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Game Changing Development Program
HET2 Astrobee Transition Report

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HET2 Astrobee - Signature Page

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Baseline	-	04/15/2020	Develop an initial baseline of the HET2 Astrobee Transition Report

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1.0 Project Summary

The purpose of the Human Exploration Telerobotics 2 (HET2) project is to mature telerobotics technology to increase the performance, reduce the cost, and improve the success of human space exploration. To do this, HET2 developed a new free-flying robot, Astrobee to: (1) off-load routine and repetitive work from astronauts, and (2) extend and enhance crew capabilities. HET2 tested these robots in laboratories on the ground and on the International Space Station (ISS).

Future human space missions in Earth orbit, to the Moon, and to distant destinations offer many new opportunities for exploration. However, astronaut time will always be in short supply, consumables (e.g., oxygen) will always be limited, and some work will not be feasible, or productive, for astronauts to do manually. Remotely operated robots, however, can complement astronauts by performing this work under remote supervision by humans from a space station, spacecraft, habitat, or even from Earth.

Telerobots, particularly semi-autonomous systems, can increase the performance and productivity of human space exploration. Telerobots are well suited to performing tasks that are tedious, highly repetitive, dangerous or long-duration, such as routine in-flight maintenance, systematic surveys, etc. Telerobots can also provide side-by-side assistance to astronauts during both intravehicular (IVA) and extravehicular activities (EVA). Telerobots can also perform "follow-up" work to complete or supplement tasks started by humans.

Today, astronauts on the ISS not only conduct science activities, but they also perform a variety of tasks required for ISS housekeeping and in-flight system maintenance. The remote monitoring and operation of many ISS systems by ground control has become an accepted practice for certain ISS tasks during the past decade. In terms of telerobotics, however, these tasks are limited to coarse positioning maneuvers of external payloads/structures using manipulator arms, such as the Space Station Remote Manipulator System (SSRMS).

Other types of robots, particularly free-flyers and dexterous humanoids, offer significant potential to perform a greater variety of tasks. These tasks include routine, repetitive or simple but long-duration work, such as conducting environment surveys, taking sensor readings or performing routine maintenance. Thus, the central focus of HET2 is to develop, test, and demonstrate how advanced telerobots, which can be operated by ground controllers on Earth and by astronauts in space, can effectively and efficiently carry out these tasks.

1.1 Objectives

The Astrobee Element (FY15 to FY19) focused on developing a new free-flying robot suitable for performing IVA work on the ISS. The new robot was built upon technology and lessons learned from the Smart Synchronized Position Hold, Engage, Reorient, Experimental Satellite (SmartSPHERES) robot, which was developed and tested by the Human Exploration Telerobotics (HET) project under the Technology Demonstration Missions (TDM) program. Astrobee was designed to address a variety of scenarios, which were developed and detailed in collaboration with the Advanced Exploration Systems (AES) program and the ISS SPHERES Facility in the Human Exploration and Operations Mission Directorate (HEOMD).

Scenarios include mobile sensor (including imagers), automated logistics (e.g., mobile inventory), and free-flying robotic testbed.

Success for Astrobee involves developing and testing robot technologies required for autonomous operations (including free-flying mobility), remote operation by ground controllers, and human-robot interaction with crew. These technologies include propulsion, robot user interface (proximal and remote), supervisory control, payload interface, and navigation. Successful on-orbit testing and demonstration of these technologies following the ISS payload process will bring the system to TRL 8. Table 11 specifies which capabilities must be demonstrated for minimum and full success.

Astrobee objectives are enumerated in Table 1. Note that 3 additional units (2 flight, 1 ground) funded by the AES program were delivered to the ISS Program Astrobee Facility.

Table 1 Astrobee Objectives

Objective #1	Design, build, and test 3 Astrobee free flyer robots (2 flight, 1 ground), 2 Docking Stations (1 flight, 1 ground), and all associated hardware, software, and ground systems needed to operate Astrobee on ISS.
Objective #2	Develop supporting technologies include propulsion, robot user interface (proximal and remote), supervisory control, payload interface, and navigation.
Objective #3	Check out, tune, and characterize performance on board the ISS during commissioning.

1.2 Relevance

HET2 is well aligned to the 2013 NASA Strategic Space Technology Investment Plan (SSTIP) in several ways. First, the SSTIP identifies "Robotics and Autonomous Systems" as a core technology area that is indispensable for NASA's present and planned future missions. Second, the SSTIP recommends that research and development address autonomous robotics and more on-board autonomy. Finally, the SSTIP specifically identifies free-flying and humanoid robots to assist crew in performing routine or hazardous tasks as examples of strategic investment.

Since the inception of HET2, the 2017 SSTIP recognized the important role that robotics can plays in human exploration missions in predeployed assets ahead of human arrival. The SSTIP identified new “challenges for robotic inspection, maintenance, repair, and autonomous operations, both in space and on the surface.”

One of the ways that HET2 tested technologies was on the ISS. These technologies will benefit both current ISS missions and future missions, particularly deep-space human exploration. As such, HET2 is also well aligned with NASA's strategy for Strategic Objective 2.1: “NASA will continue to expand the use of the ISS on-orbit research program, including continuing to increase utilization of internal and external research facilities.” (2018 Strategic Plan)

HET2 is broadly relevant to the 2015 "Robotics and Autonomous Systems" (TA 4) NASA Technology Roadmap. Astrobee advances technology in six of the sevel major TA 4 roadmap areas: Sensing & Percetption, Mobility, Human-System Interfaces, Autonomy, Autonomous Rendezvous & Docking, and RTA Systems Engineering.

Finally, HET2 addresses the NASA Strategic Plan 2018 (NPD 1001.0C) as follows:

Objective 2.2: Conduct Human Exploration in Deep Space, Including to the Surface of the Moon.

- HET2 will increase knowledge and understanding of how to design and operate remotely operated space robots in conjunction with human spaceflight
- HET2 will increase the capabilities of robots to perform IVA/EVA work in space
- HET2 will increase the efficiency of human explorers by allowing routine, repetitive work to be off-loaded to robots
- HET2 will enhance the capabilities of human explorers by enabling robots to be remotely operated by crew
- HET2 will develop two new classes of space robots (IVA free-flyer and dexterous humanoid) that can be used to tend, or caretake, human spacecraft / habitats that may be intermittently manned
- HET2 will advance exploration by enabling robotically tended "waypoint" facilities to be considered for deep-space exploration
- HET2 will produce numerous innovations in perception, control, and human-robot interaction for space robots

Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation.

- HET2 will create two new space robots (Astrobee and Robonaut 2) that incorporate a wide range of commercial off-the-shelf (COTS) components
- HET2 will mature, integrate and test open-source software and open standards for robotics and telerobotics
- HET2 will develop telerobotics technology that can be applied to a wide range of NASA missions, including the ISS, cis-lunar waypoint, Mars orbit, etc.

1.3 Technical Approach

The Astrobee element conducted incremental design and development of a free flyer that meets project, stakeholder, and ISS interface and safety requirements. Stakeholders include the ISS SPHERES Facility, the SPHERES Working Group, HEOMD AES program, ISS program, Flight Operations Directorate (FOD), Payload Operations & Integration Center (POIC) and others. The project and stakeholders have provided general and scenario specific functional requirements.

Astrobee will function as a micro-gravity research facility that will eventually succeed the existing SPHERES facility. In contrast to SPHERES, which was designed to simulate satellites (e.g., in terms of propulsion method), the Astrobee is designed as a robot. In particular, the

Astrobee is based on mobile robot engineering principles (autonomy, perception, navigation, middleware, etc.), supports telerobotic operations (crew and ground control), and is capable of autonomous docking and resupply (similar to how robotic vacuum cleaners can autonomously recharge themselves). Consequently, Astrobee is not a “drop-in” replacement for SPHERES and is not able to do everything that the current SPHERES can do. However, Astrobee is able to do many more things than the current SPHERES are capable of performing.

The ISS Program levies interface requirements on Astrobee for both launch and on-orbit. The ISS Payload Safety Review Panel (PSRP) approves ISS safety certifications. Complying with certain safety standards mitigates many of the standard ISS safety standards, while others are met by design.

Astrobee was 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. The Astrobee system was tested incrementally, as each prototype was developed and delivered. Each prototype had stated objectives, both as overall system, and for subsystem development. The Astrobee 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 Astrobee Element accepted the risk of damage to prototype hardware in order to take advantage of the less burdensome processes.

Prototype 1 was developed for risk reduction purposes and focused on open-loop operations and basic linear/rotational acceleration with two variable pitch propellers (VPP).

Prototype 2 was a flat-sat structure, focused on closed loop control, and provided a platform for further subsystem testing and risk reduction. This prototype included four VPP fans, and tested closed loop navigation using augmented reality (AR) target tracking and docking approaches.

Prototype 3 built upon the Prototype 2 structure. Though by this point, the flight propulsion design had progressed to an impeller-based design, the VPP fans were used for propulsion. Prototype 3 focused on avionics (C&DH, EPS and GNC) , and FSW Vision Based Navigation (VBN) without fiducials. This prototype implemented mostly flight-like avionics components.

Prototype 4 was a flight-like unit in form, fit and function. However, this prototype was not assembled and integrated to a standard for flight qualification. This unit was used to address all remaining risks associated with certification or flight unit development. The testing was focus on validation of the remaining Astrobee capabilities. [Prototypes 4C/4D/4E]

The Certification Units were developed from the final Prototype 4 design, with modifications as a result of Prototype 4 testing. These units were used not only for performance testing, but also for ISS interface requirement verification and certification.

Finally, two Flight Units were developed. Two additional Flight Units were also built for AES (1 additional on-orbit unit, and a flight spare). These units were developed and assembled following ARC procedures and processes for flight hardware. They were then shipped to JSC for launch processing.

2.0 Accomplishments Summary

2.1 Year 1 Accomplishments

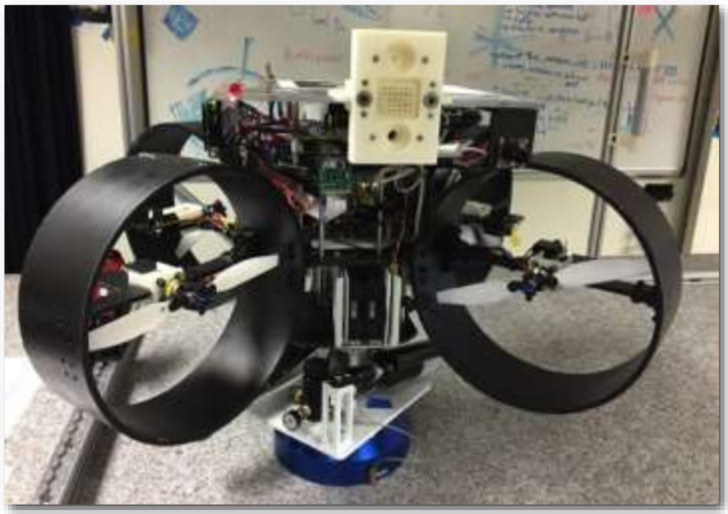

Figure 1. Prototype 3 with docking mechanism.

In Year 1, we completed development and testing of Prototype 2. Prototype 2 implemented interim avionics (low- and mid-level processors), flight software (FSW) using Robot Operating System (ROS), and propulsion (4 fans with variable pitch propellers). The platform provided 3-DOF mobility (x, y, yaw) and enabled testing of augmented reality (AR) target tracking to perform docking.

Prototype 3 (Figure 1) utilized the same propulsion hardware as Prototype 2, but added near flight-like Command and Data Handling (CDH), Comm, Guidance Navigation and Control (GNC), and Electrical Power System (EPS). FSW implemented markerless, vision-based navigation and we prototyped the perching arm and docking mechanism. Testing included: dock function and continuity, avionics jitter, perching, and navigation.

Year 1 also saw the completion of three important preliminary reviews: Periodic Technical Reviews (PTR) #1 and #2, and Payload Safety Review Panel (PSRP) #1. PTR 1 was a stakeholder review of plans, requirements, concept of operations, trade studies, testing, safety, risks, cost and schedule. The purpose of PSRP 1 was to review the Astrobee Safety Data Package (SDP) and agree upon standard and unique ISS hazards. PTR 2 was similar to a Preliminary Design Review (PDR) in which stakeholders reviewed the preliminary Astrobee design, prototype testing, safety, risks, cost and schedule, and we baselined design overview documentation.

2.2 Year 2 Accomplishments

Figure 2. Prototype impeller-based propulsion module

Figure 3. Prototype 4C

Due to feedback from stakeholders at PTR 1, Year 2 saw a complete propulsion redesign from a variable pitch propeller-based to an impeller-based system (Figure 2). During the course of the year, the propulsion system went from drawing board to flight-like prototype with every major part (plenum, nozzle, impeller, controller board) the result of multiple iterations of prototyping and rework. Benefits of the redesign include: better compatibility with the overall flight design, better stability, and improved motion accuracy.

In Year 2, we advanced several subsystems. Avionics design matured to a stack of five custom boards connecting two propulsion modules, six external sensors, three payloads, and a variety of other hardware, and we verified that the power system can support multiple hours of operations between charges.

The GNC team demonstrated reliable localization based on sparse mapping, optical flow, and IMU, and significantly increased software capability to support large area mapping. The team also adapted the motion control approach (algorithms and software) to the new propulsion system.

The Ground Data System team completed an intial prototype of the Astrobee Control Station based on the VERVE robot user interface (previously used with SmartSPHERES). The team conducted usability tests with a wide range of users and integrated the Control Station with the Free Flyer simulator and Prototype 4.

The new propulsion system was implemented in Prototype 4 (P4) (Figure 3), the first flight-like prototype. P4 reduced risk for the cert unit, allowed the team to practice Integration and Test (I&T) procedures, matured wiring, sensor mounting brackets, etc., and refined the design for crew servicing. Using P4, we tested all L2 requirements that had significant design impacts and verified motion control, navigation, payload integration, etc. We also uncovered and resolved avionics and thermal issues during integration of the prototype.

PSRP #2 updated the list of standard and unique hazards, determined how hazard controls were to be implemented, and identified verification methods and potential safety non-compliance.

PTR #3 was similar to a Critical Design Review (CDR) in which stakeholders reviewed final design, prototype testing, safety, risks, cost and schedule, and we baselined the detailed Astrobee design, and matured the conops.

2.3 Year 3 Accomplishments

Figure 4. Prototype 4E mounted in tilted configuration

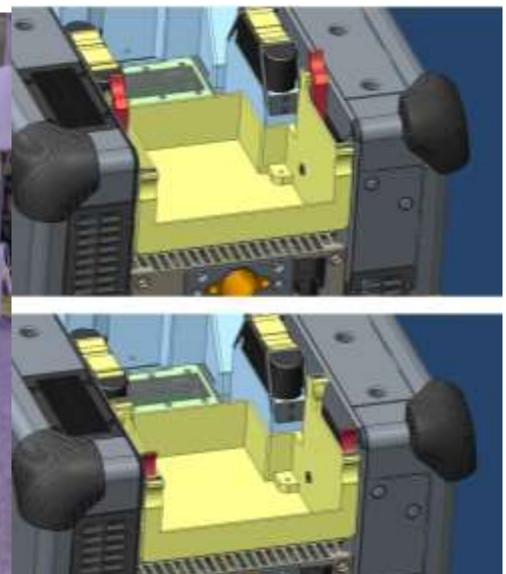

Figure 5. Payload no-tool mounting design: levers in closed position (top), and open position (bottom)

In Year 3, we worked to finish prototyping and complete the Astrobee design. The mechanical team completed the impeller-based propulsion module design, updated the payload retention mechanism (Figure 5), prototyped finishes for 3D printed parts, and prototyped the propulsion module skin.

The avionics team redesigned the EPS board to address a regulator issue, selected a solution for the SciCam's obsolescence issue, completed the Prototype 4E avionics modifications, and upgraded the Mid-Level and Low-Level Processors to Ubuntu Linux 16.04.

Meanwhile, the Crew Control Station passed a required Crew Usability test, in which a Crew Office representative worked with the interface to determine its usability for personnel in microgravity.

We passed thermal and EMI risk reduction tests with Prototypes 4D and 4E, and conducted a Delta PSRP #2 to review the Astrobee Safety Data Package reflecting design changes since PTR 3. Also on the safety front, we resolved several issues with PSRP in out-of-board meetings, including: touch temperature, flammability of paint on printed parts, and collision.

We released Astrobee Robot Software and the Simulator as open source (GitHub, Apache 2 license). Several collaborators downloaded and built the system. We also released the mechanical ICD to our collaborators.

By the end of the year, we had completed the design, began procurement of the Cert Unit parts and began L3 avionics integration.

2.4 Year 4 Accomplishments

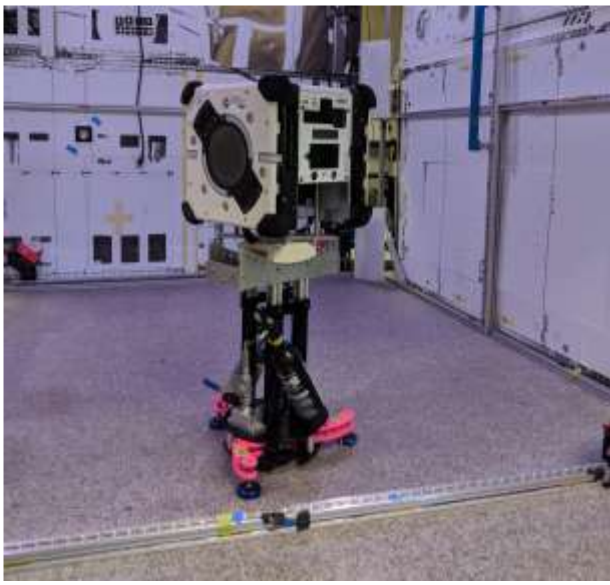

Figure 6. Astrobee free flyer certification unit on the granite table

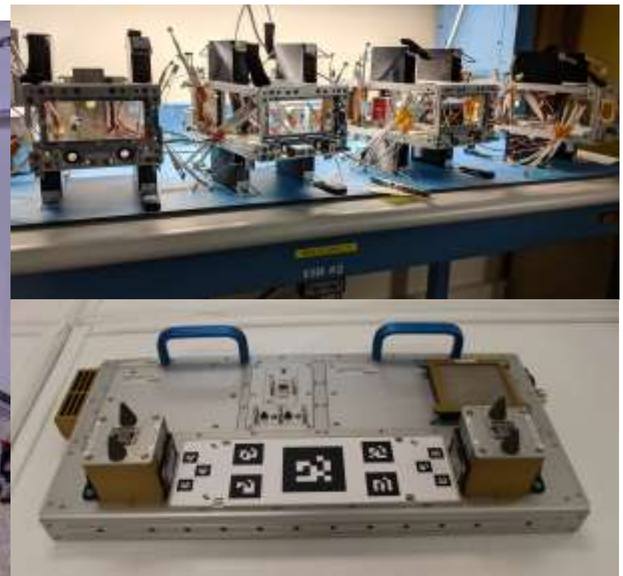

Figure 7. 4 Free Flyer flight core frames (top) and flight Docking Station at Cargo Mission Contract (bottom)

In Year 4, we completed the free flyer certification unit (Figure 6), including a rework of the propulsion modules to address an issue with the regulators supplying power to the nozzles. We began integration of the free flyer core modules, including the core stacks and harness assemblies (Figure 7 top).

We completed integration and testing of the docking station certification and flight units. Testing and inspection included: qualification and acceptance vibration, thermal, Joint Station LAN (i.e. networking), power quality, EMI, acoustic, and human factors. Flight Docking Station S/N 002 was delivered to the Cargo Mission Contract (CMC) at JSC on 9/18/2018 (Figure 7 bottom).

In Year 4, we made considerable progress on implementing the Astrobee ground data system. We acquired and installed the ground server at Ames and the DDS relay server at Marshall. We also completed test of the ground segment communications path from ARC through the Huntsville Operations Support Center (HOSC) at MSFC.

At PSRP #3, we discussed all open hazards. The panel approved most, pending final verification and agreed that we would try to close all remaining hazards out of board (i.e. no delta Phase 3). On 5/9/2018, we met with a PSRP splinter to discuss collision testing results.

We received verbal approval to close our collision hazard. This meant that, from a safety perspective, Astrobee would be allowed to operate autonomously on Station.

An Astrobee Robot Software update was released on 12/22/2017. The Crew Control Station passed Payload Software Integration and Verification Facility (PSIVF) testing for Incr 59.

We also successfully tested the first Astrobee Guest Science payload, REALM RFID Recon, on the cert free flyer. The REALM payload flew the robot on the granite table while searching for RFID tags.

2.5 Year 5 Accomplishments

Figure 8. Anne McClain unpacks Bumble Bee

Figure 9. David Saint-Jacques maps the JEM

Figure 10. Christina Koch observes localization and mobility test

Year 5 saw the completion of flight hardware integration, several launches, and operational firsts on orbit.

The Astrobee docking station (dock) launched on board Northrup Grumman 10 (NG-10) on 11/17/2018, and Canadian astronaut David Saint-Jacques installed and checked out the dock in the Japanese Experiment Module (JEM) on 2/15/2019.

We completed integration, testing, and delivery of the free flyer flight units. We completed building all flight free flyers on 1/4/2019, and the first two (Honey and Bumble) were shipped to JSC on 1/8/2019. The second two (Queen and spare) were shipped to JSC on 1/22/2019. Pre-launch testing (EMI, JSL, and acoustic) completed on 1/30/2019.

An issue was found with the perching arm gripper requiring a design modification that delayed completion of the flight build by 2 months. Four flight grippers were shipped to JSC on 3/28/2019 and underwent acoustic testing on 4/2/2019.

The first two Astrobee free flyers, Honey and Bumble, along with the docking station spares kit, launched on the Northrup Grumman 11 (NG-11) rocket from Wallops Flight Facility on 4/17/2019. The Cygnus spacecraft was captured and berthed at the ISS on 4/19/2019.

On 4/30/2019, Astronaut Anne McClain unpacked, powered on, and checked out the first Astrobee robot, Bumble Bee (Figure 8). All robot subsystems operated nominally.

On 5/13/2019, McClain manually "flew" Bumble throughout the Japanese Kibo laboratory module to collect NavCam imagery. We used this data to build a feature map for localization. McClain then collected calibration data for Bumble's NavCam, DockCam, and Inertial

Measurement Unit (IMU). Comparison of data collected on orbit to pre-flight shows that Bumble suffered no loss of calibration during launch.

On 5/23/2019, Saint-Jacques performed a second Astrobee mapping activity, collecting additional navigational camera (NavCam) imagery of the JEM (Figure 9).

On 6/14/2019, Bumble flew under its own power on the ISS for the first time. During the first Localization and Mobility session, the Astrobee team verified the robot's ability to hold position (station keeping against a variety of external forces), to perform specific motions (translations and rotations), to navigate using its computer vision system, and to autonomously undock.

The 3rd Astrobee free-flying robot, Queen Bee, launched aboard the SpaceX CRS-18 Falcon 9 on 7/25/2019. Also onboard were 3 perching arms (one for each of the flight robots) and 8 Li-Ion batteries. Astronaut Nick Hague captured the Dragon capsule using Canadarm2 on 7/27/2019.

On 8/28/2019, we completed our fourth Localization and Mobility on-orbit activity with Astronaut Christina Koch. We saw improvement in Astrobee localization using a new map of the JEM that kept more features than previous maps. During the activity, we completed several successful autonomous flights, including a simple camera survey of panel JPM1F3.

3.0 Technical Performance

3.1 Key Performance Parameters

The HET2 Key Performance Parameters (KPP) for Astrobee are listed in Table 2. This table shows the current state-of-the-art (represented by the SPHERES free-flyer currently on ISS), project threshold values (minimum success), and project goal (full success).

Maximum velocity is based on the speed required by research payload users and flight controllers. Flight time represents performance needs to conduct ISS Flight Operations Directorate (FOD) tasks, such as providing camera views of astronauts doing a maintenance task. The reported flight time is the estimated time available for an Astrobee to fly to its work area and support an activity, making reasonable assumptions about what components are active and drawing power. Note that the robot battery actually provides 30 minutes of “flyback reserve” time on top of the reported KPP value, to ensure that the robot can always return to the dock. Dock and resupply indicates whether (or not) crew time is required for replenishment of consumables (e.g., electrical power). Number of expansion ports represents the number of payloads that can be hosted. Consumables used per test session represents the quantity of supporting consumables that must be upmassed to support one operational session. ISS operational space represents the volume in which a ISS free flyer can operate.

Table 2. Key Performance Parameters

Performance Parameters	State of the Art	Threshold Value	Project Goal	Current Value
KPP 1: Max velocity (cm/s)	4	10	40	40
KPP 2: Flight time (hr)	0.5	2.0	5.0	3.1

Performance Parameters	State of the Art	Threshold Value	Project Goal	Current Value
KPP 3: Dock & resuppy	Crew tended	Crew tended	Autonomous	Autonomous
KPP 4: Hosted payloads	1	2	4	3
KPP 5: Consumables per ISS test	6	0	0	0
KPP 6: ISS operational space	2m x 2m x 2m	JEM, US Lab, and Node 2	All USOS	JEM
Notes: The "State of the Art" for ISS free-flying robots is SPHERES.				

3.2 Benefit to Agency and STMD strategic needs

Table 3 KPP Relevance

KPP#	Description	Trace to objective	Rationale
1	Max velocity	0g robotics research	Guest science that needs high performance
2	Flight time	Mobile camera tasks	Dwell to observe crew activity
3	Dock & resupply	All	Minimize impact on crew time, allowing more frequent operations
4	Hosted payloads	0g robotics research	Guest science that needs multiple payloads
5	Consumables per ISS test	All	Minimize impact on crew time, allowing more frequent operations
6	ISS operational space	0g robotics research, free flyer sensor tasks	Guest science or sensor measurements that need to be taken in specific locations on the ISS

Table 3 links the individual KPPs to Astrobee's top-level objectives. In turn, section 1.2 Relevance links Astrobee objectives to the NASA Strategic Plan and other guiding documents.

3.3 Technology gaps closed during execution

Arguably, the most significant technologies developed for Astrobee were:

- The vision-based navigation approach based on fusion of sparse prior maps, IMU integration, and visual odometry. This is critical for enabling infrastructure-free navigation throughout the ISS USOS.
- The propulsion module design with a fully enclosed impeller and six variable-flow-rate nozzles. This simple, robust design provides high energy efficiency to support extended Astrobee sorties.

A list of 26 publications (authored both by the Astrobee team and external collaborators using Astrobee) can be found at: https://www.nasa.gov/content/research-publications-0

3.4 Remaining gaps, performance and risk

Overall, for most Astrobee KPPs, the project achieved acceptable KPP values somewhere between the threshold value and project goal.

The only KPP to fall below the threshold value was the ISS operational space. This was not due to any fundamental technical problem; rather, schedule delays, caused in part by lack of ISS crew time availability, prevented timely completion of the mapping activities that would have enabled Astrobee mobility in modules other than the JEM.

Going forward, as Astrobee is now an operational system, future development work will likely be guided less by the KPPs as currently formulated, and will relate more to satisfying the needs of specific guest scientists and other users such as FOD. A key focus is continuing to mature the ops approach to improve reliability and reduce the burden on ISS crew, Astrobee facility staff, and other resources.

4.0 Programmatic Performance

4.1 Cost Performance

The IVA Free-Flyer project as proposed to the DPMC in March of 2014 offered 3 options with increasing scope and levels of funding. Option 1 had an end product of 1 engineering unit at the end of 3 years at an average of 8 FTE and $2.4M procurement per year. Option 2 had an end product of 4 flight units ready to launch at the end of 3 years at an average of 12 FTE and $3.7M procurement per year. Option 3 had an end product of 4 flight units checked out on-orbit at the end of 3 years at an average of 15 FTE and $5.1M procurement per year. The Astrobee element, as originally approved in 2014, was to deliver a slightly scaled down Option 2 deliverable (2 flight free fliers) with Option 2 FTEs and Option 1 procurement.

Over the course of the project, Change Requests (CRs) provided additional budget to make up for resources deficiencies and to extend the project to include on-orbit commissioning. See Table 7 for the full history of resource-related CRs.

Table 4 shows the planned project life cycle cost originally approved for Astrobee.

Table 5 shows the Astrobee actual costs.

Table 4. Planned Project Life Cycle Cost

Table 5. Actual Project Life Cycle Cost

4.2 Schedule Performance

Table 6 shows the Astrobee controlled/API miletstones, while Table 8 shows the full CR history of milestones for the project.

Table 6. Project Controlled Milestones

ID	Title	Description	Deliverable	Planned Date	Actual Date
FY15#1	Prototype 2 Testing Complete	Closed-loop operations and propulsion system	-	02/15/2015	02/15/2015
FY15#2	Prototype 3 Testing Complete	Basic commanding and VBN capabilities	-	07/28/2015	07/28/2015
FY16#1	Prototype 4 Testing Complete	Obstacle avoidance, ground systems, control station, thermal, and free-flyer fault handling	-	04/25/2016	04/27/2016
	First Hardware (Dock) On-Dock	Delivery to Cargo Mission Contract (CMC) for launch	Docking Station	09/20/2018	09/18/2018
	Second Hardware Delivery to ISS Program (2 Free Flyers)	Delivery to Cargo Mission Contract (CMC) for launch	2 Free Flyers	03/06/2019	03/06/2019
	Astrobee Autonomous Flight Demonstration	Autonomous execution of an Astrobee sortie plan	-	06/26/2019	08/28/2019
	Astrobee Completion/Transition Review	Review plans and status of transition to ISS facility	Report	04/15/2019	10/01/2019

Table 7 Astrobee CR History - Budget

Table 8 Astrobee CR History - Milestones

CR ID	Approval Date	Milestone	Due Date	Change	Note
GPCB-CR-00258	4/1/15	FY15 #2 Prototype 3 testing complete	6/30/15	Move to 8/6/15	Update based on PTR 1
GPCB-CR-00362	3/30/16			L1 requirements added to project plan	
GPCB-CR-00508	10/3/17	Test Readiness Review		New key milestone on 12/12/17	Delta PTR3: additional prototyping needed (P4E) to address avionics issues
	10/3/17	FY17 #1 Cert Unit testing complete	8/30/17	Move to FY18 #1 Cert/Flight Units testing complete on 3/15/18	
	10/3/17	FY17 #2 Flight Units testing complete	9/30/17	Move to FY18 #1 Cert/Flight Units testing complete on 3/15/18	
	10/3/17	FY18 #1 Astrobee first flight/basic mobility complete	4/30/18	Move to FY18 #2 on 5/31/18	
	10/3/17	FY18 #2 Astrobee operations demonstration		Rename to FY18 #3	
GPCB-CR-01015	3/5/18	FY18 #1 Cert/Flight Units testing complete	3/15/18	Controlled to Key w/ date 5/30/18	Program requested changes for clearer tracking. Due dates align w/ SpX-15
	3/5/18	FY18 #1 First Hardware (1 Free Flyer + Dock) On-Dock		New API milestone on 4/4/18	
	3/5/18	First Hardware Launch		New key milestone on 6/6/18	
	3/5/18	FY18 #2 Astrobee first flight/basic mobility complete	5/31/18	Controlled to Key w/ date 7/27/18	
	3/5/18	Astrobee Autonomous Flight Demonstration		Key to API (FY18 #2) on 8/15/18	
	3/5/18	FY18 #3 Astrobee operations demonstration	9/15/18	Controlled to Key	
GPCB-CR-01023	4/19/18	FY18 #1 First Hardware (1 Free Flyer + Dock) On-Dock	4/4/18	Move to 8/20/18	Procurement and integration delays caused slip of API milestones
	4/19/18	FY18 #2 Astrobee Autonomous Flight Demonstration	8/15/18	Move to 1/31/18	
	4/19/18	First Hardware Launch	6/6/18	Move to 11/8/18	
	4/19/18	Astrobee first flight/basic mobility complete	7/27/18	Move to 1/17/19	
	4/19/18	Astrobee operations demonstration	9/15/18	Move to 2/28/19	
	4/19/18	Commissioning Complete		New key milestone on 3/31/19	
	10/12/18	Cert/Flight Units testing complete	5/30/18	Rename to Dock Cert/Flight Units Testing Complete	

CR ID	Approval Date	Milestone	Due Date	Change	Note
GPCB-CR-01040	10/12/18	FY18 #1 First Hardware (1 Free Flyer + Dock) On-Dock	8/20/18	Rename to FY18 #1 First Hardware (Dock) OnDock on 9/20/18	Electrical anomaly in prop module requires 6 months to implement fix and complete flight build
	10/12/18	Astrobee first flight/basic mobility complete	1/17/19	Move to 5/22/19	
	10/12/18	FY18 #2 Astrobee Autonomous Flight Demonstration	1/31/19	Move to 6/26/19	
	10/12/18	Astrobee operations demonstration	2/28/19	Move to 7/10/19	
	10/12/18	Free Flyer Ground Verifications Complete		New key milestone on 2/7/19	
	10/12/18	Second Hardware Delivery to ISS Program (3 Free Flyers)		New key milestone on 3/6/19	
GPCB-CR-01105	6/10/19	Closeout Review	4/15/19	Move to 9/30/19	Gripper issue delays perching arm launch
GPCB-CR-01127	7/24/19	Second Hardware Delivery to ISS Program (3 Free Flyers)	3/6/19	Key to API (FY19 #1) for 2 Free Flyers on 4/17/19	Program requested elevation of milestone from key to API
GPCB-CR-01132	8/16/19	FY18 #2 Astrobee Autonomous Flight Demonstration	6/26/19	Move to 8/31/19	Slip due to localization, imagery distribution, and crew availability issues

5.0 Infusion & Dissemination

The Astrobee system will be transitioned from a technology development project under GCD to an ISS research facility operated by the Astrobee Facility (formerly SPHERES Facility) team at ARC under the ISS Research Integration Office (OZ).

The Astrobee development and facility teams collaborated on many activities such as requirements development, facilities upgrades, integration, testing, certification and flight unit builds, and on-orbit operations.

To commission Astrobee on ISS, the project performed several development and testing activities in 0g to provide the facility program with a robotic system that is ready for research facility operations. To ensure the system is ready for handover, the project focussed on the verification and validation of Level 1 functional requirements on the ISS, and the supporting activities required to perform those verifications.

5.1 Deliverables

The following are the planned deliverables and items delivered by the Astrobee development project to the Astrobee facility.

Table 9. Hardware Deliverables

Qty	Part Name	Part Number	Location	Delivered
3	Astrobee Free Flyer Flight Unit	A9SP-1500-M130-1	ISS	3 on Station, 1 at JSC bonded stores
3	Astrobee Free Flyer Ground Unit	A9SP-1500-M130-1	ARC	2 at ARC
3	Flight Perching Arms	A9SP-1500-M520	ISS	3 on Station
3	Ground Perching Arms	A9SP-1500-M520	ARC	1 at ARC
1	Flight Docking Station	A9SP-1500-M170-2	ISS	1 on Station, 1 at JSC bonded stores
1	Ground Docking Station	A9SP-1500-M170-2	ARC	1 at ARC
12	Batteries	IE-0001/ND2054	ISS	24 on Station, more at JSC bonded stores
1	GDS Ground Data Storage server		ARC	1 operational at ARC
1	GDS DDS repeater		MSFC	1 operational at MSFC, 1 hot swap shipped to MSFC

Table 10. Software Deliverables

Package	Location	Delivered
Astrobee Flight Software	Astrobee Free Flyer and Docking Station	Deployed on Station, Open Source release
Crew Control Station	ISS EXPRESS Laptop Computer	Deployed on Station, Open Source release
Ground Control Station	ARC MMOC Workstation	Deployed in MMOC
Simulator	Various	Open Source release
Engineering Tools	ARC MMOC Workstation	Deployed in MMOC

5.2 Success Criteria

The following are the minimum and full success criteria agreed upon by the SPHERES/Astrobee Facility for activities to demonstrate that the system is advanced and mature enough for transfer. Descriptions of demonstrating activities are in the Commissioning Activities section.

Table 11. Minimum Success Criteria

Criteria	Demonstrating Activity	Status
ISS demonstration of:		
Ground control	Localization & Mobility	Complete
JEM map	Localization & Mobility	Complete
Software upgrade	Calibration & Mapping	Complete
Hazard detection	Localization & Mobility	Awaiting crew time (next LoMo)
Dock/undock	Calibration & Mapping	Complete
Streamed video	Dedicated activity	Awaiting crew time
Payload & Guest Science operations	Operations & Payload Demos	Awaiting crew time
Ground Activities:		
Guest Science data distribution	Ground test of hivemind	Complete
Handover of all deliverables		Complete

Table 12. Full Success Criteria

Criteria	Demonstrating Activity	Status
ISS demonstration of:		
Crew control	Crew Interface	Completed ORTs, crew procedure awaiting ECR
USOS map (prioritize N2 & USL)	TBD	
Signal lights	TBD	
Perch/unperch	Payload Demo	Completed ORTs, crew procedure awaiting ECR
Multi-robot operations	Crew Interface	Completed ORTs, crew procedure awaiting ECR
Mobile camera operations	Localization & Mobility	Complete

5.3 Commissioning Activities

The ISS activities can be categorized as installation and activation, basic checkout, mapping, performance tests, and ground support activities. Each ISS activity requires preparatory activities such as developing and conducting training for crew and ground, developing crew and ground procedures, and conducting operational readiness tests.

5.3.1 Preparatory Activities

5.3.1.1 Crew Training

Crew training requirements are decided with the Training Strategy Team (TST) per the usual ISS payload process. Astrobee familiarization training consists of a 20-minute Onboard Training (OBT) video for all crew members and covers descriptions of the Astrobee hardware and basic interactions. Operator-level training is another 20-minute OBT video for crew members that will use the Astrobee Crew Control Station. Short videos demonstrating specific techniques (e.g. dock installation template application, free flyer calibration maneuvers, etc.) have been embedded in the corresponding crew procedures for specific commissioning activities.

5.3.1.2 Ground Training

All team members, both Astrobee development and facility, that have operations roles were trained for those roles. We applied an iterative method of developing ground procedures for each activity followed by operational simulations in Operational Readiness Tests (ORT) (Section 5.3.2). Lessons learned from the ORT were used to modify ground procedures and we repeated the cycle as often as possible. Less experienced team members shadowed more experienced members throughout the process, eventually taking the lead role while the experienced person observed.

All team members, both Astrobee development and facility, that have engineering roles were trained in a similar manner. In addition to ORTs, we used Engineering Readiness Tests (ERT) to simulate the operational use of many of the subsystems.

5.3.1.3 Crew procedures

Nearly all the ISS activities that involve crew require crew procedures. This task involves determining what the crew will do during each crew-tended ISS activity, developing the crew procedure, and conducting procedure verification (PV) activities in one of the test facilities. The procedure is then reviewed and approved by the ISS crew office and payload ops lead, per the usual ISS payload process. The Astrobee ops team verified procedures through multiple ORTs with different subjects performing the role of crew member.

5.3.1.4 Ground procedures

Ground procedures have been developed for all ground support activities that involve commanding or uploading files. Ground procedures were also verified through ERTs and ORTs.

5.3.2 Operational Readiness Tests

Operational Readiness Tests (ORTs) ensure that the team, facilities, products, and logistics are all well prepared for an activity. The Astrobee development and facility teams conducted multiple ORTs for each ISS activity.

Fidelity of ORTs varied from procedure read-throughs to full hardware-in-the-loop simulations run from the ARC Multi-Mission Operations Center (MMOC), through the Huntsville Operations Support Center (HOSC), controlling the Cert Unit flying on the granite table with a subject performing the role of crew member.

ORTs cover nominal and off-nominal scenarios with contingencies inserted that impact crew and/or ground steps.

5.3.3 ISS Activities

Astrobee commissioning was broken down into 10 on-orbit activities. Some activities are repeated for each robot, and some are repeated multiple times on a single robot (e.g. LoMo).

Table 13 On-Orbit Commissioning Activities

ID	Activity	Contents
1	Checkout	- Crew inspects the robot - Functional tests of all hardware
2	Calibration & Mapping	- Crew inspects the robot - Functional tests of all hardware
3	Localization & Mobility (LoMo)	- Verify robot localization within JEM - Robot performs increasingly complex motions to test mobility system
4	Checkout & Calibration	- Combination of 1 & 2 without mapping
5	Ops Demo	- Demonstrate an operational mission scenario
6	Payload Installation	- Crew installs payload (perching arm) - Functional tests of payload
7	Payload Demo	- Operational demonstration of payload (perching arm)
8	Crew Interface	- Crew controls an Astrobee using the Crew Control Station on an EXPRESS laptop
9	Performance Characterization	- TBD tests to further characterize Astrobee performance
10	SPHERES/Astrobee Hand-off	- Symbolic passing of the torch from SPHERES to Astrobee

5.4 Completed Commissioning

Nearing the end of the Astrobee project, our goal was to complete sufficient commissioning to support initial testing of the first Guest Science payloads. A list of completed activities may be found in Table 14.

Three factors have impacted the commissioning schedule:

1) Localization Performance: We initially reserved some repeat activities in the schedule to allow for on-orbit mapping and localization tuning. However, we found that it required more time than expected.
2) Imagery: Despite having met with ISS Imagery Working Group repeatedly from early in project life, some portions of the working group seemed to have an incompete understanding of our operational concept. A new requirement to route imagery/video through the Photographic Technology Laboratory (JSC Building 8) was levied late, after start of on-orbit ops. In the interim, crew is required to observe all robot ops.
3) Crew Time: Crew availability has been extremely limited during the last two months of the fiscal year (and through the rest of the calendar year). The commissioning schedule has had to be continually adjusted and the pace of robot operations has slowed from approximately every 2 weeks to every 1-2 months.

Nevertheless, the project has achieved minimum success on 5 out of 6 KPPs and full success on 3 of 6. We anticipate meeting the remaining success criteria through a period of extended commissioning agreed upon with the Astrobee Facility (Section 5.5).

Table 14 Completed Commissioning Activities

Crew Activity	Robot	Date
Checkout	Bumble	4/30/2019
Calibration & Mapping	Bumble	5/13/2019
Additional Mapping	Bumble	5/23/2019
Localization & Mobility 1	Bumble	6/14/2019
Localization & Mobility 2	Bumble	7/12/2019
Localization & Mobility 3a	Bumble	7/24/2019
Localization & Mobility 3b	Bumble	8/28/2019
Checkout & Calibration	Honey	10/30/2019
Localization & Mobility 4a	Bumble	11/01/2019

5.5 Extended Commissioning

The Astrobee project, Astrobee facility, ISAAC project, and AES R2 Autonomous Logistics (R2AL) project have worked out a plan for completion of commissioning that does not require extension of the Astrobee development project.

Extended commissioning addresses the needs of the ISAAC and R2AL projects that utilize the Astrobee development team (primarily Flight SW). Those two projects will provide resources toward remaining activities. Additionally, the Astrobee Facility is requesting an over-guideline to complete commissioning tasks.

5.5.1 Phase 1

Phase 1 of Astrobee extended commissioning involves completion of the minimum set of activities that would enable support of initial Guest Scientists. Phase 1 activities are shown in Table 15. The first Guest Science payloads include (Payload Name, Developer):

- RFID Recon, JSC
- SoundSee, Astrobotic / Bosch
- Gecko Gripper, Stanford
- Kibo-RPC, JAXA

Table 15 Phase 1 Extended Commissioning Activities

Crew Activity	Robot	Desired Date
Localization & Mobility 1	Honey	Dec 2019
Payload Installation (includes HW checkout)	TBD	Dec 2019
Localization & Mobility 4b (optional)	Honey or Bumble	Jan 2020
SPHERES/Astrobee Hand-off	TBD	Jan 2020
Payload Demo	TBD	Jan 2020

Depending on the success of the Honey LoMo activity, a second LoMo during Phase 1 may not be necessary.

The Payload Installation and Demo activities, while originally planned to involve the perching arm, could also be initially performed with the RFID Recon payload. However, to support Stanford’s Gecko Gripper, the perching arm will have to be installed and checked out.

5.5.2 Phase 2

Completion of Extended Commissioning Phase 2 enables support of all known users with goals of improving robustness and reliability, and characterizing the Astrobee system. The Astrobee Facility is targeting the end of June 2020.

Objectives for this phase include: extending the survey capability, performing robotic mapping runs (rather than having crew manually moving the robot), operating autonomously for 4 hours (including perching, recharge, etc.), mapping of additional modules, performing module-to-module translation, improving the ISS model, and verifying SpeedCam functionality on-orbit.

5.5.3 Long-term Efforts

Long-term efforts are those that were in the original commissioning plan, but for which there is currently very little or no demand by existing Guest Scientists. These include the following crew activities: Crew Interface Demo, Queen Bee Checkout & Calibration, Queen Bee Localization & Mobility, and hardware checkout of the remaining perching arms. All but the Crew Interface Demo, will have been performed on-orbit at least once, so all necessary ops products are available and it is anticipated that they can be perfomed at relatively short notice when crew time becomes more readily available.

Additional nice-to-have capabilities that may be addressed over the long-term include: a high accuracy ISS model, more Human-Robot Interaction (framework is in place), more reliable perching, and Astrobee-Astrobee comm (concepts are in place).

5.5.4 Building 8 Integration

Due to concerns about crew privacy and proprietary payloads that may be viewed inadvertently through Astrobee's cameras, the ISS Imagery Working Group has required that Astrobee video be streamed through Building 8 before allowing the robots to operate on ISS without crew supervision.

The Astrobee facility has worked with Building 8 to develop an integration plan with the milestones described in Table 16. Meanwhile, an update to the Astrobee PIA addressing Imagery is currently in review.

Table 16 Building 8 Integration Milestones

ID	Description	Target Date
1	Astrobee Control Station running in Bldg 8	8/29/2019 (Completed)
2	Astrobee Sci-Camera streaming to Bldg 8 decoder via Gate-to-Gate VPN	2/29/2020
3	PD/PI distribution method tested and available	3/31/2020

6.0 Technology Readiness Level (TRL) Assessment

Table 17. Technology Readiness Assessment

Technical Capability Elements	TRL		Comments
	Entry	Exit	
Vision-based navigation for IVA operations	3	8	Map data collection will be needed for additional modules beyond Kibo, and throughout operations to account for configuration changes between operations.
Fan-based propulsion for microgravity	3	8	
ISS 3-D path planning	3	8	
Zero-g robotic perching	3	6	On-orbit testing planned 2nd quarter FY20
ISS free-flying robotic system	3	8	Basic flying system demonstrated on-orbit, some features (e.g. perching) to be demonstrated 2nd quarter FY20

7.0 Lessons Learned

7.1 Value of early prototyping

Astrobee invested in building multiple generations of integrated prototypes even before the formal system requirements review with stakeholders. The experience gained during that early testing was vital for fleshing out the architectural assumptions and subsystem interfaces that allowed us to develop relevant and verifiable requirements.

7.2 Keep an open mind as objectives change

The SmartSPHERES project had, as one of its more ambitious secondary goals, demonstrating simultaneous localization and mapping (SLAM) to build a map of portions of the ISS interior while controlling the flight of a SPHERES satellite. That effort had promising initial results, but was not fully realized. When the SmartSPHERES veterans on our team started to design the vision-based navigation for Astrobee, it was natural to see the SmartSPHERES SLAM code base as the obvious core technology to build on. However, we kept an open mind and realized that, because Astrobee operates in the bounded and mostly static ISS environment, it is acceptable to collect on-orbit imagery data with astronaut support, build a map on the ground (where it can be manually registered to the ISS CAD model used in the Control Station), then uplink the map for on-orbit use. This approach resulted in simpler and more robust flight software.

7.3 Total lifecycle impact of complexity

Systems implemented purely for research can tolerate a much greater degree of complexity than systems that must support end users over an extended lifespan. This is particularly true for human spaceflight systems that have challenging additional requirements related to the launch vibration environment and astronaut safety. Every additional part triggers another safety analysis and is another potential point of failure for the deployed system. In retrospect, given the hurdles we encountered already during development and verification, some of the “nice-to-have” components of the Astrobee design (e.g. flashlights, laser pointer, microphone) perhaps should not have made the cut for inclusion in the baseline Astrobee hardware, especially given we have the ability to add them as part of future payloads.

7.4 Modularity grows in importance as projects scale

With multiple subsystem teams working in parallel, it was important to use a modular design with clear interface definitions so that component-level verifications would assure the system would work when integrated. Some Astrobee design choices that improve modularity include: (1) Propulsion airflow is decoupled from the core avionics. (2) Computing is distributed across three processors to isolate robust real-time code from experimental code. (3) Astrobee’s flight software embodies a modular architecture with clean separation between ROS nodes. However, in some cases our best efforts at modularity failed due to interfaces we overlooked. For example: (1) Electromagnetic interference (EMI) injected onto the main power bus by the propulsion modules caused communications failures, discovered late in the integrated testing process, triggering a redesign that added months of delay to the project schedule. One cause was that “power quality” EMI requirements at the module interface had never been defined or verified. (2) Although the acoustic noise generated by individual nozzles subjectively seemed insignificant, it was unexpectedly amplified when the nozzles were mounted on the plenum, whose base is a thin aluminum sheet that apparently acts as a sounding board; the nozzle mounting had to be modified to include acoustic isolation.

7.5 Schedule overlap trade-offs

The Astrobee project had initially planned to build a fully flight-like certification unit that would go through formal verifications prior to starting integration and test (I&T) of the flight units. During the final phases of development, we made a difficult decision to add one more generation of integrated prototype testing prior to starting the certification unit, which unavoidably slipped the certification unit I&T schedule to overlap substantially with flight unit I&T. The result was that when lessons learned during certification forced design changes, in some cases we had to rework the flight units—a problem that bit us multiple times. Nevertheless, with hindsight, we believe we took the correct approach to ensure the design was sufficiently mature before starting the certification unit.

7.6 Trade-offs in testing rigor

There is often a tension between rigorous testing to fully validate robustness vs. the desire to avoid costly delays due to damaging one-of-a-kind prototype hardware. An example is Astrobee’s heat sink assembly for the MLP and HLP, which had a design flaw that caused it to damage the processors during launch vibration testing of the certification unit, forcing a difficult late redesign. We missed an early opportunity to discover the flaw when we conducted an informal risk reduction vibration test on the avionics stack, but (with the best of intentions) chose to run the test at a reduced amplitude relative to the final verification test, and so avoided triggering the problem. With better discussion and clarity about test objectives, we would have tested at full amplitude and caught the problem early.

7.7 The limits of designing for repair

Whenever field-expedient repair is possible, there is a question of how to design to enable that repair. Astrobee started with an ambitious approach of requiring many components to be on-orbit replaceable units (ORUs). That complicated design, requiring use of captive fasteners, constraining geometry to enable astronaut access, and increasing size and weight. In retrospect, it would have been better to focus on replaceability of only a few larger sub-assemblies, achieving most of the benefit at lower cost.

7.8 3D printing considerations

Through many failures involving 3D printed plastic parts, our team collected 3D printing rules of thumb that other projects may find useful, including: (1) Prefer assembly using brass threaded heat-set inserts that avoid galling. (2) Incorporate increased tolerances for 3D printing variability, and complement with post-print machining when tighter tolerances are needed (e.g. drill out holes for inserts). (3) If appearance is important, bead blasting and painting work well, but manual finishing steps greatly impact cost and schedule, and transitioning to painted parts may cause new problems with fit. (4) Use caution when transitioning from in-house prototyping to an outside vendor, as differences in printing processes can cause new problems.

7.9 COTS part obsolescence

The development cycle for spaceflight projects tends to be much longer than that for consumer electronics devices; projects should plan accordingly. Astrobee benefited greatly from availability of COTS integrated parts like the IMU and cellphone-derived system-on-module MLP and HLP processors, but obsolescence caused problems, including: (1) A few parts (e.g., the original SciCam) reached end-of-life and became unavailable before we stocked sufficient inventory to last for the life of the project, forcing us to redesign with an alternative part. (2) In a cascading effect, the new SciCam part required a new HLP part for compatibility, which in turn triggered significant effort porting parts of the flight software to the new HLP. (3) Long-anticipated Linux drivers enabling GPU-accelerated computer vision on the MLP never materialized because the vendor lost interest after they released their next-generation processor board.