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Robotic Interface Best Practices and Lessons Learned for Surface Operations

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ROBOTIC INTERFACE BEST PRACTICES AND LESSONS LEARNED FOR SURFACE OPERATIONS

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Table of Contents

Table of Figures

Table of Tables

INTRODUCTION

PURPOSE

The purpose of this document is to provide guidance for designing and organizing interfaces between robotic systems, crew operations, and cargo/payloads for use on the lunar or Martian surface. The best practices and lessons learned contained herein pulls from experiences in both terrestrial and low-earth orbit robotic operations. This document attempts to turn that cumulative experience across NASA's expertise into a set of guiding principles to aid in establishing interoperable robotic systems, architectures, or interfaces for the lunar surface, and eventually Mars. Following these guidelines will help promote compatibility with the widest range of potential robots and robotic applications possible.

SCOPE

The Best Practices (BP) and Lessons Learned (LL) within this document can apply to but are not limited by the following interfaces for the lunar and Martian surface:

- Grasping Interfaces - such as end effectors and grasp fixtures
- Crew-Robotic Interfaces - such as shared crew and robot workspaces, methods of control by crew and ground, and shared crew and robot softgoods handling
- Operational Interfaces – Tasking of robotic systems, visual identifiers, and Alerts and Information sharing

This document does not contain any verifiable requirements. This document also does not have direct applicability to microgravity robotic interfaces. In cases where any robotic interface to cargo or payloads is also meant to be EVA-compatible, these BP and LL are expected to be incorporated on a non-interference basis with respect to EVA requirements as outlined in EHP-10028.

The BPs and LLs contained in this document do not assume any specific, existing, or in-development robotic system. They are meant to inform design choices to make an interface that is “robotic-forward” and increase the likelihood that an interface will be compatible with a future, yet-to-be-designed robotic system. The more of these BPs and LLs that can be accommodated in an interface design, the simpler a robotic system can be to successfully make use of the interfaces on the lunar or Martian surface.

Once the process of designing a new interface and/or a robotic system has been initiated, requirements will need to be documented. The owners of this document can provide insight and guidance in the development of those requirements. None of the BPs or LLs in this document should be turned into programmatic or system level requirements within other documents without consultation with the document POCs in Appendix B.

While many of the BPs and LLs within this document are applicable to all classes and sizes of robotic interface, this document explicitly targets interfacing with human-class payloads and does not directly provide BPs and LLs for heavy lift or cargo-offloading on planetary bodies. It is recommended that when utilizing this document for large interface tasks (ex. lifting with cranes or forklifts, docking or berthing of habitats) that these BPs and LLs be filtered and incorporated with other applicable requirements, BPs, and LLs elsewhere.

CHANGE AUTHORITY/RESPONSIBILITY

This document is a Data Managed (DM) product that is managed by the product owners and does not require board approval to be changed. The intention is to continually update this document as the robotics community learns more about the use of new robotic systems, especially in lunar environments.

DOCUMENTS

REFERENCE DOCUMENTS

A reference document is a document that provides additional information for the reader and may contain other interoperability standards or best practices outside the scope of this document (Ex. Lunar Power, Communications, etc.) and may or may not be cited in this document.

Table 2-1: Reference Documents

Document Number	Document Revision	Document Title
EHP-10012	REV A.4	Extravehicular Activity and Human Surface Mobility Program (EHP) Systems Requirements Document
EHP-10028	REV B	Extravehicular Activity and Human Surface Mobility Program (EHP) Exploration EVA (xEVA) System Compatibility Standards
EHP-10069	REV A	Extravehicular Activity and Human Surface Mobility Program (EHP) Lunar Surface Integration Phase Power Specification
EHP-10070	REV A	Extravehicular Activity and Human Surface Mobility Program (EHP) Navigation Specification
EHP-10095	Baseline	Extravehicular Activity (EVA) and Human Surface Mobility Program (EHP) Lunar Surface Induced Environments Document
ESDMD-001	REV C	Moon To Mars Architecture Definition Document
ISO 10218-1	2025	Robotics — Safety requirements- Part 1: Industrial robots
ISO 10218-2	2025	Robotics — Safety requirements - Part 2: Industrial robot applications and robot cells
ISO/TS 15066	2016	Robots and robotic devices — Collaborative robots
JSC-65828	B	Structural Design Requirements and Factors of Safety for Spaceflight Hardware
M2M-30044	Baseline	Moon to Mars (M2M) Lunar Surface Databook
M2M-30159	REV J	Moon to Mars (M2M) Design Specification for Natural Environments (DSNE)
M2M-30202	REB B	International Communication System Interoperability Standard (ICSIS)

Document Number	Document Revision	Document Title
M2M-30204	A	International Space Power System Interoperability Standards (ISPSIS)
M2M-30205	Baseline	International Thermal System Interoperability Standards (ITSIS)
M2M-30207	REV Baseline	International External Robotic Interface Interoperability Standards (IERIIS)
M2M-30208	Baseline	International Software System Interoperability Standards (ISwSIS)
M2M-30209	REV F	International Docking System Standard Interface Definition Document (IDSS IDD)
M2M-43025	Baseline	Lunar Surface Command and Control Interoperability (LuCCI) Project Interoperability Requirements
NASA-STD-1008	Baseline	Classifications and Requirements for Testing Systems and Hardware to Be Exposed to Dust in Planetary Environments
NASA-STD-3001	Volume 2, Rev. E	NASA Spaceflight Human-System Standard Volume 2: Human Factors Habitability, and Environmental Health
NASA-STD-5017	B	Design and Development Requirements for Mechanisms
NASA-STD-5020	B	Requirements for Threaded Fastening Systems in Spaceflight Hardware
NASA-STD-6016	A	Standard Materials and Processes Requirements for Spacecraft

TERMINOLOGY AND CRITICAL DEFINITIONS

This document will borrow coordinate frames from the International External Robotic Interface Interoperability Standards (IERIIS) and definitions of key terms from other NASA documents. The definitions in Section 3.1 are a combination of definitions from other documents that are summarized here for completeness and several terminology definitions from within NASA that are critical to understanding some of the best practices and lessons learned within this document. The coordinate frames used within this document are as defined in Section 3.2 and Figure 3-1 through Figure 3-5.

DEFINITIONS OF CRITICAL TERMINOLOGY

Table 3-1: Terminology Definitions

Term	Description
Automation	A pre-programmed sequence of related functions performed by a system. (From EHP-10012 RV B)
Autonomy	The ability of a system to achieve goals in a dynamic environment while operating independently of external controls; includes the deliberate allocation of authority and responsibility for specific functions or behaviors to an Actor (or agent). (From EHP-10012 REV B)
Best Practice	While not considered requirements, best practices are highly desirable for the design of hardware compatibility with future robotics interfaces. (From EHP-10028 RV Baseline)
Demate	The act of isolating a mechanical connector’s services by physical disconnection and removal of one compatible connector from its receptacle. (Adapted from EHP-10028 RV Baseline)
Electrical Interface	A point where two components meet to create an electrical connection.
End Effector	The device, tool, tooling, at the end of a robotic manipulator’s kinematic stack which is used to interact with the environment. If a robotic tool with grasping capability grasps something and begins manipulating it (ex. a tool or PGT) than the item being manipulated assumes the “role” of the end effector from a control and kinematic perspective.
Fiducial	A predefined marking which can be used as a reference point to localize an object of interest. (ex. a target or cross hair mark)
Flight	The sequence of events that takes place between liftoff and landing of a transportation vehicle.
Grasp	The task of attaching a robotic end effector to a piece of hardware for the purposes of interacting with or maneuvering the hardware.

Lesson Learned	Lessons learned come from the experiences of various robotic experts and provide insight into how a particular design choice or action may have either adversely or positively affected the outcome of a robotic task.
Maintenance	The function of keeping items or equipment in, or restoring them to, a specified operational condition. It includes servicing, testing, inspection, adjustment/alignment, removal, replacement, access, assembly/disassembly, lubrication, operation, decontaminate, installation, fault location, calibration, condition determination, repair, modification, overhaul, rebuilding, and reclamation. Maintenance includes both preventative and corrective maintenance, both on-orbit and on the ground. (From EHP-10012 REV B)
Mate	The process of physically joining one compatible umbilical or mechanical connector to another such that the connectors will, thereafter, remain joined without continued crew or robotic effort. This includes the opening of any isolation devices and joining of electrical and data pins and sockets necessary to provide full umbilical services. (Modified From EHP-10028 RV Baseline)
Mating Interface	The physical interface that allows two items to come together and mate
Mechanical Interface	A point where two components meet to make a Physical connection.
Payload	Hardware inclusive of scientific, logistic, or technological instruments for utilization purposes. (From EHP-10028).
Pose	The position and orientation of something relative to a known reference frame.
Line of Action	The linear path along which an object travels on approach for mating an interface.

ROBOTIC COORDINATE FRAMES

Documented within this section are definitions of robotic end effector and mating interface coordinate frames that are extrapolated from IERIIS. These coordinate frames are important for understanding the loads and operations described within this document’s best practices and lessons learned. To aid in visualization and application to any specific future system, the placement of coordinate frames has been described and illustrated in such a way that any potential system, regardless of purpose, sensor package, or size should be able to be placed within the frames for reader comprehension. While any future system need not follow the coordinate frames described herein, they are recommended as they align with existing space robotic operational and design practices.

The operational Coordinate Frame (CF) for a robotic manipulator End Effector (EE) should be oriented such that the +x axis is aligned, relative to the EE’s insertion axis. The +z-axis is aligned such that it points away from a chosen interface alignment sensor (ex., a camera, laser, or lidar sensor - where applicable) on the robotic EE. The +y-axis is oriented to complete the right-handed Cartesian system. This is shown on an example EE in Figure 3-1.

When no alignment sensor is present, or if the sensor is installed along the +x-axis, the orientation of the y-axis will be such that it aligns with the longer (primary) axis of the robotic EE mating plane or any bilateral line of symmetry and be coincident to any mating plane. The positive direction on this axis should be in the direction most towards any electrical connectors on the Outer Mold Line (OML) of the EE as shown on an example EE in Figure 3-2.

If the robotic EE mating plane is radially symmetric, then the +y-axis will fall face towards the most prominent clocking feature on the robotic end effector OML. If the entire end effector is perfectly symmetric, then a clocking feature should be added to the design on the OML or mating plane. The +z-axis in this case shall be completed by right-hand-rule. This is shown on an example EE in Figure 3-3

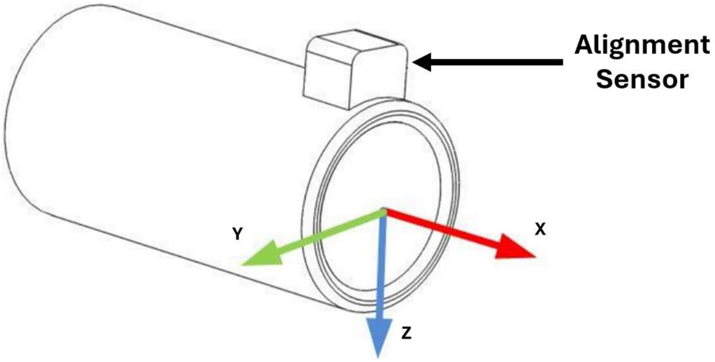

Figure 3-1: Robotic System End Effector Standard Operational Coordinate Frame for End Effectors with Alignment sensors.

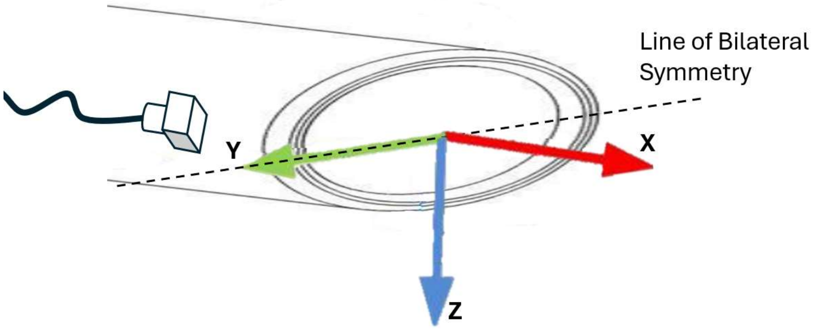

Figure 3-2: Robotic System End-Effector Standard Operational Coordinate Frame for Bilaterally Symmetric End Effectors Without Alignment Sensors.

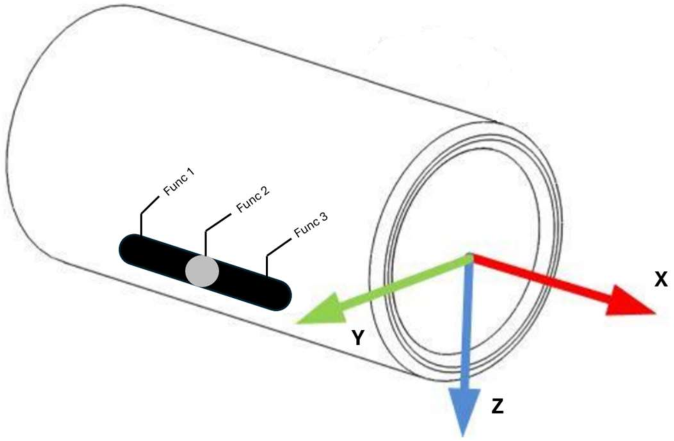

Figure 3-3: Robotic System End Effector Standard Operational Coordinate Frame for Radially Symmetric End Effectors Without Alignment Sensors.

Similarly, a standard operational mating CF will be located on any mating interface that is not actively manipulated and emplaced on cargo, payload decks, rovers, or other areas of use. The EE CF and mating coordinate frame +x-axis should be coincident when interfaces are mated. Ideally, the entire coordinate frame should be coincident, but this may not always be possible.

If applicable, the mating interface frame +z-axis should point radially away from a selected alignment sensor or feature. If no alignment feature is present, or if the feature is centered on the x-axis, then the coordinate frame will be aligned with the fixture mounting plane such that the +y axis points to the most prominent clocking feature on the interface or mounting plane (ex. Antenna, handle, marking, line of symmetry, etc.). The +z axis will be placed to complete the right-handed Cartesian system.

The mating coordinate frame should be identifiable to an approaching crew member or autonomous system by an alignment reference marking (arrow, light, etc.) on the system the interface is placed upon. The reference marking should be used to indicate the direction of the +z-axis of the mating interface reference frame. This marking will provide a CF clocking indication of the +z and +y axis relative to the +x-axis via right-hand rule. Figure 3-4 depicts an example of an interface with a mating coordinate frame which is coincident with the EE operations frame from Figure 3-1. Figure 3-5 depicts a marking implementation for a hypothetical interface on a Cargo Transfer Bag (CTB).

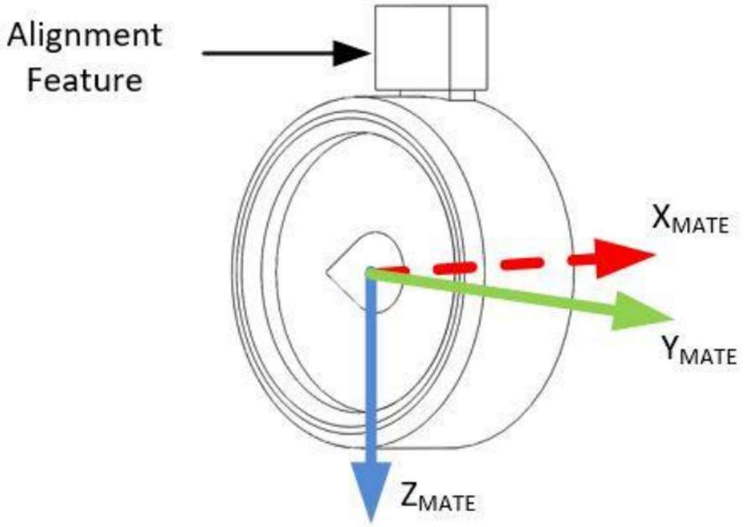

Figure 3-4: Standard Mating Coordinate Frame for Mating Interfaces with an Alignment Sensors.

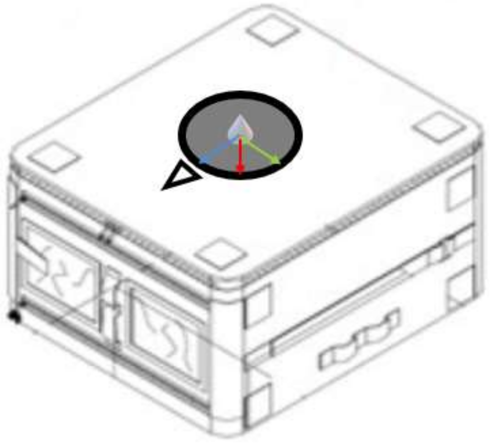

Figure 3-5: Standard Mating Coordinate Frame Implemented on a Cargo Carrier Without Alignment Sensors. In this example the +z-axis is Marked with a Black Arrow.

ROBOTIC INTERFACE BEST PRACTICES

The following list of best practices for robotic interface design are split into two sections. The first section covers EVA and EVR common interface. The second section of best practices does not preclude EVA interoperability but are focused on the robotic interface design needs beyond what is needed for crewmembers as specified for EVA in EHP-10028

EVA AND EVR COMMON INTERFACE BEST PRACTICES

EVRBP-0001 Keep Out Zones

During concurrent EVA and EVR operations, EVA keep-out zones should be clearly defined and indicated around the worksite in a manner perceivable by the robotic system. Any robotic system should have a signal or awareness for when the worksite barrier has been broken.

Rationale: The crew's Situation Awareness (SA) may be stretched while performing EVA and having clearly defined keep-out zones that are indicated in some way (ex., labels, lights, etc.) will provide an added buffer for the crew's safety and awareness, and enable robotic systems to comprehend areas that are dangerous to operate in when crew are present. When robotic systems are in use (automated, IVA operated, or ground operated), they should be able to respond to stimulus (external) or on-board recognition such that when crew enter an area of operations and breaches a robotic workspace (keep-out zone), the robotic system pauses in a safe configuration until crew exits the area. This is done to prevent potential injury to crew through accidental contact.

EVRBP-0002 Softgoods Restraints

Softgoods (ex., EVA handles, tethers), cables, and hoses that are not intended for robotic interaction should be constrained in such a way that they are kept clear of robotic grasp areas, targets, and worksites even after incidental contact or under dynamic conditions.

Rationale: See EVRLL-02

EVRBP-0003 Shared EVA and EVR Grasp Location

Interfaces should be designed such that EVA crew members and EVR robotic systems grasp, apply forces and torques, and lift at the same locations using the same interface

Rationale: Having one interface that both EVR and EVA use for handling will simplify the payload design by reducing the number of interfaces as well as providing a common load path for EVR and EVA. Having a single grasp location also limits potential confusion for both crewmembers as well as robotic operators/agents and prevents duplicate operational planning. See EVRLL-05 for additional insight on shared grasp locations.

EVRBP-0004 Shared EVA and EVR Interface Loads

The forces and torques required for actuation (Push, Pull, Twist, or combinations) and insertion of/into interfaces should be minimized where practical and should not exceed the maximum EVA loads defined within EHP-10028 and NASA-STD-3001.

Rationale: The more force a human class robotic interface requires for actuation the more force and torque a robotic system must react, increasing both mass and system stiffness. This drives many secondary and tertiary impacts into the overall robotic system through increased power needs, system complexity, system safety and sensing needs, thermal system management, volume, reach and workspace size, and cost. Limiting the forces required for EVR activities to the same that a typical crewman can perform in an EVA defines a common and easily achievable goal for the design.

EVR INTERFACE BEST PRACTICES

EVRBP-0005 Robotic Interoperability Standardization

Robotic system interfaces should adopt a set of unified design standards emphasizing interface commonality and interoperability, where feasible, for both the human-robot interface and the robot-hardware interface design.

Rationale: In complex, integrated robotic systems, unified interface standards and a common set of interface sizes and shapes are essential for safety, efficiency, and interoperability. With human-robot operations, standardizing elements of the user interface such as control inputs (ex., input configurations), displays (ex., color coding, iconography), feedback mechanisms (ex., visual, haptic, aural, etc.), and command syntax reduces the training burden for astronauts and ground controllers, ensuring that operators can interact with diverse robotic platforms while limiting the need to learn unique or inconsistent controls. Similarly, standardizing robot-hardware mechanical interfaces (ex., grapple fixtures, tool changes), electrical connectors (ex., power and data pinouts), and communication protocols (Ex. Ethercat, Controller Area Network (CAN), MIL STD 1553), along with limiting the number of physical interface variants, simplifies mission logistics by reducing the need to carry, maintain, and replace multiple unique and/or specialized supporting parts or adapters in environments where mass and volume are at a premium.

From a systems integration perspective, consistent interface design enables plug-and-play compatibility across robotic subsystems, fostering modularity and adaptability in evolving mission architectures. In contingency scenarios, standard interfaces also improve reliability by allowing rapid substitution of hardware and minimizing human error under stress. Furthermore, uniformity in design streamlines testing and validation, lowers development costs, and accelerates the certification process.

By adopting unified interface standards and minimizing size/shape variations, mission teams enhance usability, safety, maintainability, and resilience, all of which are critical for the success of long-duration, high-risk operations on the lunar surface and beyond.

EVRBP-0006 Sequential Mating Concepts of Operations

Interfaces should not expect robotic systems to be able to provide multiple simultaneous actions. Instead, interfaces should expect any operations to consist of several serial actions by a robotic system to accomplish a mate.

Rationale: When doing complex tasks such as robotic outfitting, construction, logistics delivery, or offloading, multiple actions will frequently need to be accomplished by a robotic system to complete an operation. Robotic interface actions could include items such as removal of covers, extension of pins, unscrewing or unlocking features to separate items, and/or rotating levers or pushing buttons to ready a workspace. Several of these actions could be done simultaneously (ex. insertion of electrical pins during a mechanical mate). However, space-rated robotic systems can struggle doing multiple of these functions at the same time, and complex actions make troubleshooting for off-nominal events more difficult. Thus, each action in an operation should be done as its own step/item – ex. remove dust cover and then insert item. Following this BP will allow the interface to be used by less capable robotic systems.

EVRBP-0007 Minimization of Mating Complexity

Where feasible, the complexity of robotic grasped/inserted interfaces should be limited to A) only requiring one concurrent DOF (ex. not require concurrent linear and rotary motion at the same time) and B) be as physically and kinematically resilient to off-nominal forces and grasp locations as possible

Rationale: Space robotic systems, while exceptionally capable, can struggle to provide high forces and torques in multiple axes while simultaneously providing very fine movement and alignments during mating and insertion. For example, interfaces should allow for alignment of the interface and end-effector before applying high forces and torques for mating. Applications where two DOF are concurrently actuated, such as concurrent linear and rotary motion (ex. threading) or concurrent linear motion in two axes (ex. pushing a pin in to overcome a preload, while dragging said pin in a planar motion) may not be achievable for some robotic systems. Therefore, it is ideal to design robotic interfaces such that these actions can be done sequentially, potentially with a release and re-grasp of the system to allow a robotic system to configure into a kinematically advantageous position prior to final insertion/mating. Items such as 38999 connectors should be avoided if possible as they require fine alignment, moderate force, and rotation all at the same time.

Increased resiliency to grasp location will allow for nominal operations to continue even if an ideal grasp location is not achieved (ex. location grasped on an EVA handrail or handle). This is critical in an unstructured environment such as the lunar surface where errors in localization may lead to wide distributions of realized grasp locations. Similarly, having more resiliency for insertion operations allows for successful insertions at greater initial contact misalignments. This additional "slop" in interfaces will be critical for systems that may see significant thermal growth, and elastic deformation under larger loads.

EVRBP-0008 Unique Identification of Payloads and Respective Interfaces

Items that will be grasped by a robotic system should be identifiably distinct from other nearby objects. Reference features should break one or more axes of symmetry to make payload orientation unambiguous. Furthermore, interfaces on similar objects should have a unique identifier (UID) for each instantiation of said objects through sensing (ex., visual identification or RFID).

Rationale: Robotic operations on the Lunar and Martian surface will likely require semi-autonomous or autonomous activities; thus, items that are to be interacted with by robotic systems should have visual or other identifying means by which they can be described. Tasking a robotic system requires a way for the system to comprehend the task and recognize items such as a CTB or a power connector within their environment. Such markings could be on an interface or grasp location but could also be on the item itself so long as its position relative to the interface location is also known. Similarly, when there are multiple items (ex. several cargo bags or connectors) each item should not only be identifiable as what it is but also be uniquely identified relative to other like items (ex. Cargo bag 1 vs Cargo bag 2).

EVRBP-0009 Connection Success Alerts

Verification of successful connections from inserting or plugging in any connector should be provided in at least two dissimilar modalities to the robotic system on the surface.

Rational: When an interface is utilized to mechanically or electrically mate items, there should be two dissimilar methods to allow a robotic system or remote operator to know when the mate is successful and complete. This is critical in instances where mating planes are occluded from views provided by the system. When there is uncertainty if a connection has been made, there can be exceptionally long delays in task completion and occasionally damage can occur if a wrong assumption is made with limited information.

Single point verification (such as power received over pins, or a torque out value) can be triggered through faults or off-nominal conditions. Therefore, a combination of dissimilar feedback such as visual means (lights, color changes, indicators), proprioceptive feedback (torque, force, number of mechanism turns), and electrical/RF (power transfer, communication from other-side) should be used so that faults or off-nominal events do not hinder informational flow of successful connections.

EVRBP-0010 Subject Matter Expertise Interactions

When possible, contact robotics experts (see POCs In Appendix B) within NASA early in hardware and interface development to facilitate discussions on Interface design and interoperability. This aids and will save time for implementation, improve robotic compatibility and functionality, and reduce future schedule, cost, and integration pains.

Rational: Integration and discussion with SMEs and SEI personnel across NASA early in the process will prevent contractual or requirement changes after PDR/CDR level designs have been made and improve the chances of successful compatibility with robotic systems.

EVRBP-0011 Mechanical Alignment Aids

Mating or alignment operations should be assisted by guiding features included on the objects being aligned. These features should be able to support reactionary loads without imparting extraneous loads into the grasp interface and should be verified through worst-case misalignment testing.

Rationale: Much like humans, robots will perform alignment operations through a combination of visual and tactile feedback. Increasing the size of the guiding features allows for more tactile feedback, less precise positioning requirements from the robotic system, and reduces the precision needed for visual feedback and the complexity of the data to interpret. These features should not create so much force that they overcome the grasp of the robot and cause the object to slip.

EVRBP-0012 Marking and Identification of Interface Grasp Location

Grasp locations on the object being robotically manipulated should be visually distinct with contrasting colors and other identifiable features from the rest of the object and the surrounding environment. Where possible, dedicated markers that can be used to establish the location of the object should be included.

Rationale: After long periods of use in a dusty environment, it can become hard to recognize distinct segments of an object through visual perception alone, especially in harsh lighting conditions. Color contrast and other methods of visual distinction, such as three-dimensional targets, are imperative for efficient object recognition.

EVRBP-0013 Interface Orientation Preference

Objects with preferred orientations or directions of motion should have those preferences clearly marked.

Rationale: Some objects that require manipulation may be keyed, such as radially asymmetric connectors, or be sensitive to the direction of the gravity vector in the case of heavy payloads. If those requirements must be followed, they should be easily identifiable with a standard, recognizable marking (ex. fiducial, visual markings, etc.).

EVRBP-0014 Visual Grasp Target Identification

When utilizing visual targets to localize interfaces (ex. fiducial markers, retro-reflective tape), targets should be placed non-planar (relative to the grasp interface) whenever possible. If possible, multiple fiducials should be used and placed on differing cross-planes (each out of plane) whenever possible.

Rationale: Fiducials and other planar targets struggle to provide accurate pose information for rotations that are out of the rotational plane (pitch and yaw). However, if they are placed out of plane (ideally several, all in different cross-plane orientations) or are otherwise designed to be three-dimensional, it significantly increases the accuracy of the estimation of the out of plane rotations when using computer vision and for crewed operation using overlays.

EVRBP-0015 Defining Interface Misalignment Envelope based on Perception Accuracy

The precision/accuracy of the inputs to the pose estimation (ex. sensors), and the precision/accuracy of the localization methodology itself, should be used to quantify requirements for allowable grasp misalignment.

Rational: The more accurate the location and pose of an interface can be calculated by a robotic system's sensors, the less compliant the system need be, and the less misalignment compensation capability is required for successful grasping operations. For example, if a visual *sensor is used to identify a 6 DOF pose of an interface but can only accurately localize the interface (3σ/99.7% accuracy) within a 0.5-meter radius, the interface should be designed with allowance for misalignments of at most 0.5 radial meters (see EVRBP-11).*

EVRBP-0016 Flexible Goods Interfaces

Flexible goods (ex. straps, Velcro, fabric handles) should not be utilized by robotic systems as an interface. However, if flexible goods must be used, they should have interfaces that provide some rigidity that can be grasped by a robotic system. These interfaces should be designed in such a way that they will always be available to grasp and in an expected orientation.

Rationale: Rigid interfaces are more reliable for robots to interact with compared to flexible interfaces. Flexible interfaces require additional work to understand the precise position and orientation to interact with because they can be in a variety of configurations which must be determined for each interaction. If flexible interfaces must be used, integration of elements that make the interaction point more rigid and reliable will lead to a greater chance of success. If soft goods and tethers are to be utilized in an interface then they should be appropriately modeled throughout the design, to avoid possible interference during operations and assembly.

EVRBP-0017 Adding Compliance to Relieve Misalignment Loads

If alignment is required between two interfaces, the contact point between those interfaces should be designed with some level of force and torque compliance when possible. The amount of physical compliance required should be informed by the expected level of sensor accuracy, robotic positioning capability, the amount of forces and torques the system can provide and react, and the system's tolerance to failure. In cases where the interfacing systems are unknown, the maximum practical compliance should be pursued.

Rationale: When robots are aligning two interfaces, there will likely be some amount of misalignment, which might be somewhat mitigated if there are guiding features on the interfaces (see EVRBP-11 and EVRBP-15). Adding compliance to the interaction points will help reduce the forces and torques imparted on the interaction surfaces during this process, allow for self-correction of misalignments, and will allow for smoother transitions to attachment, avoiding harsh, discrete interactions.

EVRBP-0018 Grasping in a Gravity Field

When handling large payloads in the presence of gravity, grasp alignment should be such that the gravity vector goes through the grasping interaction point and the center of mass as closely as possible to limit the torques reacted at the interface.

Rationale: The torque felt at the interaction point, as well as the internal forces and torques that a robot must provide to manipulate a payload will be amplified by the distance between the center of mass of the payload and the interface, perpendicular to the gravity vector. If the interaction point and the center of mass are aligned in such a way that during nominal operations, the gravity vector runs through both of them, the resultant forces and torques will be minimized.

ROBOTIC INTERFACES LESSONS LEARNED

EVRLL-0001 LINE OF ACTION

Having the line of action for grasp and insertion/extraction be the same and coincident with the primary axis of the end effector (x-axis) simplifies operations. Having actions take place in planes orthogonal to the view of boresight cameras can be confusing to operators and complicate software that relies on having visual perception along the axis of movement. Furthermore, when the line of action for grasp and insertion/extraction is in line with the EE x-axis (See Figure 3-4), it aligns the vector of force application with the strongest axis of a robotic system. In addition, for many commercial robotic manipulators, applying insertion/extraction along the EE x-axis avoids applying forces through the rotational axis (ex. the motor is applying the force through torque) of any wrist motors.

EVRLL-0002 COVERS, TETHERS, AND SOFT GOODS

Covers and soft goods such as multi-layer insulation help protect components from the extremes of non-terrestrial environments, keeping dust and debris off sensitive surfaces or providing thermal protection. These covers can, however, pose a challenge to robotics as shown in Figure 5-1. Soft goods can billow or shift in lower gravity, impeding robotic access or creating unexpected contact points with the surrounding worksite that lead to counter-intuitive forces working against the robotic operation. Soft goods can also get trapped between the component and its surrounding worksite, preventing proper placement. These types of covers should be securely fastened down, particularly around robotic access points or near worksite structure.

Cables, tethers, and wires can add constraints to a robotics workspace, as they can limit reach and rotation of the system. Free hanging soft goods also increase the likelihood of inadvertent snags or collisions on areas of the robotic manipulator that are not always monitored for forces and torques (ex. base). In some instances when robotic systems are handling payloads/connectors with cables, avoiding system singularities can create issues in completing the task as the cables may prevent or limit rotations of ±180 degrees (ex. joint reposition or flip).

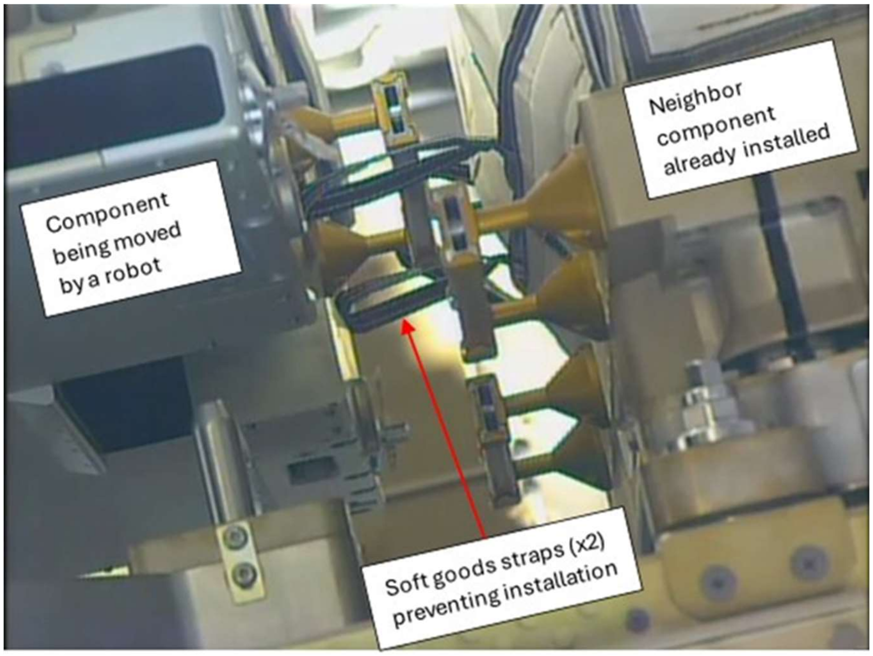

Figure 5-1: Example of International Space Station Robotic Operations Impeded by Soft Good straps

Hard covers or components attached to a worksite with tethers can get entangled in surrounding structure or on a component and prevent the robot from completing its task as shown in Figure 5-2. A means of robotically securing the cover away from the active worksite is desirable to avoid impeding the main robotic task, though it also adds time to the overall operation.

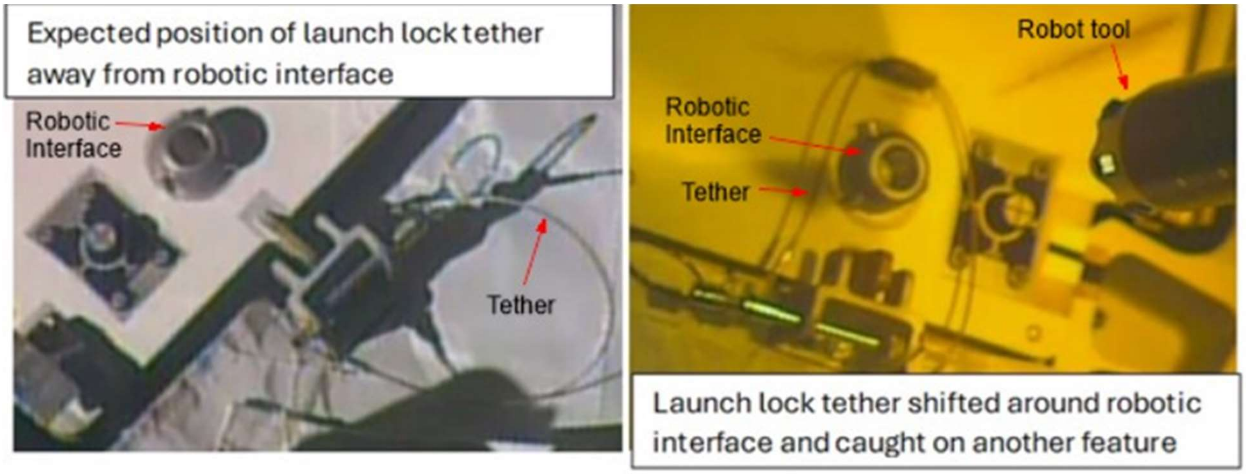

Figure 5-2: Example of International Space Station Robotic Operations Impeded by Tethers and Semi-rigid Wire Handles

EVRLL-0003 CRITICALITY OF FREQUENT INTERFACE TESTING PRIOR TO FLIGHT

Over the life of the ISS, ground testing has uncovered several significant design issues in robotic mechanisms that were not caught by analysis and/or CAD inspections. Repeated experiences have shown that analysis and inspection are not adequate to verify or validate robotic interfaces against their requirements. This is in part because analysis and inspection are predicated on how the validator anticipates robotic systems and interfaces to be utilized. Thus, to ensure functionality upon flight, all robotic interfaces should be tested on the ground in analogous conditions with analogous systems and operations.

An example of this was on the Materials International Space Station Experiment Flight Facility (MISSE-FF). MISSE Materials Science Carriers (MSCs) and avionics boxes used an early form of the Oceaneering GOLD-2 mechanism coupled with a ball/socket interface to stabilize the MSC base during launch. Testing discovered potential binding/jamming issues associated with the ball/socket interface as well as an overlooked internal hard stop on the bolt drive mechanism that resulted in internal damage. Such issues were not discovered through inspection and analysis alone.

EVRLL-0004 TASK ANALYSIS AND FUNCTION ALLOCATION

One of the most critical lessons learned in the development of robotic systems involving human-robot interaction (HRI) is the importance of completing thorough Task Analysis and Functional Allocation Analysis early and iteratively throughout the design lifecycle. These analyses are essential for understanding the operational context, identifying the roles and responsibilities of both human and robotic agents, and ensuring that system functions are allocated in a way that optimizes performance, safety, and usability.

Task Analysis provides a structured understanding of the goals, actions, decisions, and information needs associated with each task the system must support. In HRI contexts, this analysis helps uncover not only what tasks need to be performed, but also how humans and robots will coordinate, communicate, and adapt to dynamic conditions. Without this insight, there is a high risk of designing robotic behaviors or interfaces that are misaligned with user expectations or operational realities.

Functional allocation analysis builds on task analysis by determining which agent (human, robot, or combination) should perform each function. This decision must consider factors such as cognitive workload of the user, physical capabilities of the crew and/or robot, reliability, and adaptability. Inappropriate allocation can lead to over-automation, under-utilization of human strengths, or increased risk of human error. For example, assigning a robot to perform a task requiring nuanced judgment or improvisation may result in degraded system performance or mission failure.

These analyses must be iterative and updated regularly throughout the design process. As system requirements evolve, prototypes are tested, and operational feedback is gathered, both task demands and the capabilities of the human and robotic agents may change. Iterative refinement ensures that the system remains aligned with user needs and mission goals, and that any disparities in function allocation are identified and corrected before they become costly or hazardous. Iteration also supports the integration of emerging technologies or updated operational procedures without compromising human-system performance.

The systematic application and continuous refinement of task analysis and functional allocation analysis are vital to the success of robotic systems involving HRI. These processes help ensure that the system is not only technically capable but also operationally effective, human-aware, and resilient in real-world conditions.

EVRLL-0005 GENERALIZED GRASPING AND SECURING PAYLOADS

Analysis should be done for the grasp of any interface to make sure that the item being grasped is secured for all potential applied loads. This includes the grasping forces and torques required to overcome gravitational loads (weight) and inertial loads (acceleration) but also any loads that will be put into the grasp to place and mate an item or overcome the forces and torques to be applied with the item itself (ex. a tool that is being grasped which itself will interact with another interface).

Soft EEs used for grasping in terrestrial applications work well for securely grasping items with frictional and normal forces, but do not have the material properties to survive in lunar environments. While testing has shown that parallel grasping can pick up many human interfaces, they struggle to apply the forces and torques required to utilize said interfaces. Many human connectors are not shaped to accept grasping by rigid parallel jaw grippers due to human ergonomic considerations.

Testing within NASA has shown that adding a minimum number of recesses, keys, or flats on human interfaces greatly increases the ability of robotic systems to apply force with minimal impact on human useability. Such design features can also help lock the grasp in position with mirrored features on an end effector (ex. keys for key slots, protrusions for recesses, etc.) and relax the required force to maintain the grasp through robotic operations,

The location of features to allow force application is highly dependent on the application and directionality of forces and torques. Therefore, design modifications should be considered for every specific application/interface investigated for robotic use and adjudicated with the EVA office on a case-by-case basis.

EVRLL-0006 INTEROPERABILITY AND STANDARDIZATION FOR ROBOTIC INTERFACES

As alluded to in EVRBP-05, it is critical that systems should standardize robotic interfaces which emphasize commonality and interoperability. Not adhering to this BP from the onset of a project can cause exceptionally high operational costs and complexities over the full lifecycle of a system or mission architecture. Over the life of the International Space Station (ISS), over 9 separate robotics-compatible payload standards have been developed and are routinely used on the orbiting laboratory. Early ISS systems developed for the space station were primarily designed for EVA and later adapted for robotic use. Two principal interface types were developed and have widespread use, one clocked and circular (Micro-conical in Figure 5-3) and one rectangular with aggressive chamfers (H-Fixture and Micro-fixture in Figure 5-3). However, the OTCM of the SPDM on orbit (Figure 5-4) can only natively interface with the latter rectangular connectors which are interoperable to one another.

Due to the lack of upfront standardization, the only way to utilize Micro-conical interfaces is with an adapter or tool called the Remote Micro Conical Tool (RMCT), Figure 5-5. Such tools and adapters, which are developed after the fact to allow different sets of interoperable interfaces to work together, are inherently complex, costly to develop, and have continued operational costs for maintenance. Experience has shown that significant operational expenditure and headache can be avoided with a reasonable amount of developmental forethought towards how varying interfaces will be interoperable at a minimum required functional threshold.

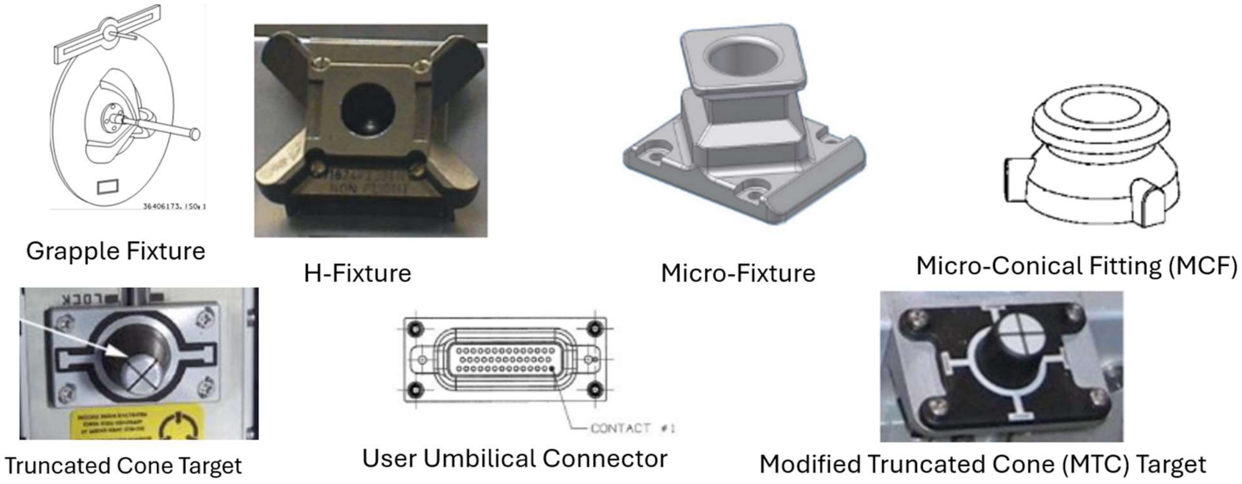

Figure 5-3: Graphic Representing the various robotic interfaces, targets, and connectors utilized by the ISS Mobile Servicing System (MSS).

The lesson on commonality and interoperability is also extensible to grasp targets and visual localization aids. If varying sensor modalities and concept of operations are needed to localize different interfaces, then a robotic system may not be able to use all needed interfaces. Forethought should be put into the types of sensing equipment that robotic systems will have in the anticipated operational environment and into standards for alignment built for the operational environment.

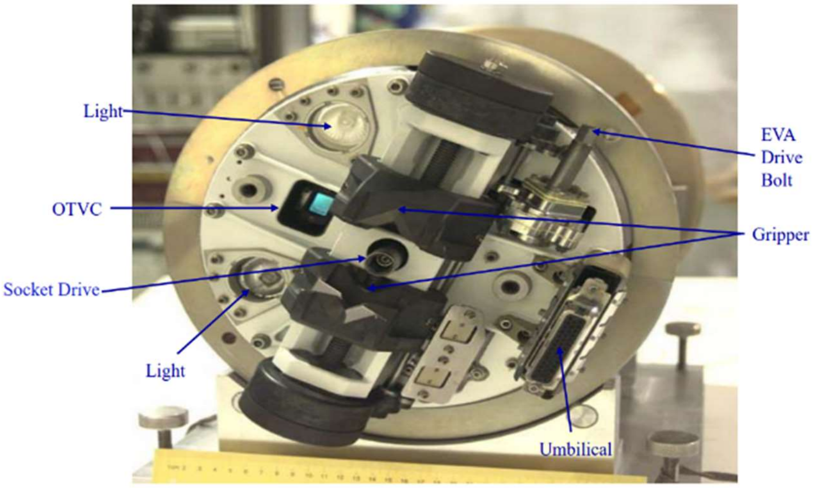

Figure 5-4: The ISS SPDM's OTCM Robotic End Effector

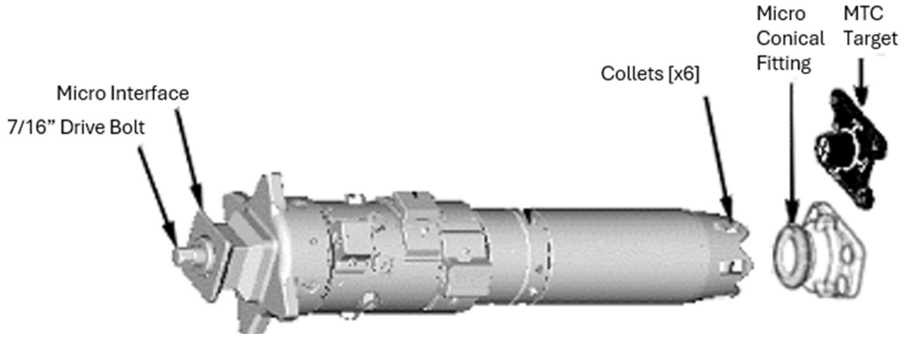

Figure 5-5: The RMCT was designed, in part, to adapt between the Micro Interface which the OTCM can grasp, and the Micro Conical Fitting.

EVRLL-0007 CONSIDER FUTURE OPERATIONS WHEN PLANNING FOR ROBOTICS

A best effort should be made to plan for future operations that may require robotic support along the lifetime of the mission. The best practices outlined in this document are most effective when applied as early in the mission lifecycle as possible. If robot operations are deemed to be required on systems that were deployed without robotic compatibility in mind, the program will have to choose between spending EVA time to retrofit the system for robots or designing and launching complex adapter hardware. Both options incur significant costs.

The ISS robotics architecture was largely defined, in a short amount of time, to support assembly operations. Design decisions made during this phase of planning drove significant impacts to post-assembly robotic operations. The original Mobile Transporter concept contained rails that spanned the entire length of the truss elements, including the outboard array elements. These outboard rails were removed from the ISS baseline during manifest reviews ahead of Space Shuttle retirement in 2011. As a result, ISS robotics are limited to basepoints inboard of the solar arrays, and ~60 of 250 robotically compatible ORUs are now out of robotic reach thus requiring EVA to replace. Post-assembly array & battery upgrades have also been adversely affected due to this lack of robotic access.

In post-Columbia ISS baseline reviews, SPDM readiness & manifest capability was in doubt, so robotic access to otherwise robotically compatible ORU and spares was not prioritized when trying to address thermal challenges for early ISS attitudes & Shuttle flight profiles. As a result, many robotically compatible spare parts were launched covered by robotically incompatible soft good covers preventing use of robotics for maintenance operations. Subsequently, many hours of EVA time have been dedicated to removing these covers to reenable the option for robotic maintenance & recovery.

ROBOTIC INTERFACE DESIGN CONSIDERATIONS

In addition to direct lessons learned and best practices within the robotics community, there are also many considerations that should be considered for the systems on either side of the interface, which can influence requirements levied on a robotic interface itself. In general, these considerations either come from the robotic system utilizing the interface, or the environment in which the interface exists.

ROBOTIC DESIGN CONSIDERATIONS THAT INFLUENCE INTERFACES

Interface and robotic manipulator design go hand in hand. Just as an interface can drive robotic system requirements, so too can robotic capabilities influence interface designs. In practice such requirements are cyclical in nature prior to PDR unless an a-priori interface or robotic system is known. These considerations should help guide such cyclical conversations.

Reacting Loads and Moments with a Mobile Base

Any robotic interface must have enough strength to react the moments and torques created by the weight of the payload being interfaced with. When a mechanical interface is grasped, the aforementioned loads and moments must be reacted at the base of the robotic system. Terrestrial applications of robotic serial manipulators typically react loads through a fixed base, or a large platform on a prepared surface. On planetary surfaces, most robotic manipulators will be on mobile platforms. In such implementations, force/torque reaction calculations of the integrated system should also take into account the acceptable bearing load of the loose regolith supporting the robotic operation, the tip-over load of the mobile system, the strength of the attachment point to the mobile system, and the allowable slope for any manipulation task.

Different allowable interface loads, grasp locations, and robotic movements may be needed in different situations, depending on the soil composition supporting the mobility system (ex. Loose sand vs gravel vs solid rock) and the workspace of the robotic system mobility platform in question. Robotic system and interface designers should work with mobility platforms to understand imparted load, tip-over, and operational requirements.

Managing Inertial and Gravitational Loads

Grasping interfaces designed for humans are often placed with two-handed operations in mind. For example, a heavy suitcase will likely have a handle on both ends to allow a person to use both arms to lift while keeping the center of mass in a manageable location. This is acceptable for a robot if it also happens to have two arms. However, many robotic systems are not capable of this bimanual manipulation, meaning that different load paths will need to be considered in the design of the object being manipulated and the evaluation of the robot’s capabilities. Large moments caused by large distances between the payload center of mass and grasp point are usually the limiting factor when determining a robot’s load capacity. See EVRBP-18 for additional information.

Computation Power

As robotic tasks become more complex, they will require more computational power to execute. Computational power needs are impacted by several factors but can quickly scale up with the number of sensors present on a system, the amount of data which needs to be processed and contextualized, and the amount of decision making on said data which is done in-situ. While terrestrial systems are able to easily scale to the required computational needs of a robotic system, space-grade compute is significantly harder to scale. Items such as Graphical Processing Units (GPUs) are inherently more difficult to radiation harden than Central Processing Units (CPU) and Floating-Point Gate Arrays (FPGAs).

Therefore, it is best to consider the available computational needs of a system early in the design cycle. While initial prototyping may be exceptionally easy with terrestrial products, the code and system will have to undergo qualification testing to show its robustness to space, lunar, and Martian environments. Reducing computing needs earlier in the design cycle through practices such as mechanical design for control (ex. optimizing mechanical designs to simplify control paradigms) and adding resiliency and robustness to mechanical and electrical systems.

LUNAR ENVIRONMENTAL ROBOTIC INTERFACE CONSIDERATIONS

EVR surface operations will expose interfaces to a variety of harsh conditions. When interfaces are in use with a robotic system they serve as active mechanical systems, subjected to all the environmental challenges that accompany spaceflight mechanisms.

Lighting

When utilizing any methods for sensing which rely on incident light (ex. solar illumination) it is critical to consider the lighting type (ex. IR, Visual Spectrum) and quality (ex. intensity, incident angle) in operational areas. Without an atmosphere or means to diffuse or diffract light shadows are nearly, if not completely, devoid of light on the lunar surface. As such, lunar night and lunar shadows are nearly synonymous. This can even be seen at equatorial high noon during Apollo missions, Figure 6-1.

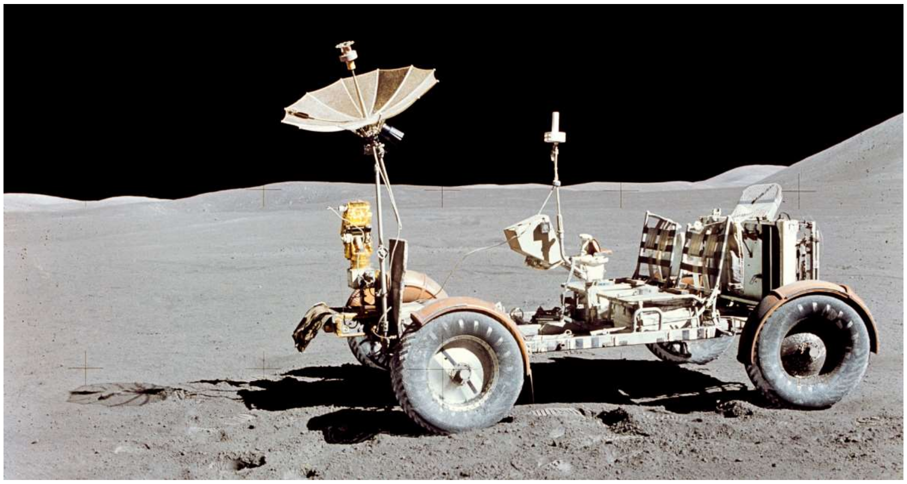

Figure 6-1: Image of Apollo LRV near Lunar Noon showcasing Shadow Darkness

Areas at the south pole are lit at extremely oblique angles between 1 and 2 degrees of altitude. The low incident angle of sunlight interacts with Lunar topography (Figure 6-2) to create large dynamic shadowed areas. Dynamic shadows add complexity to determining areas of lunar night on the south pole. Thus, determining the availability and quality of light for operations on the lunar surface requires both geospatial and temporal knowledge. NASA has provided publicly available simulations of lunar surface south pole lighting for years 2023 to 2030.

When designing robotic and interface sensors it is important to understand the operational constraints that lighting adds to the system. Having redundant modalities of sensing (ex. vision, lidar, and radar) can reduce operational constraints and increase environmental resiliency. To ensure reliable mating, robotic interfaces must be designed to mitigate self-eclipsing of ambient sunlight. This may require using supplemental lighting for fiducial visualization when necessary.

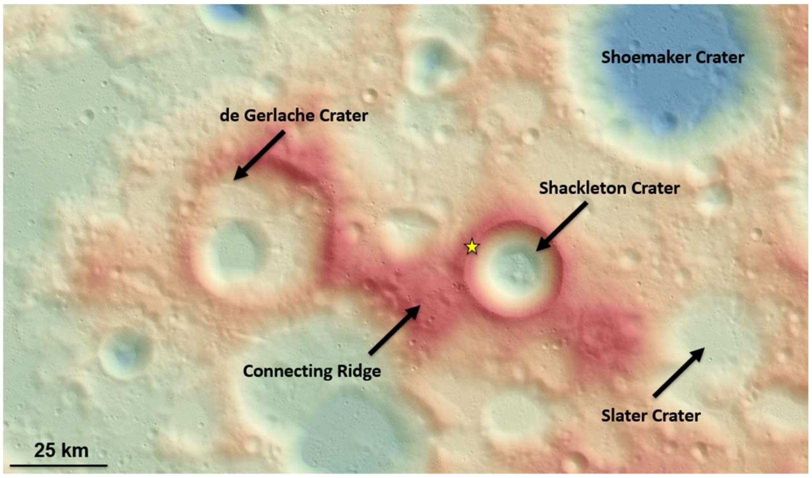

Figure 6-2: Lunar South-Pole Topography

Thermal Considerations

The lunar surface is one of the most thermally challenging operational areas in the solar system with respect to total daily temperature differential. While this document neither covers the specific regional temperatures to design interfaces to nor expected temperature differentials at grasp/mate, the Design Specification for Natural Environments (DSNE) and Lunar Surface Databook documents called out in the reference material can help provide those specifics. For a local reference, Seasonal Temperature Averages for the Lunar South Pole are Shown in Figure 6-3. When designing robotic interfaces for these temperatures there are primary, secondary, and tertiary effects to consider for a specific system.

The primary thermal consideration is that a grasp or mating interface needs to interface with its apposing side at significant temperature differentials. It is likely that one side of the interface will be in full sunlight upon approach, while the other side will have been in shadow (self-eclipse) for a significant period. Fit checks should be performed with the maximum required thermal differential required to ensure that thermal expansion does not create interference and prevent mechanical mating and electrical pin insertion (if applicable).

The secondary consideration is that any interface mechanisms will need to function at any given temperature extremes, potentially after sitting at very low temperatures for a winter season. While mobility systems and cargo will provide keep-alive power for critical avionics and payloads, distal interfaces may not be kept warm. Heaters, batteries, and other systems for thermal conditioning may be added for additional tertiary considerations.

Finally, a tertiary consideration is the additional mass penalties that an interface’s thermal management system would create. For large systems, surviving the lunar night can be a significant energy demand, and thus battery mass driver. Smaller and distally located systems will need more energy per base unit mass than central avionics systems. Any additional energy and battery mass requirements should be understood and incorporated into the total mass rating of any robotic interface (if applicable).

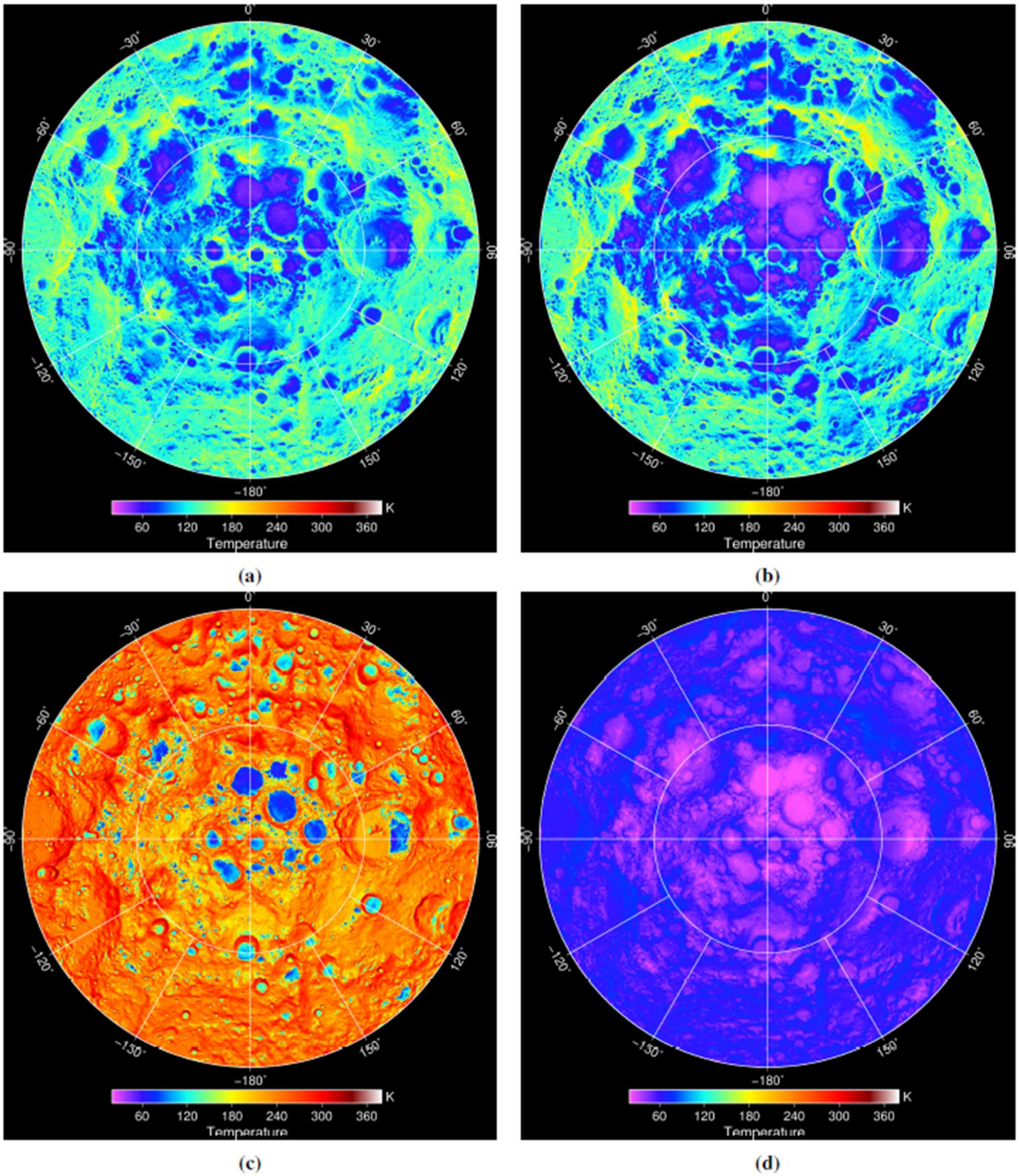

Figure 6-3: LRO Diviner Data Showing the Average Surface Temperature During a) Southern Summer and b) During Southern Winter. c) Shows the Maximum Surface Temperature During the Southern Summer, while d) Shows the Minimum Surface Temperature During the Southern Winter. Data available from the [Planetary Data System]

Voltage Differentials and ESD Isolation

<Reserved – FWD-#001>

Radiation Susceptibility

<Reserved – FWD-#002>

Inconsistent Communication

As systems progress further away from the Earth, the challenges of communication latency and dropout become more prevalent. All systems will need to maintain some level of autonomy to be able to manage themselves, and robotics are no exception. When planning to operate a system through robotics, the concept of operations must be robust to this lack of real time oversight. A common practice, sometimes called supervised autonomy, is to plan multiple operations in sequence to be executed with a single operator command. The time horizon of this operational sequence can be tailored to the specific environment and task.

Dust

Dust should be at the forefront of any lunar surface interface design. The fine particulate sizes of dust on the lunar surface create uncertainty to the state of contamination of surfaces and increases opportunities for contamination to occur. The small sizes and low lunar gravity allow for electrostatic instead of gravitational forces to dominate the distribution of dust and allow it to stick to anything which also carries a charge, Figure 6-4.

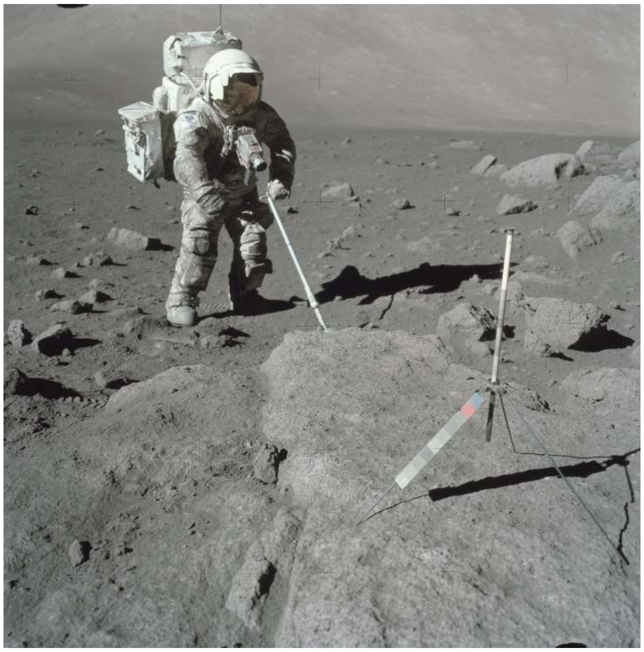

Figure 6-4: Jack Schmitt collects a lunar sample During Apollo 17 EVA 2 showing The Amount of Dust Accumulated on his Apollo EVA suit after only 1.5 EVAs.

The dust itself is not weathered or worn but instead is jagged and abrasive to mechanisms, suits, and human skin and lungs. Designing for lunar regolith and dust in interfaces is a challenge because, just like on earth, soil/regolith properties are highly dependent on their location. Wide variations in regolith properties across the lunar surface may allow nominal operations for interfaces in one area, while degrading performance in others. The problem is compounded due to our knowledge of regolith properties only aligning with the locations of the Apollo landings and not the Lunar South pole where NASA currently targets operations to occur.

While lunar dust creates a direct environmental concern for designers, it also exacerbates other lunar environment challenges such as thermal and lighting considerations. Dust can easily obscure unprotected cameras or sensors and even reduce the efficiency of radiators and solar panels. Over the past several decades NASA, industry, and academia have created technologies and processes for managing and mitigating the effects of dust. Some of the technologies created range from passive coatings and airlock filters to electrodynamic dust shields and electrostatic sprays.

The keys to managing lunar surface dust effects on interfaces are the ability to 1) Tolerate dust Exposure through resilient systems and dust tolerant mechanisms, 2) Have the ability to detect or monitor dust on sensors and interfaces, 3) Minimize dust ingress into systems, 4) Have the ability to remove dust, if it is determined to be detrimental to operation. All these items should be considered and incorporated into designs early and thoroughly tested in dusty environments.

Additional information on how to test systems in dust can be found in NASA-STD-1008, which is detailed in Table 2-1: Reference Documents. Tests also may use different simulants of lunar regolith depending on the properties which are of concern to those running tests (ex. abrasion, size, cohesivity, etc.). To help, NASA JSC's Astromaterials Research & Exploration Science group has created a list of testing facilities along with a simulant advisory council to aid NASA and industry teams.

MARTIAN ENVIRONMENTAL ROBOTIC INTERFACE CONSIDERATIONS

<Reserved – FWD-#006>

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APPENDIX A: Acronyms and Abbreviations and Glossary of Terms

Table 7-1: Acronyms and Abbreviation List

BP	Best Practice
CAN	Control Area Network
CDR	Critical Design Review
CFS	Coordinate Frame System
CPU	Central Processing Unit
CTB	Cargo Transfer Bag
DOF	Degree of Freedom
DOF	Degree Of Freedom
EE	End Effector
EVA	Extra-Vehicular Activity
EVR	Extra-Vehicular Robotic activity
Ex.	Example
FPGA	Floating-Point Gate Array
GPU	Graphical processing Unit
HRI	Human Robotic Interaction
IERIIS	International External Robotic Interface Interoperability Standards
ISS	International Space Station
LL	Lesson Learned
LRO	Lunar Reconnaissance Orbiter
MSS	Mobile Servicing System
MTC	Modified Truncated Cone
OML	Outer Mold Layer
ORU	On-orbit Replacement Unit
OTCM	ORU Tool Change out Mechanism
PDR	Preliminary Design Review
POC	Point of Contact
RFID	Radio Frequency Identification
SEI	System Engineering and Integration
SME	Subject Matter Expert
SO	Standard Operations
SPDM	Special Purpose Dexterous Manipulator
SSRMS	Space Station Remote Manipulator System
UID	Unique Identifier

APPENDIX B: NASA POCs

Table 7-2: Robotics POCs at NASA with Expertise for Robotic Interface Designs and Considerations

- STMD Principal Technologists: https://www.nasa.gov/stmd-principal-technologists/
- JSC Front Door: https://www.nasa.gov/reference/jsc-robotics/

APPENDIX C: Planned Forward Work

Table 7-3: List of Forward Work for Document

FWD work ID	FWD Work Description	Planned Release
FWD-#001	Expected voltage differentials for mating power connectors that have a supplied voltage are expected to be covered in another document (Ex. EHP-10069). However, any interface will likely have a voltage differential at contact due to electrostatic accumulation. FWD Work will cover expected voltage differential at contact based on materials, and proper grounding, bonding, and insulation techniques to protect interfaces	REV A
FWD-#002	FWD work to provide guidelines and consideration for interface radiation susceptibility and mitigation required on the lunar surface.	REV A
~~FWD-#003~~	~~Dust is a critical consideration for interfaces operating on the lunar surface. Dust resiliency and/or mitigation will need to be evaluated. FWD work is to clearly define ways to test/investigate dust resiliency.~~	~~Baseline~~
FWD-#004	Creation of a Best Practice for Relative Navigation accuracies and conops	REV A
FWD-#005	Lesson Learned from LaRC on Connection Success Alerts	REV A
FWD-#006	Additional Environmental Considerations for Martian operation will be incorporated and added as they become applicable	TBD
FWSD-#007	Incorporation of best practices as it relates to cable backshells and positions of wire protrusions on electrical connectors for the lunar surface	REV A