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Astrobee On-Orbit Commissioning

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Abstract

The Astrobee free flying robots operate autonomously inside the International Space Station (ISS) with oversight from a ground operator or ISS crew. They replace the Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) as research platforms for zero-g free-flying robotics. Astrobee can also serve as a mobile camera/sensor platform for flight and payload controllers to improve ISS operations. Development began in late 2014, and flight hardware deployed to the ISS on several launches starting from November 2018 to October 2019. Shortly after the first two robots arrived in April 2019, we began a series of commissioning activities to validate the Astrobee robots. This paper reviews the Astrobee system and describes the on-orbit commissioning activities and results.
Keywords: ISS, Astrobee, free-flyer, robot

Acronyms/Abbreviations

DOF	Degrees of Freedom
EKF	Extended Kalman Filter
EXPRESS	EXpedite the PRocessing of Experiments to the Space Station
GDS	Ground Data System
GTSAM	Georgia Tech Smoothing and Mapping
ISAAC	Integrated System for Autonomous and Adaptive Caretaking
ISS	International Space Station
IMU	Inertial Measurement Unit
IVA	Intravehicular Activity
JEM	Japanese Experiment Module
Kibo-RPC	Kibo Robot Programming Challenge
LIDAR	Laser Imaging, Detection, and Ranging
LoMo	Localization and Mobility
MSCKF	Multi-State Constraint Kalman Filter
REGGAE	REduced Gravity Gecko Adhesion docking Experiments
RFID	Radio-Frequency Identification
RMSE	Root Mean Square Error
SLAM	Simultaneous Localization and Mapping
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellites
USOS	U.S. Orbital Segment
VERTIGO	Visual Estimation and Relative Tracking for Inspection of Generic Objects
VIO	Visual Inertial Odometry

1. Introduction

We developed a free-flying robot system, "Astrobee", to perform Intravehicular Activity (IVA) work on the International Space Station (ISS) [1]. The Astrobee system includes three free-flying robots, a dock (for recharging electrical power and transferring large data files), and a ground data system that is used for communication, control and data transfer.

Free-flying space robots can be used when humans are present to off-load routine work, to increase crew productivity, and to handle contingencies. We designed Astrobee to address three objectives:

- Provide a microgravity robotic research facility in the ISS U.S. Orbital Segment (USOS), which will replace the existing ISS SPHERES facility. Astrobee includes multiple free-flying robots to support testing of cooperative and coordinated activities and payloads.
- Provide remotely operated mobile camera views the ISS USOS. The primary intent of these views is to enhance the situation awareness of mission control, particularly of the ISS IVA environment, astronaut activities, and payload status.
- Perform mobile sensor tasks in the ISS USOS. Example tasks include inventory using a RFID scanner and IVA surveys (sound levels, air quality, etc.).

Starting in April 2019, we began a series of activities to commission the space and ground segments of the Astrobee system. The high-level goals of commissioning include: 1) verify that all the flight hardware survived launch, 2) calibrate instruments and map the ISS USOS, and 3) validate Astrobee capabilities on-orbit.

2. System Description

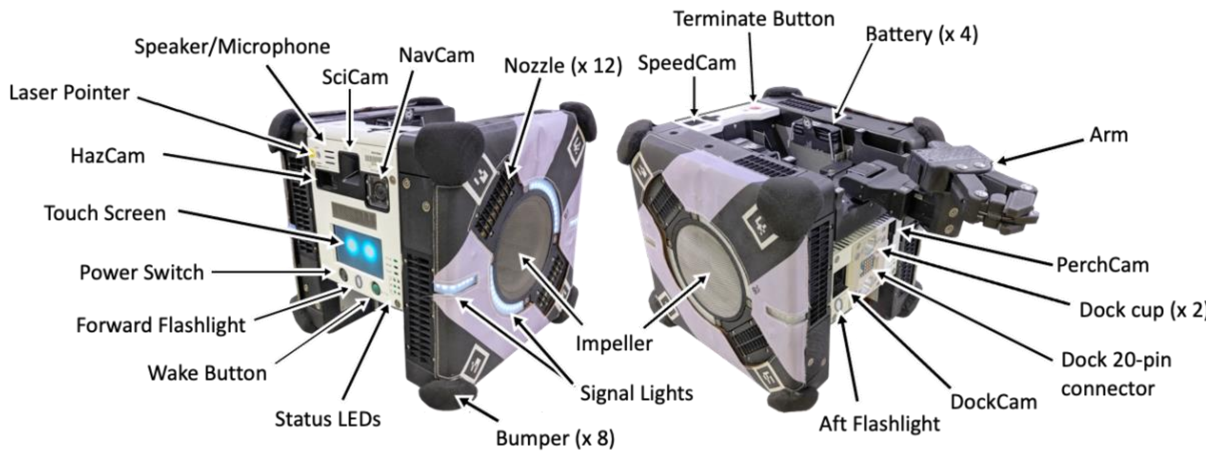

Fig. 1 Astrobee robot. Left: Forward and left faces. Right: Top and left faces, with Perching Arm deployed.

An Astrobee robot (Fig. 1) is a 32 cm-on-a-side cube with a mass of approximately 10 kg. Two fan-based propulsion modules on opposite sides of a central avionics core provide holonomic motion in six degrees of freedom, meaning it has the ability to move instantaneously in any direction and rotate about any axis. This all-electric system requires no consumables except for battery charging, accomplished by autonomously connecting to its docking station [2].

Astrobee has three available payload bays for perching arm, guest science payload, or new sensor integration. Each bay supplies battery power and a USB connection to the robot's main processors.

2.1 Sensors

In its baseline configuration, i.e., without any additional payloads in its payload bays, Astrobee uses a suite of commercial off-the-shelf external sensors (Fig. 1). The forward face includes the NavCam, a fixed-focus color camera with a wide field of view used for general-purpose navigation; the HazCam, a LIDAR imager used to detect obstacles; and the SciCam, an auto-focus color camera used for live HD video downlink.

Astrobee's aft face houses the DockCam, a color camera nearly identical to the NavCam, used to improve accuracy while backing into the dock by tracking fiducials; and the PerchCam, a LIDAR identical to the HazCam, used to localize relative to ISS handrails when Astrobee perches autonomously.

2.2 Localization

Astrobee traverses the USOS with a vision-based navigation system that compares existing features of the ISS interior with an on-board a priori map, combined with visual-inertial odometry measurements [3]. Visual odometry compares features across frames in the image stream, allowing the robot to continue navigating for short distances across areas where no map features are recognized (for example, if part of a module was reconfigured since the last map update). Cooperative markings (or fiducials) are used only for autonomous docking, in order to achieve the roughly 1 cm position accuracy needed for successful mating with the dock.

We found that Astrobee's ability to recognize features in its a priori map degraded quickly with the age of the map, due to ISS environment changes. Section 4 discusses the recent improvements we have made to Astrobee's localization system.

2.3 Perching Arm

Astrobee can carry a perching arm in its top-aft bay that allows it to grasp ISS handrails and dwell for extended periods, so Astrobee can reduce its power consumption and its interference with ISS operations [4, 5]. The perching arm can also support future manipulation research. Astrobee's perching arm has three degrees of freedom: two joints and a gripper. The joints allow the arm to stow completely within Astrobee's top payload bay, and when perched, provide pan/tilt pointing for Astrobee's forward-facing cameras.

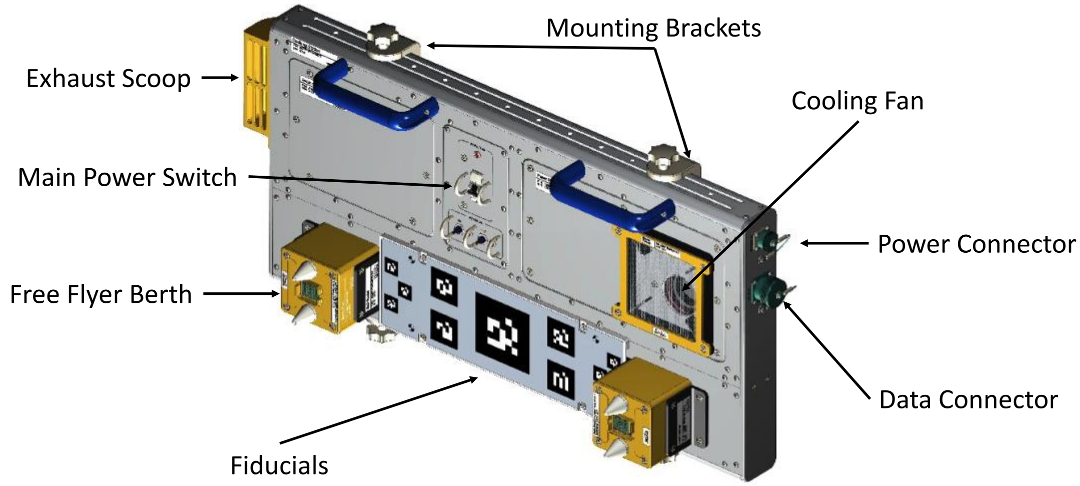

Fig. 2 Astrobee Docking Station

2.4 Docking Station

The Astrobee Docking Station (Fig. 2), or dock, is approximately 85 cm x 38 cm x 28 cm, not including mounting bracketry. It has two berths, each providing power and Ethernet connectivity to one Astrobee robot.

When docking, Astrobee autonomously approaches its berth using visual servoing relative to fiducials mounted to the dock. Once contact is made, a system of conical lances (on the berth) and cups (on the robot) guides the final mating, accommodating up to about 1 cm of alignment error. Once docked, retention force is provided by retractable magnets within each berth.

2.5 Ground Data System

Operators monitor and command Astrobee through a user interface called the Control Station that runs on a laptop [6]. A simplified Crew Control Station is installed on two EXPRESS laptop computers on ISS so that Astrobee guest scientists can ask crew to control Astrobee as part of an experiment. However, in most cases a Control Station running on the ground controls Astrobee. Astrobee research facility staff and guest science researchers all use Control Station instances installed at their own institutions. The Astrobee Control Station provides tools for planning, execution monitoring, and supervisory control of up to three Astrobees.

The Astrobee Ground Data System (GDS) also includes servers for archiving and distributing Astrobee data, and a suite of engineering tools to support ongoing maintenance and upgrades of the Astrobee software.

3. Commissioning Activities

Astrobee on-orbit commissioning takes an incremental approach, gradually demonstrating increasing capability, with planned repeat activities to account for the inevitable problems that will be exposed when any robotic system is tested in a new environment. Commissioning consists of several types of activities: hardware checkout and calibration, ISS interior mapping, performance tuning and characterization, and operational demonstration.

Hardware checkout and calibration of each free flyer is independent of the others, however improvements to software performance (for example, on the localization subsystem) on one robot improves all. Therefore, the commissioning schedule concentrated first on one robot, before moving on to the others. The Astrobee base system was tested before moving on to testing payloads.

3.1 Activity Types

We defined a series of activities to verify Astrobee system capabilities. Each type of activity would be standalone, meaning we would generally not consider combining activities until later robots, when we had gained sufficient operational experience. Also, some require post-activity data analysis before the next can be performed. We assumed crew time would be needed for most of these activities, though we hoped to lessen our reliance on crew toward the end.

3.1.1 Checkout

Crew unpacks and inspects the hardware, checks for structural integrity, and looks for damaged or missing parts. The astronaut performs any necessary assembly or mounting, and then powers up the system. The ground team then begins commanding to run the hardware through a series of functional tests with crew verifying that the associated motion and/or signals occur.

3.1.2 Calibration

Crew manually moves the robot while Astrobee collects sensor data. Camera calibration data is collected while the astronaut moves the robot in a series of patterns while pointing the cameras at a calibration target. For the NavCam and DockCam, we used a checkerboard target that was available on the ISS from the SPHERES VERTIGO (Visual Estimation and Relative Tracking for Inspection of Generic Objects) project [7]. SciCam calibration used the Docking Station fiducials as the calibration target. For IMU calibration, the astronaut spun the Astrobee on each coordinate axis.

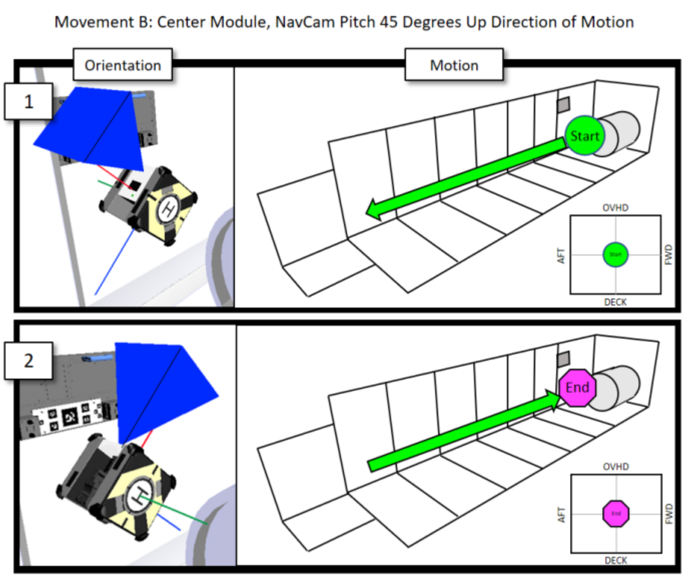

Fig. 3 Example mapping pass from crew procedure

3.1.3 Mapping

To map the Japanese Experiment Module (JEM), home of the Astrobee Docking Station, the robot collects a sequence of images from the NavCam that shows all surfaces of the module from different viewing angles and distances. Crew manually "flies" the robot throughout the module with varying orientations. An example motion is shown in Fig. 3 in which Astrobee views the Overhead at a 45-degree angle.

3.1.4 Localization & Mobility (LoMo)

We verify that the robot is able to localize within the module. Astrobee then performs increasingly complex motions to test the mobility system. We planned to repeat this activity multiple times as we tuned the system and increased complexity.

3.1.5 Crew Interface

The Astrobee system includes a Crew Control Station that allows an ISS crew member to control the robot from onboard the Station. In the Crew Interface activity, an astronaut verifies the crew's ability to load and run plans, teleoperate, and execute guest science commands.

3.1.6 Ops Demo

Once base capabilities have been verified, an Ops Demo activity validates the use of Astrobee in an operational mission scenario. Astrobee would perform a complete autonomous visual inspection sortie: undock, move to inspection target (e.g. a payload rack), image the target from multiple viewpoints, and redock.

3.1.7 Payload Installation

Shortly after commissioning began, several hardware payloads joined Astrobee on orbit and provided candidates for a first payload installation. This included the perching arm, an RFID reader [8, 9], and a microphone array [10]. These payloads use a quick release installation mechanism designed for ease of use by astronauts in a microgravity environment. A Payload Installation activity, similar to a Checkout activity, ensures that the payload hardware is working post-launch, but also verifies the functioning of the Astrobee payload bays, and validates the installation mechanism.

3.1.8 Payload Demo

A Payload Demo activity is an operational demonstration showing the ability of the system to achieve the payload conops. For instance, for the perching arm, this would be a demonstration of autonomous perching, panning and tilting of the robot while perched, and autonomous unperching.

3.1.9 SPHERES/Astrobee Hand-off

The final activity of commissioning would be a symbolic passing of the torch from SPHERES to Astrobee. This would primarily be a photo opportunity to see the two systems together, before the SPHERES were down-massed.

3.2 Results

3.2.1 Early Commissioning

We began commissioning activities on our first free flyer, Bumble, on April 30, 2019. Table 1 shows the sequence of activities. The hardware checkouts and calibration activities showed that the robot survived launch well with all sensors retaining their pre-flight calibration. Initial mobility testing proved that the propulsion system and rate control is responsive and capable of maneuvering in the ISS environment.

During early LoMo activities, localization worked well, and Bumble flew complex maneuvers, executed plans, and undocked and docked autonomously. We were confident to move on to checking out the second Astrobee, Honey.

As we began to operate Bumble, concerns about crew privacy with regard to imagery acquired by Astrobee were raised. The ISS program levied a constraint that, until we could enable ground monitoring of the Astrobee image/video stream by the Video Control Center at Johnson Space Center, all activities involving cameras required the presence of crew.

Crew time became particularly scarce early in 2020, and between that and the onset of the COVID-19 pandemic, we experienced a 4-month drought in activity. However, since the Astrobee system was designed to be operated by guest scientists from their home institutions, we were able to adapt to work-from-home conditions rather quickly and began operating again on April 30 by controlling Astrobee on ISS from team homes. Ironically, it became easier to operate the robots on-orbit than the ground units in the lab, since lab access was limited by pandemic restrictions.

3.2.2 Activities Resume

On resuming operations, we found that localization performance had significantly deteriorated. We determined that, due to changes to the configuration of the JEM, especially lighting and cargo storage, the localization system no longer recognized the landmarks in its a priori map of the module. We therefore began regularly updating the a priori map, while also developing a software upgrade to improve robustness by reducing reliance on the map, as described in Section 4.

Meanwhile, because commissioning was taking longer than anticipated, we decided to concentrate on guest science activities and bring on additional capabilities only as they were needed. Capabilities not needed by current customers, like Crew Control, dropped to the end of the priority list.

Also occurring in mid-2020, our ability to stream imagery and video to the Video Control Center came online, so that crew was no longer needed to monitor Astrobee's imagery. This enabled a new type of activity called Crew Minimal. Crew would still help by adjusting lighting, moving stowage, or occasionally rescuing Astrobee if it became unrecoverably lost, but for the most part, did not need to be scheduled to support the main portion of the activity. This reduced reliance on crew has enabled Astrobee activities to be scheduled much more frequently.

3.2.3 Recent Work

Late in 2020, Astrobee successfully hosted its first powered payload, SoundSee, demonstrating the ability to power and communicate with a device in a payload bay.

The next capability needed by a guest scientist was the perching arm. On February 4, we were able to install and checkout all three flight arms in the two available robots, leaving one installed on Honey for upcoming guest science operations.

Most recently, we tested the new localization software described below in two Crew Minimal sessions. The last was the first time Astrobee did not require a crew rescue, with over 2 hours of flying with multiple sorties.

Remaining capabilities that yet to be verified include autonomous perching and obstacle detection. Crew control and operation of the third Astrobee, Queen, have been descoped from commissioning and will be performed on an as needed basis. The Astrobee Facility continues to balance user deadlines with infrastructure testing.

Table 1 On-orbit Astrobee Commissioning Activities as Executed

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
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	

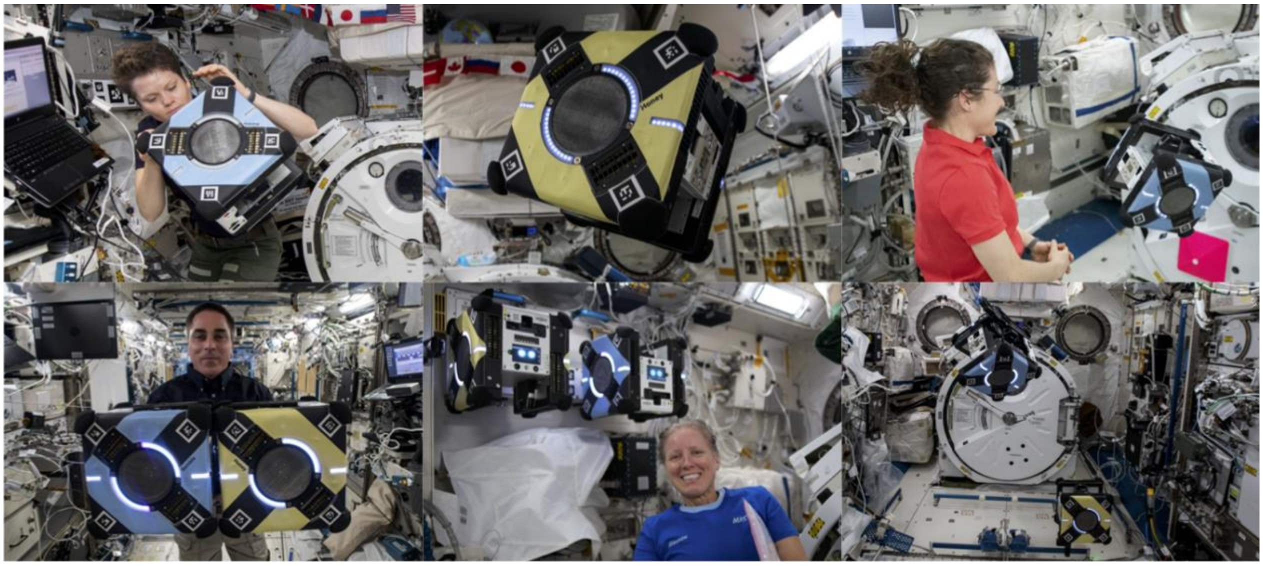

Fig. 4 Astrobee and Astronauts. Clockwise from Top Left: Anne McClain (NASA), Honey floating, Christina Koch (NASA), Honey perched on deck handrail with Bumble floating, Shannon Walker (NASA), Chris Cassidy (NASA).

4. Localization Improvements

From January through April 2020, we had a long period of inactivity on-orbit, primarily due to the lack of available crew time. When operations started back up again in late-April, we found that performance of the localization system had significantly degraded. Due to changes in the environment (lighting, equipment configurations, and stowage), Astrobee's map was no longer valid. Despite additional mapping activities, we have found that the ISS environment is too dynamic for Astrobee's baseline localization system. Starting in Summer 2020, we began to look for ways to make Astrobee more robust to change.

To improve the performance of the localizer we decided to change the Extended Kalman Filter (EKF)-based implementation described in [3] to a graph-based one detailed further in [11]. Whereas the previous EKF-based localizer utilized an MSCKF [12] for visual-inertial odometry (VIO) and localization, the new AstroLoc localizer takes advantage of nonlinear optimization using the GTSAM library [13]. The main challenge in adopting a graph-based approach for localization for Astrobee is making the system efficient enough to run on Astrobee's compute platform. Whereas many modern VIO systems incorporate loop-closures in a simultaneous localization and mapping (SLAM) approach, this is too computationally expensive for Astrobee. Therefore, we focused on creating an efficient localizer with our existing optical flow features, IMU measurements, and map associations.

The AstroLoc graph-based localizer uses IMU preintegration factors [14] as well as visual odometry smart factors [15] to efficiently incorporate inertial and visual data. Map associations are incorporated as image projection factors and if each projection suffers a cheirality error, a pose prior factor is inserted in their place. Marginalization is performed by inserting prior factors for the oldest states in the graph containing estimates and covariances from the most recent round of optimization.

AstroLoc is carefully tuned to increase accuracy while limiting computational cost. The costliest aspect for the localizer is the incorporation of smart factors. Although these provide a performance improvement from bundle adjustment, their error and Jacobian matrix calculations are the most expensive for our localizer. Therefore, to limit the computation cost, we limit the number of smart factors used and carefully choose measurements for each smart factor from the same subset of timestamps to limit constraints between non-consecutive states. We additionally limit the duration of the state estimates in the graph that we optimize for, the number of map associations included in the graph, and the number of optimization iterations the graph performs. Detailed results on the accuracy versus efficiency trade-offs are provided in [11].

As the graph-based approach for AstroLoc introduces additional optimization delay, we augment the most recent localization estimates from AstroLoc with the latest IMU measurements to give a more recent estimate of Astrobee's pose and velocity to our controller. We integrate all IMU measurements received since the most recent graph-based localization state using the localizer's most recent estimate for the IMU biases. With this approach, we are able to provide localization updates at the roughly 62.5 Hz that our controller expects. Tailoring the graph-based optimization times limits the amount of IMU extrapolation we need to perform and limits the potential errors.

AstroLoc yielded significant improvements over our previous EKF-based approach. We evaluated it in two modes: (1) Localization mode runs the full localization system integrating both prior map matching and VIO as they would normally be used during real ISS operations; (2) VIO-only mode disables prior map updates, providing a more rigorous test of the ability of VIO to maintain a fix for extended periods. Evaluated on a dataset of 12 ISS activities, AstroLoc showed a reduction in pose RMSE of 94.11% in localization mode and 71.51% in VIO-only mode. Most importantly, it avoided the two lost robot events suffered by the EKF-based approach. Even with the lost robot events removed from our dataset, AstroLoc still showed a reduction in pose RMSE of 54.29% in localization mode and 16.75% in VIO-only mode.

5. Guest Science

Much of the work of the Facility in 2020 was in support of the first Astrobee guest science activities. In particular, a lot of effort was put into making the Kibo Robot Programming Challenge (Kibo-RPC) [16], sponsored by the Japan Aerospace Exploration Agency (JAXA), a success despite the limitations of the localization system. Kibo-RPC encouraged students across the Asia Pacific region to develop software to control Astrobee to achieve the goal of the competition scenario. Initial rounds were run in simulation and the finalists from Australia, Indonesia, Japan, Singapore, Taiwan, Thailand, and UAE uploaded their software to Bumble on the ISS. On October 8th, 2020 the finals took place.

Overall, the activity was extremely successful, enabling students to run their software and some even multiple times within the time allocated for the activity. Hundreds of students across the Asia Pacific region participated in real time. JAXA will be running a second competition in 2021.

The REduced Gravity Gecko Adhesion docking Experiments (REGGAE) [17] experiment runs completed in January 2021. Funded by the German Aerospace Center (DLR) at the Technische Universität Braunschweig, REGGAE is an investigation to demonstrate automated docking between a chaser satellite and a target satellite, simulating orbital debris removal using gecko-inspired micropatterned dry adhesives.

Automated docking using gecko-like adhesives in 6-degrees-of-freedom (DOF) was demonstrated for the first time. Past state-of-the-art testing was all done with manual docking. Also shown for the first time was using mushroom shaped micro-structures in the gecko material in 6-DOF. This is in contrast to other popular gecko materials that use asymmetric micro-structure geometries.

Other guest science experiments that have completed at least their first on-orbit activity include:

- SoundSee: A microphone array developed by Bosch and Astrobotics that collects sound data that will be used to build sound maps of the ISS. Future sorties will look for anomalous sounds that could indicate equipment in need of maintenance or repair.
- RFID Recon: An RFID reader developed by Johnson Space Center (JSC) that can be used as a mobile interrogator for an automated logistics system for space vehicles [8, s9].
- Integrated System for Autonomous and Adaptive Caretaking (ISAAC): A system under development at Ames Research Center (ARC) and JSC that integrates vehicle systems with Intra-Vehicular Robots (IVR) to perform caretaking tasks such as monitoring, maintenance, logistics, and repair.
- Astrobatics: A software-only payload from the Naval Postgraduate School that uses the Perching Arm to self-toss as a form of propulsion, demonstrating an alternative form of motion that can save propellant.

6. Conclusion

The Astrobee development project had planned to complete on-orbit commissioning of the space and ground segments of system before “handing over the keys” to the Astrobee Facility for operational use. Setbacks due to crew unavailability, operational constraints to address crew privacy concerns, poor localization performance, and the COVID-19 pandemic slowed the pace of testing such that even as of the writing of this paper, the system is not yet completely “commissioned”. Remaining capabilities that still need verification include autonomous perching and obstacle detection. Crew control and operation of the third Astrobee, Queen, will be verified at a later time. The Facility has been able to support guest science by prioritizing additional capabilities on an as-needed basis. For example, no current guest scientist requires control by crew, so that capability has been given the lowest priority. Additionally, some guest scientists have verified capabilities or calibrated instruments as part of their activity. Astrobee is a working facility on the ISS with a pace of operations that now exceeds what was seen on SPHERES.

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