, 2021.

Initial Results: Reduced Localization Drift

EKF Loc



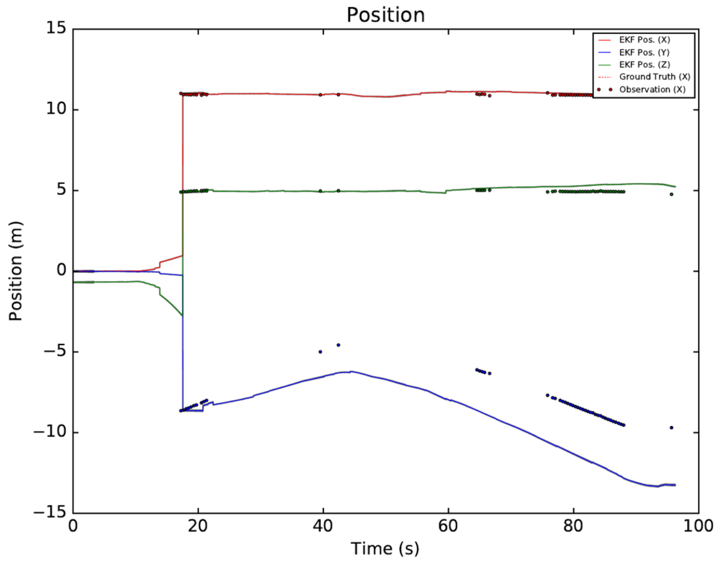
Graph Loc



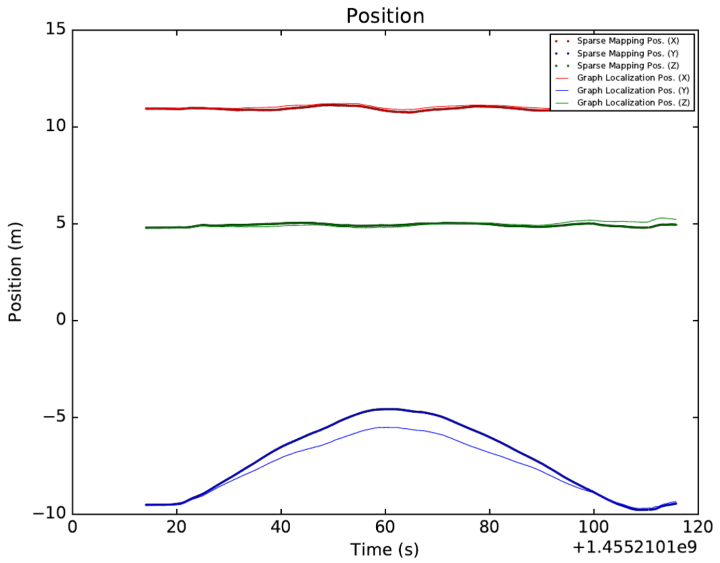
EKF struggles on this recording when a large gap between map estimates occurs, graph-based method is able to handle this period

Initial Results: VIO Mode, Reduced Drift

EKF VIO



Graph VIO



Drift accumulates over time in EKF VIO due to approximations EKF makes, graph-based approach suffers less drift at an increase in computational cost

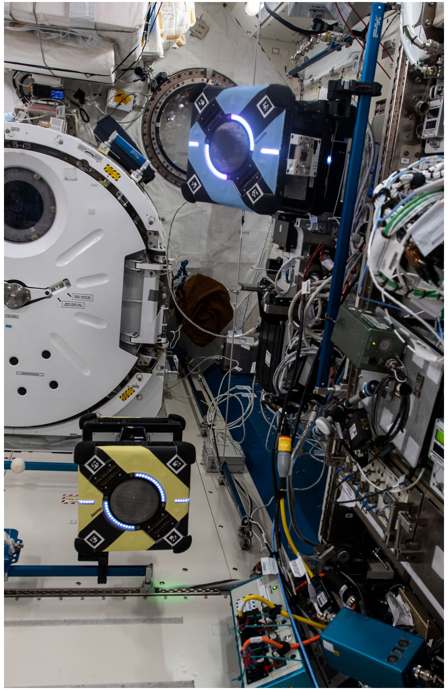
Guest Science

- Astrobee Facility began on-orbit operations for Guest Scientists in May 2020
- Activities completed to date:

Investigation	Institution	# of Activities	Status
Kibo-RPC	JAXA	4	Complete
REGGAE	Technische Universität Braunschweig	2	Complete
SoundSee	Bosch & Astrobotics	2	On-going
RFID Recon	NASA JSC	1 dedicated 2 ride-along with ISAAC	On-going
ISAAC	NASA ARC & JSC	2	On-going
Astrobatics	Naval Postgraduate School	1	On-going
Gecko Gripper	Stanford University	1	On-going

Conclusion

- Commissioning met several setbacks
  - Crew unavailability
  - Crew privacy concerns
  - Poor localization performance
  - COVID-19 pandemic
- Need to verify autonomous perching and obstacle detection to complete baseline
- Additional capabilities will be brought on-line as needed
- Astrobee is now a working facility
- Pace of operations exceeds SPHERES



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