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Game Changing Development Program

Human Exploration Telerobotics 2 (HET2) Project Plan

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Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 2 of 46

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Human Exploration Telerobotics 2 - Signature Page

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Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 3 of 46

Document History Log

Status	Document Revision	Effective Date	Description of Change
Baseline	Initial	11/17/2014	To develop an initial baseline of the HET2 Project Plan
Revision	A	01/27/2016	Added Robonaut 2 plan for FY16-Q1. Clarified that Robonaut 2 element is only active during FY15 and FY16-Q1. Changed "Free-Flyer" to Astrobees. Updated Astrobees budget, tasks, success criteria/TRL, schedule, and KPP's. Added Astrobees L1 requirements. Added Task Agreement for SUPERball Bot. Revised reference to NASA Technology Roadmap (TA 4).
Revision	B	tbd	Extended Astrobees to FY18. Revised Astrobees FY17 task milestone dates. Added Astrobees ISS commissioning task including two controlled milestones in FY18. Updated GCD chief engineer. Clarified Astrobees transition to the AES/SPHERES program.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 4 of 46

Table of Contents

1.1 Introduction.....	6
1.2 Technical Objectives.....	7
1.2.1 Astrobees.....	7
1.2.2 Robonaut 2.....	7
1.2.3 Success Criteria.....	8
1.3 Impact.....	8
1.4 Relevance.....	9
2.1 Concept of Operations.....	11
2.2 ISS Testing.....	12
2.3 Astrobees Element.....	13
2.3.1 Level 1 Requirements.....	13
2.3.2 Astrobees Technology Development Task.....	14
2.3.3 Astrobees Validation and Test Task.....	18
2.3.4 Astrobees ISS Commissioning Task.....	19
ASTROBEE AUTONOMOUS FLIGHT DEMONSTRATION.....	21
2.4 Robonaut 2 Element.....	22
2.4.1 R2 Climbing Task.....	22
2.4.2 R2 IVA Task Development.....	23
2.4.3 R2 Efficient Programming.....	24
5.1 Organizational Structure.....	30
5.2 Reporting.....	32
5.2.1 Project Reporting.....	32
5.2.2 Programmatic Reporting.....	33
5.3 Reviews.....	33
5.4 Risk Management.....	34
5.5 Configuration Management.....	34
6.1 Funding Requirements.....	35
6.1.1 Astrobees External Resources.....	35
6.1.2 Robonaut 2 External Resources.....	36
6.2 Institutional Requirements.....	36
6.2.1 Astrobees.....	36
6.2.2 Robonaut 2.....	37
7.1 Astrobees.....	38
7.2 Robonaut 2.....	39

List of Tables

Table 1. HET2 Success Criteria.....	8
Table 2. HET2 relevance to the 2015 Robotics and Autonomous Systems (TA 4) technology roadmap.....	10

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 5 of 46

Table 3. Astrobee Level 1 Requirements.....	13
Table 4. Astrobee Technology Development Task Milestones.....	17
Table 5. Astrobee Validation and Test Milestones.....	19
Table 6 Astrobee ISS Commissioning Milestones.....	21
Table 7. R2 Climbing Task Milestones.....	23
Table 8. R2 IVA Task Development Milestones.....	24
Table 9. R2 Efficient Programming Milestones.....	25
Table 10. Key Performance Parameters (Astrobee).....	26
Table 11. Key Performance Parameters (Robonaut 2).....	27
Table 12. TRL Advancement (Astrobee).....	28
Table 13. TRL Advancement (Robonaut 2).....	29
Table 14. Roles and Responsibilities.....	31
Table 15. Project Resource Allocations.....	35
Table 16. WBS Dictionary.....	40

List of Figures

Figure 1. Organizational Structure.....	30
Figure 2. Key HET2 events.....	38
Figure 3. WBS Structure.....	39

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 6 of 46

1.0 Objectives

1.1 Introduction

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 will develop a new free-flying robot, Astrobee, and mature Robonaut 2, to: (1) off-load routine and repetitive work from astronauts, and (2) extend and enhance crew capabilities. HET2 will test these robots in laboratories on the ground and on the International Space Station (ISS). HET2 is a research and technology project within the Game Changing Development Program (GCD) in NASA's Space Technology Mission Directorate (STMD).

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).

However, 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.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 7 of 46

1.2 Technical Objectives

HET2 is composed of two elements: Astrobees and Robonaut 2.

1.2.1 *Astrobees*

The Astrobees Element (FY15 to FY18) will focus on developing a new free-flying robot suitable for performing IVA work on the ISS. The new robot will build upon technology and lessons learned from the Smart Synchronized Position Hold, Engage, Reorient, Experimental Satellite (SPHERES) robot, which was developed and tested by the Human Exploration Telerobotics (HET) project under the Technology Demonstration Missions (TDM) program. Astrobees will be designed to address a variety of scenarios, which will be 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). Candidate scenarios include mobile sensor (including imagers), automated logistics (e.g., mobile inventory), and free-flying robotic testbed.

Success for Astrobees 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/or navigation. Successful on-orbit testing and demonstration of these technologies following the ISS payload process will bring the system to TRL 8. Table 1 specifies which capabilities must be demonstrated for minimum and full success.

1.2.2 *Robonaut 2*

The Robonaut 2 Element (FY15 to FY16-Q1) will focus on advancing the capabilities of the Robonaut series of humanoid robots to perform both IVA and EVA on the ISS. The continued advancement of Robonaut 2, which was developed and tested by HET and other NASA projects, will build upon technology and lessons learned to date from Robonaut 2.

Minimum success for the Robonaut 2 Element involves developing and testing relevant robotic technologies, including legged mobility with climbing limbs, autonomous task software, and/or computer vision to TRL 5.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 8 of 46

1.2.3 Success Criteria

Table 1 summarizes the minimum and full success criteria for HET2.

Table 1. HET2 Success Criteria

Element	Minimum Success	Full Success
Astrobee	ISS demonstration of: <ul style="list-style-type: none"> • Ground control • JEM/Node 2/US Lab map • Software upgrade • Hazard detection • Dock/undock • Streamed video • Payload & Guest Science (GS) operations • GS data distribution 	ISS demonstration of: <ul style="list-style-type: none"> • Crew control • USOS map • Signal lights • Perch/unperch • Multi-robot ops • Mobile camera ops
Robonaut 2	Develop at least one of the following humanoid robot technologies to TRL 5: legged mobility, autonomous task software, and/or computer vision.	Transition to Human Robotic Systems (HRS) project after minimal success criteria have been met.

1.3 Impact

HET2 will benefit NASA by: (1) reducing the risks and cost in human spaceflight; (2) increasing human exploration and operation mission performance, and (3) providing remotely operated robots to improve astronaut efficiency (off-load routine and repetitive tasks) and capabilities (extend human reach and sphere of influence).

As humans prepare to venture deeper into space, consideration is being given to developing a cis-lunar "waypoint facility", perhaps at the Earth-Moon "L2 Lagrange Point", which would serve as a gateway to multiple destinations including the Moon, Near-Earth Asteroids (NEA), and Mars. This facility would enable assembly and servicing of satellites, telescopes, and deep-space exploration vehicles. This facility could also be used as a platform for astrophysics, heliophysics, and distant Earth observation. This facility would also serve as a pre-cursor for a similar facility near Mars, perhaps in orbit or deployed on the surface of Phobos.

In contrast to the ISS, which is continuously manned, a waypoint facility will be intermittently occupied. Consequently, there is a significant need to robotically care-take the facility, in order to maintain and repair systems in the absence of human crew. These robots will perform both IVA and EVA work, remotely operated and supervised

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 9 of 46

from Earth. Telerobotic caretaking would focus on inspection, monitoring, routine maintenance, and contingency handling of the facility (and possibly attached structures, vehicles, etc.). In particular, experience with the ISS has shown that power (generation, switching, storage), life support (air, water, thermal), data networking, and instruments all need to be maintained. To do this, remotely operated robots, such as Astrobee and Robonaut 2, will need to be developed, tested, and placed into operational use on the ISS to understand the associated costs, benefits, limitations, and risks.

1.4 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.

One of the ways that HET2 will test technologies is 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 Strategic Goal 1.1: "Sustain the operation and full use of the ISS and expand efforts to utilize the ISS as a National Laboratory for scientific, technological, diplomatic, and educational purposes and for supporting future objectives in human space exploration."

HET2 is broadly relevant to the 2015 "Robotics and Autonomous Systems" (TA 4) NASA Technology Roadmap. Table 2 describes how HET2 work will advance technology in all seven major TA 4 roadmap areas.

Finally, HET2 addresses the NASA Strategic Plan 2014 (NPD 1001.0B) as follows:

Strategic Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space

- 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

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 10 of 46

Table 2. HET2 relevance to the 2015 Robotics and Autonomous Systems (TA 4) technology roadmap

Technical Area	HET2 Relevance
TA4.1 Sensing and Perception	Both Astrobees and Robonaut 2 will advance technology in 3D sensing (TA4.1.1), state estimation (TA4.1.2), onboard mapping (TA4.1.3), object, event, and activity recognition (TA4.1.4), and force and tactile sensing (TA4.1.5).
TA4.2 Mobility	Both Astrobees and Robonaut 2 will advance technology in small-body and microgravity mobility (TA4.2.4), robot navigation (TA4.2.6), and mobility components (TA4.2.8).
TA4.3 Manipulation	Robonaut 2 will advance technology in manipulator components (TA4.3.1), dexterous manipulation (TA4.3.2), and mobile manipulation (TA4.3.4).
TA4.4 Human-System Interaction	Both Astrobees and Robonaut 2 will advance technology in multi-modal human-systems interaction (TA4.4.1), proximate interaction (TA4.4.3), distributed collaboration and coordination (TA4.4.5), and remote interaction (TA4.4.8).
TA4.5 System-Level Autonomy	Both Astrobees and Robonaut 2 will advance technology in activity planning, sequencing, and execution (TA4.5.2).
TA4.6 Autonomous Rendezvous & Docking	Both Astrobees and Robonaut 2 will advance technology in relative navigation sensors (TA4.6.1), guidance, navigation and control algorithms (TA4.6.2), and docking & capture mechanisms (TA4.6.3).
TA4.7 Systems Engineering	Both Astrobees and Robonaut 2 will advance technology in modularity, commonality, and interfaces (TA4.7.1), robot modeling and simulation (TA4.7.3), and robot software (TA4.7.4).

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 11 of 46

Objective 1.1: Expand human presence into the solar system and to the surface of Mars to advance exploration, science, innovation, benefits to humanity, and international collaboration.

- 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 1.7: Transform NASA missions and advance the Nation's capabilities by maturing crosscutting and innovative space technologies.

- 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.

2.0 Technical Approach

The following sections describe the technical approach that will be used for Astrobee and Robonaut 2. In keeping with NPR 7120.8, each HET2 Element will research and develop telerobotics technology in accordance with established research practices and NASA's standards to ensure the quality and acceptability in the community of the research results. In addition, both Elements will perform a variety of ground and on-orbit tests (using the ISS) to characterize, validate, and verify the performance of hardware and software (components, subsystems and integrated system).

2.1 Concept of Operations

HET2 will develop robot user interfaces, control modes, and human-robot teaming strategies to support the following concepts of operations ("conops") for telerobotics:

- Crew control. The crew performs planning, operations, contingency handling and analysis. Ground control supports crew on an intermittent and/or time-delayed basis. This conops is appropriate when conditions (orbital geometry, time-delay, etc.) make it impractical for ground control to remotely operate robots in a

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 12 of 46

productive manner. This conops is also appropriate when a robot is used to extend, or enhance, crew capabilities (sensing, force, etc).

- Crew/ground shared. Earth-based ground control performs planning and analysis. The crew performs tactical operations. This conops enables many robot command cycles to be performed, even when the robot is far from Earth.
- Ground control. Earth-based ground control performs planning, operations, and analysis. The crew performs interventions when needed. This conops is well suited for handling contingencies that are beyond robot autonomy capabilities.

2.2 ISS Testing

HET2 will make use of the ISS for testing. Although using the ISS can be complex (particularly in terms of certification and scheduling), the ISS is the only facility available for performing high fidelity, integrated simulations of future deep-space human missions. In particular, ISS testing is the only way to confirm that all significant environmental conditions, operational constraints, and other factors are replicated.

Ground-based simulators (laboratory tests, numerical simulations, etc.) lack fidelity in many areas, including:

- Effect of micro-gravity on crew (this affects sensorimotor performance, etc.)
- Effect of long-duration stay in space on crew (affects cognition, proficiency, etc.)
- Crew activities, workload, and other sources of in-flight stress
- Flight vehicle constraints (including micro-gravity workspace, crew displays, etc.)

The HET2 systems and activities on ISS are classified as ISS payloads (experiments), and as such, must follow the ISS payload process. This process may require up to 18-month lead-time to allow completion and compliance with:

- Payload agreements that provide requirements for ISS and supporting facilities
- Safety certification for launch (for hardware up-mass) and ISS operations
- Verification of interface requirements to the launch vehicle and to the ISS
- Development/delivery of engineering documents
- Development of crew procedures and training
- Scheduling of crew activity and resources

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 13 of 46

2.3 Astrobeer Element

HET2 is developing Astrobeer, a free-flying robot designed to operate inside the International Space Station (ISS). Astrobeer will address multiple scenarios: (1) micro-gravity robotics research facility on ISS, (2) remotely operated mobile sensor platform to perform IVA surveys (e.g., sound levels) and to provide mobile camera views, and (3) autonomous mobile inventory using a RFID scanner. This work will be performed during FY15 to FY18.

At the highest level, the system includes the free-flying robot itself, a dock for replenishing power, and the ground data systems for communication, control and data transfer.

Astrobeer will be self-contained and autonomous. Ideally it will be capable of fully autonomous localization and navigation inside the United States Operating Segment (USOS) of the International Space Station. Astrobeer will have video cameras on board that will allow it to serve as a remotely operated mobile camera platform, and may be used for localization and navigation.

Astrobeer will also have an expansion port(s) where additional sensors and/or hardware can be attached for demonstration, testing and use aboard the station. Additional sensors that may be attached to or integrated with the free-flyer include a RFID reader and the necessary software to communicate with the inventory management system and a HD camera.

Astrobeer will communicate principally via the station LAN. The propulsion will use electric-motor-driven fans. Localization will include vision-based navigation with and without fiducials and a IMU. Astrobeer will also include a perching arm to grab ISS handrails; this will allow Astrobeer to hold position without using its propulsion system.

2.3.1 Level 1 Requirements

Astrobeer will address the Level 1 requirements listed in Table 3.

Table 3. Astrobeer Level 1 Requirements

ID	Description
FFREQ-75	The Astrobeer system shall provide remote control of the Astrobeer free-flyer.
FFREQ-80	The Astrobeer system shall perform autonomous docking for consumable resupply.
FFREQ-83	The Astrobeer system shall host payloads.
FFREQ-89	The Astrobeer system shall stream HD video of crew activities.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 14 of 46

2.3.2 *Astrobee Technology Development Task*

Objectives

This task is focused on incremental design and development of Astrobee that meets project, stakeholder, ISS and Safety requirements. Stakeholders include the ISS SPHERES Facility, the SPHERES Working Group, HEOMD AES program, ISS program, and others. The project and stakeholders have provided general and use-case specific functional requirements.

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

As an ISS payload, 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.

The deliverables for Astrobee system include the Astrobee element, which consists of structure, propulsion, C&DH, communications, thermal, electrical power, GNC, dock mechanism, and perching arm subsystems. Astrobee system also includes the dock, payloads, and Ground Data Systems (user interfaces for crew control and ground control).

Approach

Astrobee will be developed incrementally over a series of prototypes. Early prototypes will address trade studies and areas of risk. Later prototypes will implement system requirements and incrementally mature the system design.

Prototype 1 was completed before this Project Plan was baselined. This prototype was developed for risk reduction purposes and included:

- Structure: Rough structural design for test frame, standoffs, motor mounts, propeller mounts, processor mounts, battery mounts, air bearing interface.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 15 of 46

- Flight Software (FSW): Low level Processor (LLP) operating system (OS), basic I/O for turning on/off motors, speed control, pitch control, basic software to run open-loop tests with thruster and motion control.
- Propulsion: Variable pitch propellers (not representative of final system).
- EPS: Interim battery selection, wiring/connectors for motors, motor controllers and processor, housekeeping voltage regulators design and fabrication to provide voltage levels needed by processor, motors and motor controllers.

Prototype 2 focused on closed loop navigation and interim avionics development. The subsystem development focused on:

- Structure: Improved structural design for frame, mounting for motors, propellers, both processors, battery, IMU.
- C&DH: Mid and High-level processor selection, data bus selection, and expansion port selection.
- Flight Software (FSW): LLP OS; LLP algorithms for velocity limiting; Mid Level Processor (MLP) OS; control algorithms for control of position, orientation, velocity, angular velocity, and trajectory tracking; software for closed loop tests; and data logging.
- Propulsion: Tested control of 4 variable pitch propellers.
- EPS: Battery selection, wiring and connectors for motors, motor controllers and processor, housekeeping voltage regulators design and fabrication to provide voltage levels needed by processor, motors and motor controllers
- GNC: IMU, camera for fiducial/Vision Based Navigation (VBN) tests.
- Communication: Functional communication system.
- Docking: A simple lance/cone to use as a target for navigation.

Prototype 3 focused on remote command and control, implementation of closed loop Vision Based Navigation (VBN), near-flight like avionics, and an approach to docking and perching. Subsystem development will focus on:

- Structure: Re-use of prototype 2 structure.
- EPS & C&DH: Near-flight design.
- Propulsion: Re-use of prototype 2 propulsion.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 16 of 46

- Communication: Functional communication system.
- Flight Software (FSW): LLP near-flight design. Vision-based navigation algorithms. Remote commanding. Test support software.
- GNC: Maturation to near flight design, including VBN and perching controller.
- Perching Arm: Near-flight design with a perching arm assembly.
- Control stations: The Operator UI, ISS models, commanding and monitoring. This will also include minimal RAPID/DDS protocols.

Prototype 4 will focus on the flight-like hardware design.

- Structure: Flight like design, 3D printed, no “paint job”.
- Propulsion: Flight propulsion modules.
- C&DH: Flight avionics stack.
- GN&C: Flight IMU and software.
- Flight Software (FSW): Minimal software to enable testing of all hardware-related requirements.
- Thermal: Active Thermal control.
- Docking: Full dock to include the ISS interface. Non-flight like Dock.
- Control stations: Planning module / plan editor for the Operator Control Station.

The Certification Units will be developed off the final Prototype 4 design, with any modifications derived from the results of Prototype 4 testing. These units will not only be used for performance testing, but also for environmental testing and ISS interface requirement verification and certification.

- Flight Software (FSW): Sufficient software to test hardware and all ISS and Safety requirements.
- Control stations: Crew Control Station, updated planning and commanding UI.

Finally, two Flight Units will be developed. These units will be developed, assembled, and curated in appropriate facilities following ARC procedures and processes for flight hardware.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 17 of 46

Challenges/Risks

There are several technical challenges to the development of Astrobee. First is the accuracy of a navigation system for localizing, positioning, orientation and pointing. Astrobee requires a robust navigation system that can localize throughout the entire U.S. orbital segment on ISS. Rather than build up the ISS infrastructure to include multiple positioning beacons, Astrobee team is looking for a vision-based navigation (VBN) solution. However, there are not any VBN solutions readily available for mobile devices. The HET project has tested a prototype commercial product that offers VBN, however preliminary testing of that device indicates that it will not work well in 0g. Therefore, it may be necessary for HET2 to develop its own mobile VBN system. This still may not meet Astrobee accuracy requirements. As a fall back plan, the team may propose to use Augmented Reality (AR) targets in one area of the ISS for high accuracy navigation operations.

The ISS has limitations on the amount of noise caused by a payload, both continuously and intermittently. Astrobee team will need to find high performance fans that fall within the noise limits.

One of the most significant challenges in the development of Astrobee is developing a system that meets human spaceflight safety standards for an anonymous free-flying robot. The Payload Safety Review Panel (PSRP) at JSC approves all ISS payloads. The PSRP has a standard set of hazards that each payload must assess and prove that the hazard is not applicable or mitigated. The team must also determine if there are other unique hazards for their payload. For a free-flying robot, the possibility of collisions is most definitely a unique hazard. Mitigating this hazard for an autonomous free-flyer (meaning crew cannot be used for hazard mitigation) will be a significant challenge.

Milestones

Table 4. Astrobee Technology Development Task Milestones

Controlled Milestone	Description	Date
———	Prototype 2 design ready for integration, validation & test	1/15/2015
———	Prototype 3 design ready for integration, validation & test	6/1/2015
———	Prototype 4 design ready for integration, validation & test	1/4/2016
———	Cert Unit design ready for integration, validation & test	2/1/2017
———	Flight Unit design ready for integration, validation & test	4/30/2017

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 18 of 46

2.3.3 *Astrobee Validation and Test Task*

Objectives

This task is focused on the integration, validation and testing of Astrobee development efforts. This task includes the hardware, software, procedures and project-owned facilities required to perform Astrobee system level integration, validation and tests of Astrobee, dock, payloads, and control stations.

Approach

Astrobee will be tested incrementally, as each prototype is developed and delivered. Each prototype has stated objectives, both as overall system, and for subsystem development. Astrobee testing will verify requirements allocated to the respective prototype, and validate system capabilities.

Prototype 1 testing completed before the baseline of this project plan. This testing focused on open-loop operations, and basic linear/rotational acceleration, and was conducted on the air-bearing table in the Ames SPHERES Granite Lab.

Prototype 2 testing focuses on closed-loop operations and navigation. The tests will primarily address closed-loop operation, 1-D angle and angular velocity tracking, and 2-D position, velocity and trajectory tracking. The tests will be performed on the air-bearing table in the SPHERES Granite Lab, the spherical air-bearing platform in the Ames Generalized Nanosatellite Testbed (GNAT) Lab, and will require an external positioning system for ground truth comparison.

Prototype 3 testing focuses on basic commanding and VBN capabilities. The tests will primarily address remote commanding, closed-loop VBN operation, the perching arm approach, grip and release of ISS structure. The tests will be performed on the air-bearing table in the Ames SPHERES Granite Lab and the Ames Micro Gravity Test Facility (MGTF).

Prototype 4 testing focuses on validation of the hardware design. These tests will primarily address performance and hardware related requirements. The tests will be performed on the air-bearing table in the Ames SPHERES Granite Lab, the Ames Micro Gravity Test Facility (MGTF), and will also require operator control from a remote facility, such as the Ames Multi Mission Operations Center (MMOC).

Certification Unit testing focuses on performance testing, ISS interface testing, and safety certification. These tests will primarily address overall Astrobee capabilities, ISS and launch interfaces (loads tests, ISS LAN tests, laptop interoperability, etc.) and certification of ISS hazards (material off-gassing, collision and impact resistance, etc.).

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 19 of 46

Flight Unit testing focuses on final performance verification and inspections prior to being shipped to JSC for launch processing.

Challenges/Risks

The major challenges and risks associated with Astrobees validation and testing parallel the same risks in Astrobees development. Astrobees will need meet the success criteria established for the requirements and technical challenges in design and development. Further, the test results will be presented to the PSRP for ISS certification.

Milestones

Table 5. Astrobees Validation and Test Milestones

Controlled Milestone	Description	Date
Astrobee-FY15 #1	Prototype 2 testing complete	2/15/2015
Astrobee-FY15 #2	Prototype 3 testing complete	7/28/2015
Astrobee-FY16 #1	Prototype 4 testing complete	4/25/2016
Astrobee-FY17 #1	Cert Unit testing complete	8/30/2017
Astrobee FY17 #2	Flight Units testing complete	9/30/2017

2.3.4 *Astrobee ISS Commissioning Task*

Objectives

The objectives of the Astrobees ISS commissioning task are to perform verification of Level 1 (L1) requirements (Table 3) and validation activities in order to: (1) provide the SPHERES Program with a robotic system that is ready for research facility operations and (2) support technology demonstrations for the ISS Program. To meet these objectives, this task involves ISS activities to test and demonstrate Astrobees and ground activities to support the ISS work. The ISS activities involve installation and activation, map data collection, basic checkout, performance characterization, and an operations demonstration. The ground activities involve map development and software tuning.

Approach

This task will perform all ISS activities following the ISS payload process, including working with an ISS Payload Integration Manager (PIM) and the ISS Payload Safety Review Panel (PSRP) to obtain all necessary approvals and concurrence on documentation required for ISS activities. In addition, the Astrobees Element will

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 20 of 46

coordinate and jointly perform on-orbit tests and demonstrations with the SPHERES Program, including the SPHERES chief engineer and SPHERES operations team.

The Astrobe Element will develop crew operational procedures and ground operational, troubleshooting and maintenance procedures. The team will create training material for crew and ground personnel, and conduct training for the Astrobe and SPHERES operations teams. Further, the operations teams will conduct operational readiness tests (ORTs) in advance of each ISS activity. Regression testing will be performed to verify correct performance after software configuration changes, enhancements, or patches.

The first several on-orbit tasks will require ISS crew participation. Crew will be required to install the Docking Station, plug batteries into the Astrobes, turn them on, and place them into the Docking Station for charging. Next, they will need to be present while component checks are performed (nozzles opened, signal lights turned on, touch screen displays data, etc.) to verify those components work. Crew will then hold a single Astrobe and use its cameras to map a limited area of the ISS. With a local map in place, crew will oversee some basic mobility tests, including autonomous docking (L1 requirement FFREQ-80). Once that capability is proven, crew will no longer be required to tend to Astrobe commissioning activities.

Under control from the ground (L1 requirement FFREQ-75), Astrobe will perform increasingly complex mobility maneuvers that will help tune flight software, GNC software, and ground simulators. These tests will also be used to help characterize the system. Astrobe will also be used to incrementally expand its map of the ISS. The free flyer will be commanded to the edge of its known map to "peek out" at unknown territory. The number of increments required to complete a map is the ISS USOS is not known. However, since no crew time is required to perform incremental mapping, this is not expected to be an issue.

Finally, Astrobe will be demonstrated to its prospective customers. Astrobe will demonstrate research facility operations (L1 requirement FFREQ-83) for the SPHERES Program, including operations running Guest Science software, as well as with and without a hardware payload. The Astrobe Element is dependent on the Advanced Exploration Systems Logistics Reduction (AES/LR) project having the REALM (RFID reader) payload ready for this demonstration. Astrobe will demonstrate mobile camera operations (L1 requirement FFREQ-89) for the ISS Program and Flight Operations Directorate.

Challenges/Risks

The first several ISS activities require crew time, which is not guaranteed and is dependent upon ISS operational constraints involving crew. Priority may be given to other experiments (biological experiments with expiration dates, physiological

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 21 of 46

experiments that require specific crew) or other activities (e.g., unplanned EVAs) may reduce the amount of time available for payloads. Consequently, the project is planning for significant schedule margin to mitigate this risk.

The Astrobees payload demonstration also depends on availability of the AES/LR REALM payload. If this payload is not available, then Astrobees/SPHERES will need to develop its own test payload for the demonstration.

All ISS payloads must submit a request for the number of crew hours they will require to support their on orbit activities. Astrobees commissioning activities will be attempted with as little crew time as possible and will follow the appropriate Element control plans (concept of operations, payload integration agreement, etc) as listed in Appendix D. There are certain activities that will require crew (Dock installation, system activation, ISS mapping). However, whenever possible, activities will be remotely controlled from the ground. If any of these remotely controlled activities fail (e.g., Astrobees fails to find its way back to the Dock), the project may have to ask crew to intervene. The activities will be structured to minimize the risk that crew will be needed, but this approach precludes crew from having to oversee the entirety of Astrobees activities.

Milestones

Table 6 Astrobees ISS Commissioning Milestones

Controlled Milestone	Description	Date
-----	Installation complete	1/31/2018
-----	Initial ISS mapping complete	3/31/2018
Astrobees-FY18 #1	Astrobees first flight/basic mobility complete	4/30/2018
-----	Astrobees autonomous flight demonstration	6/30/2018
Astrobees FY18 #2	Astrobees operations demonstration	9/15/2018

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 22 of 46

2.4 Robonaut 2 Element

HET2 will continue the checkout and maturation of Robonaut 2 (R2), which is currently on ISS. R2 work will focus on demonstrating legged IVA mobility using the climbing legs that were installed during the HET project in August 2014. This work will be performed during FY15 to FY16-Q1.

2.4.1 R2 Climbing Task

Objectives

This task is focused on continuing the checkout and advancement of R2 currently on the ISS. R2's legs were recently installed to its torso but R2 has yet to take its first steps so the objective of this task is to demonstrate R2's ability to climb from hand rail to hand rail gaining experience with climbing gaits, forces and ops concepts.

Approach

A series of incrementally challenging maneuvers will be scheduled for R2 beginning with the ungrasping of its currently held handrail, maneuvering away from the handrail and then using its vision system to identify and re-grasp that same handrail. Eventually, R2 will demonstrate its ability to grasp handrails from an angled approach, avoid obstacles covering handrails, climb from one handrail to the next and maneuver within the ISS Lab module. R2 will also demonstrate its ability to stow and un-stow itself without crew assistance.

This task also includes any maintenance required to keep R2 operational on ISS. Crew procedures for on-orbit tests will be developed and practiced on the R2 cert unit (on the ground). Coordination will be performed with the Payload Operations Integration Center at MSFC to obtain procedure approval and to obtain crew time for on-orbit sessions.

Challenges/Risks

Climbing has been demonstrated on the ground in a laboratory test environment so confidence is high this capability can be demonstrated on-orbit. There is always risk that hardware may have been damaged during the launch process, but checkout testing to date on the ISS has shown no indication of damage. Maneuvering within the Space Station modules, given the clutter of cables and equipment, will be a challenge R2 will have to overcome. The risk is R2 may be limited in its ability to navigate through the modules without crew assistance in clearing a translation path.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 23 of 46

Milestones

Table 7. R2 Climbing Task Milestones

Controlled Milestone	Description	Date
——	Move one End Effector to adjacent handrail	12/31/2014
——	Leg vision integration	1/31/2015
——	60 deg – multi grip handrail grab	2/28/2015
R2-FY15 #1	Self-stow/unstow	5/30/2015
——	Avoid obstacle on handrail	5/30/2015
——	Path planning integration	7/31/2015
R2-FY15 #2	Multiple steps	9/30/2015
——	Crew procedures for power fault troubleshooting	11/30/2015

2.4.2 R2 IVA Task Development

Objectives

R2 demonstrated its ability to manipulate crew interfaces and tools during the HET project (TDM). Thus, the objective of this task is demonstrate that R2 can successfully perform a complex IVA task that the ISS Program would like to perform robotically.

Approach

Work with the ISS Program to identify an IVA task that R2 can perform without crew assistance. Ideally, the task will be one that is also relevant to EVA work. Perform a ground demonstration using the R2 Certification unit to define the required procedures before progressing to the on-orbit demonstration.

Challenges/Risks

Transitioning from a technology demonstration to an operational system is a significant challenge. Successfully performing a task without crew intervention and also reducing crew workload is critical to proving the utility of R2. A key risk is that R2 will not be robust enough to operate repeatedly without crew intervention (e.g., system reboots).

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 24 of 46

Milestones

Table 8. R2 IVA Task Development Milestones

Controlled Milestone	Description	Date
——	IVA task selection	10/31/2014
R2-FY15 #3	Ground demonstration	6/30/2015
——	On-orbit initial trial	8/30/2015

2.4.3 R2 Efficient Programming

Objectives

This task will focus on developing software advances necessary to support R2 climbing and IVA task execution including machine vision, obstacle avoidance/path planning and integrated supervisory control interfaces.

Approach

Recent R2 hardware upgrades (increased computing capacity) and software upgrades (transition to open source Robot Operating System (ROS)) have paved the way for greatly enhancing the control of R2. Taking advantage of new capabilities in ROS, including the infusion of algorithms developed by other ROS users, and on-board data processing will allow for more robust path planning and machine vision for R2 and “point and click” supervisory interfaces for ground controllers.

An incremental approach will be used to increase the level of autonomy on R2. Software developed in the lab will transition to the R2 simulation for evaluation, then proceed to certification testing prior to uplink to ISS. The goal is to reach a level of autonomy where ground support is only assisting the robot 5% of the time.

During FY16-Q1, activities to position the ISS R2 unit as an exploration IVA dexterous mobile testbed on ISS will be performed. Mobility software demonstrated as part of the FY15 IVA ground demonstration will be modified to increase robustness and additional supervisory features will be added to improve handrail-to-handrail climbing. The affordance template technique used for manipulation will be implemented with handrail templates allowing the human operator to supervise the selection of handrails. Extensive ground testing will be performed to ensure readiness for use on-orbit.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 25 of 46

Challenges/Risks

Developing robust path planning and obstacle avoidance software algorithms is a major challenge. Creating software to parameterize possible grasps will also be key to developing a supervisory control interface that is easily adaptable to real time situations. The risk is that R2's safety control and monitoring system limits its capabilities, reducing its effectiveness and ability to quickly respond to on-orbit requests for support.

Milestones

Table 9. R2 Efficient Programming Milestones

Controlled Milestone	Description	Date
——	Updated R2 simulation	11/30/2014
——	Vision architecture implemented	3/31/2015
——	Grasp planning library	5/31/2015
——	Integrated supervisory control interfaces	8/31/2015
——	Supervised midrange handrail localization	12/31/2015

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 26 of 46

3.0 Performance

The HET2 Key Performance Parameters (KPP) for Astrobee are listed in

. 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 flight time allows sufficient time for Astrobee to fly to any location with ISS (and get back afterwards). *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 10. Key Performance Parameters (Astrobee)

Parameter	State of the Art (SPHERES)	Threshold Value (Minimum success)	Project Goal (Full success)
Maximum velocity	4 cm/sec	10 cm/sec	40 cm/sec
Flight time	0.5 hr	2 hr	5 hr
Dock & resupply	Crew tended	Crew tended	Autonomous
# of expansion ports	1	2	4
Consumables used per test session	6	0	0
ISS operational space	2m x 2m x 2m	JEM, US Lab, and Node 2	All USOS

The HET2 Key Performance Parameters (KPP) for Robonaut 2 are listed in Table 11. This table shows the current state-of-the-art (represented by Robonaut 2 experience to date), project threshold values (minimum success), and project goal (full success). These KPPs are important for Robonaut to achieve because they demonstrate Robonaut's independent mobility capability, including self-stowing and un-stowing.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 27 of 46

Mobility is important because it allows Robonaut to maneuver inside the spacecraft and get into position to perform various tasks and also extends to an EVA Robonaut where crew intervention will not be readily available. The KPPs also address the ISS Program's desire to reduce the impact Robonaut operations have on crew time in the near term and to help eventually reduce crew time in the long term by performing a task that would otherwise be performed by the crew.

Table 11. Key Performance Parameters (Robonaut 2)

Parameter	State of the Art (Robonaut 2 / 2014)	Threshold Value (Minimum success)	Project Goal (Full success)
Use vision to identify handrail and grab it	0	3	5
Use vision to grab handrail from angled approach	0	1	3
R2 un-stows itself from rack without crew assistance	crew performed	without crew assistance once	without crew assistance multiple times
R2 stows itself in rack without crew assistance	crew performed	without crew assistance once	without crew assistance multiple times
Vision system identifies obstacle covering handrail and plans around it resulting in proper grasp	0	1	1
R2 performs a complex IVA task	0	1	1

The Technology Readiness Level (TRL) advancement for Astrobee is detailed in Table 12 (Astrobee). The table shows the change in TRL from project start to finish for key component/subsystem technologies.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 28 of 46

Table 12. TRL Advancement (Astrobee)

Project Technology	Start TRL	End TRL	Rationale for TRL step
Vision based navigation for IVA operations	3	4	Prototype 4 testing completed in ground facilities
	4	6	Cert Unit testing completed in ground facilities
	6	8	Flight Units tested on ISS
Fan based propulsion for microgravity	3	4	Prototype 3 testing completed in ground facilities
	4	6	Cert Unit testing completed in ground facilities
	6	8	Flight Units tested on ISS
ISS 3-D path planning	3	4	Prototype 4 testing completed in ground facilities
	4	6	Cert Unit testing completed in ground facilities
	6	8	Flight Units tested on ISS
Zero-g robotic perching	3	4	Prototype 4 testing completed in ground facilities
	4	6	Cert Unit testing completed in ground facilities
	6	8	Flight Units tested on ISS
ISS free-flying robotic system	3	4	Prototype 4 testing completed in ground facilities
	4	6	Cert Unit testing completed in ground facilities
	6	8	Flight Units tested on ISS

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 29 of 46

The TRL advancement for Robonaut 2 is described in Table 13. The table shows the change in TRL from project start to finish for key component/subsystem technologies.

Table 13. TRL Advancement (Robonaut 2)

Project Technology	Start TRL	End TRL	Rationale for TRL step
Robot dexterity and leg end-effector grasping of handrails	4	6	R2 on-orbit demonstration grasping handrail nominally and at 60 deg. angled approach.
Autonomous task software	4	6	R2 on-orbit demonstration of path planning capabilities (handrail grasp with obstacle avoidance).
Sensing	4	6	R2 on-orbit demonstration of leg vision object recognition and position estimation.
Climbing	4	6	R2 on-orbit demonstration of system performance over multiple steps.

4.0 Systems Engineering

The HET2 project complies with NASA NPR 7123.1B (Systems Engineering). Element leads develop requirements, KPPs, and products that are reviewed and concurred by the PM. All software developed by HET2 will be managed according to NPR 7150.2A (NASA Software Engineering), plus any center-specific processes. The final class of each code will be determined according to its level of maturity and intended use. In most cases, the appropriate NASA line organization will be responsible for ensuring compliance, although HET2 will work with the line organizations to facilitate compliance.

HET2 will conduct Periodic Technical Reviews (PTR) in accordance with NPR 7123.1. As a NPR 7120.8 project HET2 does not conduct the same gate reviews as a 7120.5 flight project. However, since HET2 will test and demonstrate systems on the ISS, it may be appropriate to do reviews that are similar to a subset of 7120.5 reviews: System Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), etc. The PTRs for each Element will be planned and chaired by the respective Element lead. The lead is also responsible for identifying deliverables, entrance and exit criteria for each review.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 30 of 46

5.0 Management Approach

The HET2 project is managed in accordance with NPR 7120.8. Additionally, all HET2 on-orbit activities must comply with ISS Payloads processes. These processes are typically more complex than NPR 7120.8 requirements, and they include requirement verification, system and operations validation, and safety certification.

5.1 Organizational Structure

The organization structure for the HET2 is shown in Figure 1. The Game Changing Development Program Manager at the Langley Research Center (LARC) is responsible for program implementation and oversight for the Space Technology Missions Directorate (STMD) at NASA Headquarters (HQ). The Ames Research Center (ARC) leads and executes HET2. Staff includes civil servants and contractors at ARC, Jet Propulsion Laboratory (JPL), and the Johnson Space Center (JSC).

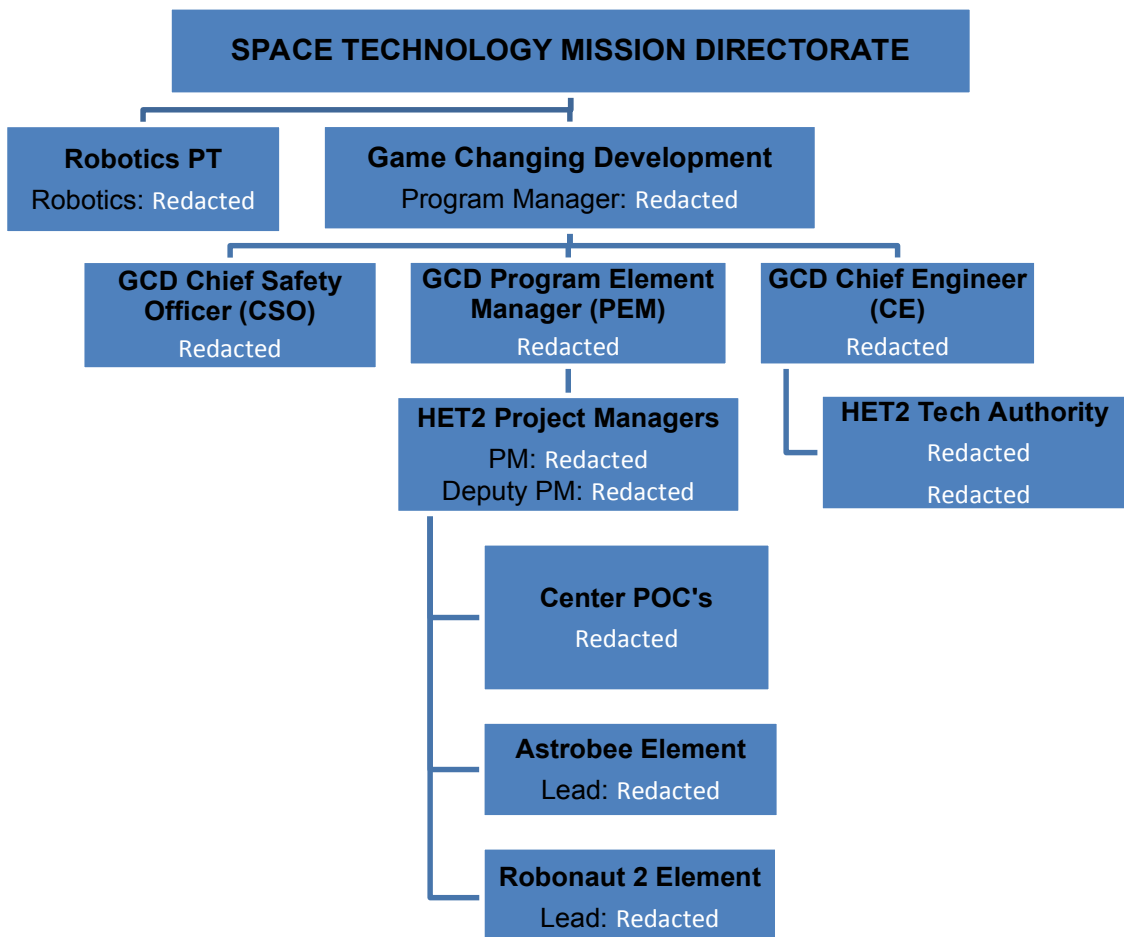


Figure 1. Organizational Structure

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 31 of 46

Roles and responsibilities for HET2 are described in Table 14. The HET2 Project Manager (PM) reports to the GCD PEM. The HET2 Deputy PM and Center Points of Contact (POCs) provide support for technical execution planning, monitoring, and reporting. The Astrobee and Robonaut 2 Element Leads are responsible for technical execution of a project element. The HET2 Independent Review Board (IRB) serves as an independent technical authority to provide the GCD Chief Engineer (CE) with feedback on project progress, engineering methodology (specifications, rules, best practices, etc), and technical and programmatic (resources, risk, schedule, etc). In addition to technical authority through GCD, each of the performing centers has technical authority reporting paths through each center's line management.

Table 14. Roles and Responsibilities

Title	Name	Responsibility
GCD Program Manager	Redacted	Project plan approval authority. Chair of GCD Program Control Board (GPCB) for resource/schedule/deliverable changes.
STMD Robotics Principal Technologist (PT)	Redacted	Sets the project's technical objectives and direction. Participates in project continuation reviews.
GCD Chief Engineer (CE)	Redacted	Program Engineering Technical Authority for NASA engineering requirements and waivers.
GCD Chief Safety Officer (CSO)	Redacted	Program Safety Technical Authority for safety requirements and waivers.
GCD Program Element Manager (PEM)	Redacted	Primary GCD contact with the Project for insight and oversight, including continuation (board chair), closeout reviews and change requests.
Project Manager (PM)	Redacted	Responsible for executing this project plan to ensure project success. Authority over project decisions consistent with the scope, technical deliverables, cost and schedule described in this plan. Responsible for reporting to the PEM and GCD Program Manager as required.
Deputy Project Manager	Redacted	Supports technical execution of the project consistent with NASA policy and engineering practices. Assists with planning, monitoring, and reporting. Reports to the PM.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 32 of 46

Element Leads	Redacted	Responsible for executing a project element to ensure project element success. Authority over project element decisions consistent with the scope, deliverables, cost and schedule described in the HET2 project plan. Reports to the PM, PI, and GCD Director as required.
Center Points of Contact	Redacted	Responsible for working Center level issues (reporting, task agreements, coordination with management, etc.)
Technical Authority	Redacted	Independent technical authority for the project. Contributes to Continuation Review inputs. Reports to the GCD Chief Engineer.

5.2 Reporting

5.2.1 Project Reporting

A set of milestones will be agreed upon with each Element and participating Center, along with associated deliverables, metrics, start and due dates, dependencies and a schedule of forecasted costing. Centers will notify the PM with as much advance notice as possible of any issue or threat to the timeliness of delivery.

Annually

- Programmatic support, as required

Quarterly

- Inputs for the HET2 quarterly report (technical progress, cost, schedule, risks)

Weekly

- HET2 Center and Element Leads shall report to the HET2 PM on a weekly basis through a management teleconference and e-mail status inputs. A written summary will then be submitted to GCD.

As Required

- Inputs for controlled (Level 1) milestone reports
- Inputs for any on-orbit ISS session (Level 2) reports
- Inputs for any problem report
- Inputs for the HET Final Report

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 33 of 46

5.2.2 Programmatic Reporting

The annual review cycle is established to facilitate decision making needed to formulate, advocate and implement the overall Program and ensure each Project is aligned to the maximum extent with GCD requirements and needs within the funding allocated. The annual review cycle includes three main elements: Planning, Programming, Budgeting, and Execution (PPBE), Project plans, and Status Review.

PPBE submits

The HET2 Project shall modify and update a PPBE plan for work planned the following Fiscal Year (FY) and estimates for work to be performed in the remaining years of the project life cycle. The PPBE plan shall include objectives, technical approach, milestones and deliverables, and funding required by Work Breakdown Structure (WBS) Element and Sub element and by Center for Full Time Equivalent (FTE), Work Year Equivalent (WYE), procurement, and travel.

Project plans

The HET2 Project Plan shall be created and submitted to GCD management for review and concurrence. The HET2 Project Plan will be updated as needed.

Quarterly

The project will provide quarterly reporting on technical, cost, schedule and risk status. The quarterly report shall contain non-proprietary technical information/content accomplishments, performance to plan, issues, and near-term plans. The report shall also contain an update on project metrics (KPP, TRL, etc).

As Needed

- List of accomplishments, upcoming events, and issues, delivered to GCD
- Controlled (Level 1) milestone reports will be submitted to GCD management.
- The HET2 Final Report will be submitted within 90 days of the last Level 1 milestone. The final report will include demonstration data to verify that objectives were met, KPPs were reached, TRL advancements were completed, technology gap assessments and conclusions.

5.3 Reviews

The project will conduct Periodic Technical Reviews (PTR) as needed for each Element. Each PTR will assess technical development, progress towards KPPs, and TRL maturation. The Project Manager and Element Lead will develop requirements and success criteria prior to conducting a PTR. Each PTR will be led by the Element Lead and will include internal (HET2) and external (STMD, GCD, Center management, collaborators, stakeholders, and subject matter experts) participation as appropriate.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 34 of 46

The project will conduct yearly Continuation Reviews in FY15 and FY16. These reviews will focus on accomplishments, progress against project objectives, Key Performance Parameters (KPP) and technology maturation for the previous year, and risks, budget, and schedule for both the previous and upcoming years. The Continuation Reviews will be led by the Project Manager and will include internal (HET2) and external (STMD, GCD, Center management, collaborators, stakeholders, and subject matter experts) participation as appropriate.

The project will conduct a Closeout Review in FY17. The HET2 Final Report will be the deliverable for the Closeout Review. The review will focus on project accomplishments, evidence of successful completion of project objectives and KPPs, and Technology Readiness Level (TRL) advancement. The project will also provide lessons learned in accordance with NPR 7120.6 Lessons Learned Process. The Closeout Review will be led by the Project Manager, and will include internal (HET2) and external (STMD, GCD, Center management, collaborators, stakeholders, and subject matter experts) participation as appropriate.

5.4 Risk Management

HET2 will perform risk management in accordance with NPR 8000.4A (Agency Risk Management Procedural Requirements). HET2 will use Continuous Risk Management to identify, track and mitigate risks. Each HET2 Element will develop and maintain a Risk List, which will describe the risk #, description, likelihood by consequence (LxC) score, handling strategy (mitigate, watch, accept, etc.), action plan (contingency or mitigation plan) and status. The risk lists will be reviewed monthly and updated to reflect newly identified risks, assessment-ranking changes, and status of the respective mitigation plans. The top Project Risks and status will be reported in the quarterly report.

5.5 Configuration Management

HET2 will define, identify, prepare, control, and disposition project records in accordance with NPD 1440.6 (NASA Records Management), NPR 1441.1 (Records Retention Schedules), and the GCDP Configuration and Data Management Plan (GCDP-01-CDMP). Project management documentation will be stored on LARC's NX Repository. At project termination, archiving of documentation will be completed per NPR 1441.1D (NASA Records Retention Schedules).

The approving authority identified in the Change Log may approve updates to products under configuration control. Peer reviews may be conducted for some products. ARC as the host center will use library, configuration management, and reporting procedures compatible with GCD requirements. Each participating center will use their center's procedures for capturing and maintaining products under configuration control.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 35 of 46

6.0 Resource Requirements

6.1 Funding Requirements

The costs and schedule for this project were planned with a resources loaded schedule that includes appropriate reserves commensurate with project phase and risk. With that said, unforeseen challenges may arise in any advanced technology project that exhaust planned resources. In these cases the project will submit a Change Request to the GCD Program to request additional resources and/or reduce project scope.

The life-cycle cost (LCC) for HET2 is summarized in Table 15. These costs do not include the SUPERball Bot task managed by HET2. The LCC shows New Obligation Authority (NOA) in full-cost, real-year dollars for FY15-18 in terms of travel, procurement, and civil servant labor at the three performing centers (ARC, JPL, and JSC). The table also indicates estimated work force, in terms of civil servants (FTE) and support service contractors (WYE). Resources for Astrobee are split between ARC and JPL. Resources for Robonaut 2 are all held at JSC.

Table 15. Project Resource Allocations

6.1.1 Astrobee External Resources

In addition to Astrobee life cycle costs funded by GCD, Astrobee element also leverages external funding and resources that directly contribute to Astrobee planning, development, testing, or indirectly by contributing to the success of Astrobee testing and operations.

The HEOMD SPHERES Program is dedicating approximately \$1.8M for two WYE who will actively participate on Astrobee team in the areas of requirements development, Astrobee design, development and testing. The SPHERES Program also provides the use of test beds, operations integration support, and sustaining engineering. During FY17-18, the SPHERES Program will support (external to the HET2 project) the production of a third Astrobee flight unit, flight spares, and SPHERES-to-Astrobee Facility preparation activities.

The HEOMD AES Logistics Project is providing a RFID Reader that will be attached to Astrobee to assist with automated logistics management. The Logistics Project is dedicating 6 FTE and approximated \$1M to develop, test and integrate the RFID Reader onto Astrobee.

The HEOMD AES Autonomous Systems Operations (ASO) Project is dedicating approximately \$1.6M for contractor support on RFID data management. This project work, which receives data from the RFID Reader mounted to Astrobee, and assesses

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 36 of 46

how such data can feed into the ISS Inventory Management System (IMS), contributes to the overall success of automated logistics management.

Finally, the ISS Program provides a variety of resources (at no cost to the project) including crew hours, testing support (e.g., networking tests in the Joint Station LAN laboratory) at JSC, payload integration and launch costs.

6.1.2 Robonaut 2 External Resources

Robonaut 2 is leveraging off of previous investments from the ISS Program and General Motors who were strong partners during Robonaut 1 and 2 developments. The ISS Program contributed \$33M in FY10-FY13. Though funding from the ISS Program has ceased, they continue to provide a variety of resources (at no cost to the project) including crew hours, testing support (e.g., networking tests in the Joint Station LAN laboratory) at JSC, payload integration and launch costs.

Additional partnerships are also being pursued with external (non-NASA) agencies and corporations.

6.2 Institutional Requirements

6.2.1 Astrobees

Astrobees will utilize several unique Ames Research Center (ARC) facilities for prototype development and testing. These facilities already exist and are used for small satellite development and testing. Some of these facilities may require modification to be used with Astrobees.

Astrobees will require the use of the ARC SPHERES Granite Lab located in ARC Building N269. This lab has an air-bearing table used for 2-DOF testing of satellites that sit on an air-bearing pallet. This allows the satellite to translate along the x and y-axes, and yaw about the z-axis. The SPHERES Granite Lab is actively used by the SPHERES Program, and as the primary Astrobees customer, they will modify the lab to conduct Astrobees testing as well.

Astrobees will also require the use of the ARC Micro Gravity Test Facility (MGTF) located in ARC Building N269. This lab suspends a satellite in free space, which allows testing translation in three axes, as well as yaw about the z-axis. This lab is maintained by the SPHERES Program, and will be upgraded for Astrobees.

Additional ground based testing will be performed in the ARC Generalized Nanosatellite Testbed (GNAT) located in ARC Building N213. This lab is used for avionics, software and sensor testing. This lab also includes a spherical air bearing, which will be used to test pointing in 3 axes.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 37 of 46

Finally, Astrobees have already been approved as a payload, and specific Astrobees requirements for ISS integration are being documented in a ISS Payload Integration Agreement (PIA).

6.2.2 Robonaut 2

Existing JSC facilities will be used for R3 development including the Robonaut 2 (R2) development lab (JSC Building 32), R2 test lab (JSC Building 9 High Bay) and Robonaut Control Center (JSC Building 9, Room 3112), and the Joint Station LAN Lab (JSC Sonny Carter Training Facility).

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 38 of 46

7.0 Schedule

The HET2 key events are shown in summary in

. A schedule slip of Program-controlled (Level 1) milestones requires approval from the GCD Program Control Board. The project manager will fill out a GCDP Change Request and the Program Control Board will disposition the Change Request.

Figure 2. Key HET2 events

7.1 Astrobee

During FY15, two controlled (Level 1) milestones were achieved: (1) Completion of Prototype 2 testing, and (2) Completion of Prototype 3 testing. In addition, two Periodic Technical Reviews (PTR) were conducted. PTR #1 reviewed system/subsystem requirements, Prototype 2 test results, and Prototype 3 test plans. PTR #2 reviewed Astrobee preliminary design, Prototype 3 test results, and Prototype 4 test plans.

During FY16, one controlled milestone will be achieved; completion of Prototype 4 testing. PTR #3 will review Prototype 4 test results, Cert and Flight Unit development plans, and Cert and Flight Unit testing plans.

During FY17, two controlled milestones will be achieved: (1) Completion of Cert Unit testing and (2) Completion of Flight Unit testing. PTR #4 will review Cert Unit test results, and PTR #5 will close out the Element work.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 39 of 46

During FY18, two controlled milestones will be achieved: (1) Astrobee’s first flight and basic mobility test and (2) Astrobee operations demonstration.

7.2 Robonaut 2

During FY15, three controlled (Level 1) milestones were achieved: (1) Demonstration of self-stowage and un-stowage operations (ground test), (2) Demonstration of multiple step operations (ground test), and (3) Demonstration of an ISS relevant IVA task performed (ground test).

8.0 Work Breakdown Structure

The Work Breakdown Structure (WBS) for HET2 is shown in Figure 3. The project is split into two Elements (Astrobee and Robonaut 2) under WBS 210935. In addition, the project may implement task agreements for exploratory technical work, i.e., research and development that is not core, nor critical to the two Elements.

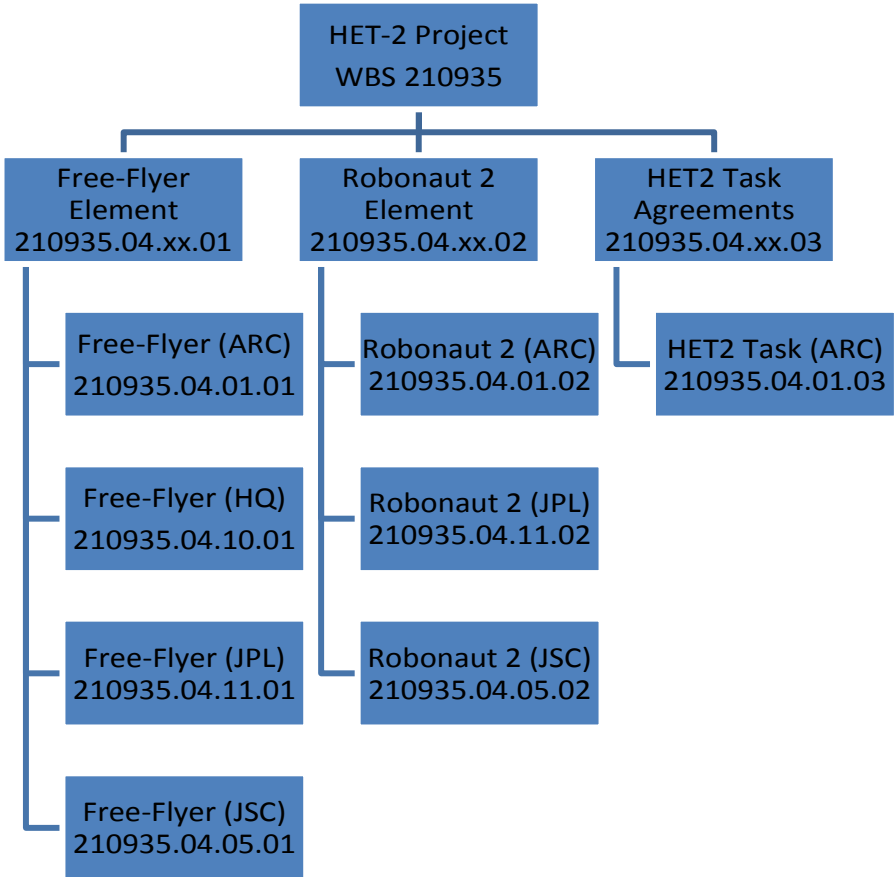


Figure 3. WBS Structure

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 40 of 46

The HET2 WBS Dictionary is given in Table 16. Astrobee research and development (WBS 210935.04.xx.01) is managed at ARC (WBS 219035.04.01.01). R2 research and development (WBS 210935.04.xx.02) is managed at JSC (WBS 219035.04.05.02).

Table 16. WBS Dictionary

WBS Element	Title	Description
219035	Human Exploration Telerobotics 2 (HET2)	Project to develop advanced, remotely operated robots to improve human exploration
219035.04	HET2 Technology Development	Technology development within HET2
219035.04.xx.01	Astrobee	Development of a new IVA free-flying robot for the ISS
219035.04.01.01	Astrobee (ARC)	Element project management (budget, schedule, risk), systems engineering (requirements, architecture, integration), development, testing, safety and mission assurance.
219035.04.10.01	Astrobee (HQ)	Astrobee cooperative agreements and contracts
219035.04.11.01	Astrobee (JPL)	Astrobee data communications and robot user interface development
219035.04.05.01	Astrobee (JSC)	Astrobee integration and testing
219035.04.xx.02	Robonaut 2	Development of a new IVA / EVA dexterous humanoid robot for the ISS
219035.04.01.02	Robonaut 2 (ARC)	Robonaut 2 engineering support at ARC
219035.04.11.02	Robonaut 2 (JPL)	Robonaut 2 engineering support at JPL
219035.04.05.02	Robonaut 2 (JSC)	Element project management (budget, schedule, risk), systems engineering (requirements, architecture, integration), development, testing, safety and mission assurance.
210935.04.xx.03	Task Agreements	Exploratory technical work
210935.04.01.03	Task Agreement (ARC)	Task agreement work performed at ARC.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 41 of 46

9.0 Strategy for Technology Transition

Technology transfer includes any systems, applications or data that is used in support of technology that is transferred in or out of the project. For technology that is transferred into the project, HET2 will document the following in the respective Element engineering and design documents:

- Identification and description of the technology
- TRL advancements
- Integration plans

For technology that is transferred out of the project, HET2 will document the following in the Project Final Report:

- Identification and description of the technology and deliverable
- TRL advancement and infusion readiness assessments
- Identification of beneficiaries and infusion points
- Description of any efforts to support beneficiaries (during or after project life cycle)

HET2 may also employ other means for releasing information and technology out of the project such as:

- Technical publications: HET2 will publish technical papers that describe HET2 technology development efforts, and present those at conferences.
- Open source releases: HET2 will strive to release non-proprietary data and software in open source repositories to further benefit the education communities and general public.
- Collaborations: HET2 will, as appropriate, share non-proprietary data, technology, plans and results with HET2 collaborative partners.

More information on the ISS commissioning activities and technology transition to AES/SPHERES Program are described in the Astrobee document IRG-FF047 Astrobee Technology Transition Plan.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 42 of 46

10.0 Security Plan

The HET2 project shall manage all IT in a cost-effective manner that ensures an appropriate level of integrity, confidentiality, and availability of information. The project will follow Agency and Center policies, procedures and requirements to protect NASA information and information technology systems in a manner that is commensurate with the sensitivity, value, and criticality of the information.

11.0 Safety Plan

As ISS payloads, all HET2 deliverables and operations are expected to meet all ISS Safety and Mission Assurance (SMA) requirements. The ISS Payload Safety Panel Reviews are critical reviews during the ISS certification process.

Each team will also follow the policies and procedures regarding SMA at their respective NASA Center.

HET2 management will provide an appendix to a single organizational level STP Mishap Preparedness and Contingency action Plan (MPCP) that coordinates and outlines necessary actions that offices, directorates and individuals must take in responding to a mishap, close call, corrective action or closure report.

12.0 National Environmental Policy Act (NEPA) Compliance

The HET2 project is a direct extension of the existing NASA activity, HET using existing NASA labs and facilities with no new environmental considerations; therefore National Environmental Policy Act (NEPA) requirements are met through this project.

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 43 of 46

Appendix A: Acronym List

CE	Chief Engineer
CONOPS	Concept of Operations
CR	Continuation Review
CRM	Continuous Risk Management
CSO	Chief Safety Officer
FOD	Flight Operations Directorate
FTE	Full-Time Equivalent
GCD	Game Changing Development
GCDP	Game Changing Development Program
GPCB	GCD Program Control Board
GS	Guest Science
HET	Human Exploration Telerobotics
HET2	Human Exploration Telerobotics 2
ISS	International Space Station
KDP	Key Decision Point
KPP	Key Performance Parameter
LCC	Life-Cycle Cost
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NOA	New Obligation Authority
NPD	NASA Policy Directive
NPR	NASA Procedural Requirement
OSHA	Occupational Safety and Health Administration
PM	Program Manager
R2	Robonaut 2
SMA	Safety and Mission Assurance
USOS	U.S. Orbital Segment

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 44 of 46

Appendix B: Key Personnel Contact Information

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Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 45 of 46

**Appendix C: Task Agreement for SUPERball Bot
(GCDP-02-TA-16028)**

Game Changing Development Program Human Exploration Telerobotics 2 (HET2)		
GCD Project Plan	Document No.: GCDP-02-PLN-14080	Revision: B
	Document Date: 12/21/2016	Page 46 of 46

Appendix D: Applicable Documents

Document #	Title
NPR 7120.8	NASA Research & Technology Program and Project Requirements
NPR 8000.4A	Agency Risk Management Procedural Requirements
PIP-14-043	Payload Integration Agreement for Astrobee
N/A	Astrobee Interface Requirements Baseline (ISS)
IRG-FF001	Astrobee Project Management Plan
IRG-FF002	Astrobee Systems Engineering Management Plan
IRG-FF003	Astrobee Safety & Mission Assurance Plan
IRG-FF004	Astrobee Configuration Management Plan
IRG-FF005	Astrobee Requirements Management Plan
IRG-FF006	Astrobee System Requirements and V&V Matrix
IRG-FF007	Astrobee Integration & Test Plan
IRG-FF008	Astrobee Software Development Plan
IRG-FF009	Astrobee Concept of Operations
IRG-FF011	Astrobee Integrated Master Plan
IRG-FF047	Astrobee Technology Transition Plan