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Future Exploration Missions' Tasks Associated with the Risk of Inadequate Design of Human and Automation/Robotic Integration

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Acronyms and Definitions

ARRV	Asteroid Robotic Retrieval Vehicle
CHM	Crew Habitat Module
ConOps	concepts of operations
DAV	Descent/Ascent Vehicle
DRM	Design Reference Mission
DSH	Deep Space Habitat
EAM	Exploration Augmentation Module
ECLSS	environmental contol and life support systems
EDL	Earth entry, descent, and landing
EVA	extra-vehicular activity
FDIR	Fault Detection, Isolation, and Recovery
HARI	Human and Automation/Robotic Integration
HAT	Human Spaceflight Architecture Team
HFBP	Human Factors and Behavioral Performance
HP-HEO	High Perigee-High Earth Orbit
HRP	Human Research Program
ISRU	in-situ resource utilization
ISS	International Space Station
LEO	low Earth orbit
LM	Logistics Module
MET	Module Equipment Transporter
MMSEV	Multi-Mission Space Exploration Vehicle
MPCV	Multipurpose Crew Vehicle
MTV	Mars Transfer Vehicle
NASA	National Aviation and Space Administration
NEA	near-Earth asteroid
SHAB	Surface Habitat
SLS	space launch system
SPEV	Small Pressurized Exploration Vehicle

Future Exploration Missions' Tasks Associated with the Risk of Inadequate Design of Human and Automation/Robotic Integration

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1. Background

1.1 Goal

NASA's Human Research Program (HRP) funds research efforts aimed at mitigating various human health and performance risks, including the Risk of Inadequate Design of Human and Automation/Robotic Integration (HARI). As such, within HRP, the Human Factors and Behavioral Performance (HFBP) Element tasked an evaluation of future HARI needs in order to scope and focus the HARI risk research plan. The objective was to provide a systematic understanding of the critical factors associated with effective HARI that will be necessary to achieve the future mission goals for near- and deep-space exploration. Future mission goals are specified by NASA Design Reference Missions (DRMs) that are pertinent to the HRP. The outcome of this evaluation is a set of NASA-relevant HARI tasks, factors, and interactions required for exploration-class missions.

1.2 Design Reference Missions

NASA currently has a large set of proposed DRMs. HRP focuses on a selected set that is defined in the Human Research Program Requirements Document (HRP-47052). All of the Human Health and Performance Risks, including the Risk of Inadequate HARI Design, are evaluated against these DRM categories. These HRP-relevant DRMs are summarized in Table 1. For example, low Earth orbit (LEO) DRM category includes International Space Station 12-month long missions (ISS12) and Commercial Suborbital missions. Deep Space Habitation DRMs include Lagrange Point 1 or 2 (L1/L2) Habitation and Asteroid Visits. For the purposes of this project, the HARI Task Scoping only assessed missions beyond LEO, namely Deep Space Sortie, Lunar Visit/Habitation, Deep Space Journey/Habitation, and Planetary Visit/Habitation.

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Table 1. HRP DRM Categories

DRM Categories	*Mission Duration*	*Gravity Environment*	*Radiation Environment*	*Earth Return*
LEO	6 months	Microgravity	LEO–Van Allen	1 day or less
LEO	1 year	Microgravity	LEO–Van Allen	1 day or less
Deep Space Sortie	1 month	Microgravity	Deep Space	Less than 5 days
Lunar Visit/Habitation	1 year	1/6 G	Lunar	5 days
Deep Space Journey/Habitation	1 year	Microgravity	Deep Space	Weeks to months
Planetary Visit/Habitation	3 years	Fractional	Planetary	Months

1.3 Assessment Method

In order to arrive at a systematic and comprehensive set of HAR tasks and factors for future missions, each HRP DRM was reviewed and analyzed. A team of HARI experts from across different centers and with varied backgrounds, collected background information for each DRM, such as published papers, reports, and presentations. Team members were assigned to a specific DRM. The resulting analysis identified HAR tasks and factors. This "bottoms-up" approach was selected in order to drive the HARI research plan (HRP's HARI Path to Risk Reduction) research tasks and priorities based on future DRM needs.

The human-automation-robotic tasks are those tasks delineated in the DRMs. Since some DRMs were less mature than others, additional materials such as NASA's Technology Roadmaps, NASA-sponsored workshop proceedings and review articles were included in the assessment, with specific attention paid to advanced automation and robotic agent operations. These are tasks that operators in spaceflight or on Earth must complete using some automated or robotic system. Additionally, the type of integration and/or interaction required to complete the task was identified or assumed by the evaluating team. Based on the required HAR tasks and required HAR interactions, the key HAR factors for future DRM missions were derived (Figure 1).

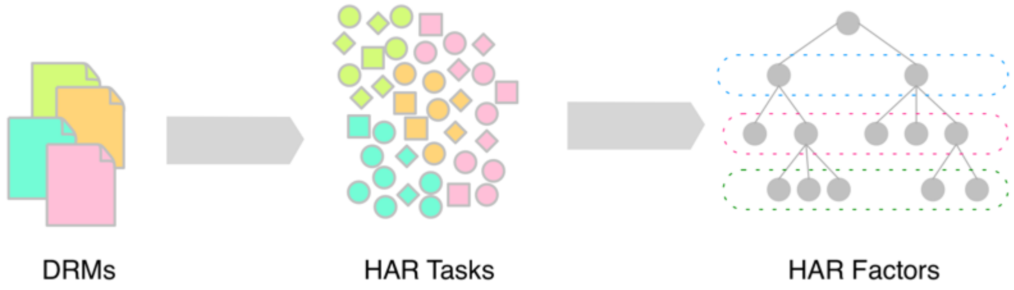

Figure 1. HARI task scoping assessment process overview.

2. Human-Automation-Robotic Tasks

The first objective was to systematically identify all the HAR tasks that could be present in future NASA missions. A HAR task was defined as a task an operator has to interact with a system that has automation and/or robotic componenets. Often task analyses are completed in order to evaluate human-machine interactions in systems. Traditionally, task analysis is defined as "the study of what an operator (or team of operators) is required to do, in terms of actions and/or cognitive processes, to achieve a system goal" (Kirwan and Ainsworth, 1992). Since the HARI Task Scoping project focused on mission concepts and architectures (as described by the DRMs), the identified tasks are high-level descriptions. Assuming further specificity or task decomposition would not have been beneficial as the mission architectures are described at high levels. It would have been too speculative to identify HAR task decompositions at the subtask or cognitive decision level. Hence, the identified HAR tasks remained at the descriptive level.

In order to achieve a systematic evaluation, an assessment framework was outlined. Using this framework, different team members evaluated the various DRMs summarizing similar sets of HAR tasks. This methodology allowed comparison across DRMs. The assessment framework consisted of an organized collection of HAR tasks. The HARI expert team defined a broad set of possible HAR tasks. All HAR tasks were considered—those performed by crew in flight and by ground controllers on Earth. Tasks are classified into four categories in order to facilitate the DRM assessment. The categories, further described below, are Spacecraft Guidance, System Management, Robotic Operations, and Mission Planning. The result of a DRM assessment was a list of HAR tasks that were present for that mission architecture. If a DRM mentioned a specific HAR task that had not been identified in the framework, it was noted and included in the assessment. These NASA-relevant HARI tasks are summarized in Table 2 and subsequently described.

Table 2: Summary of NASA-relevant HARI Tasks

Grouping	*Task*
Spacecraft Guidance tasks	• Ascent • Entry/descent • Landing • Docking/undocking • Maneuver/reboost/rendezvous • Drive/navigate
System Management tasks	• FDIR
Robotic Operations tasks	• Complex assembly, capture and berth • Complex assembly, heavy lift • Site preparation assembly, excavation • Spacecraft support, system maintenance • Spacecraft support, system preparation • Science and assigned activity support, science/sample collection • Science and assigned activity support, payload assistance • Science and assigned activity support, crew assistance–physical • Science and assigned activity support, crew assistance–cognitive • Exploration, scouting • Exploration, mapping • Exploration, sampling/analyzing
Mission Planning tasks	• Staging operations • Strategic planning • Tactical activity scheduling • Training • Medical procedures

2.1 Spacecraft Guidance Tasks

HAR Spacecraft Guidance tasks involve the dynamic control of space vehicles. Traditionally, these are considered "piloted" tasks—i.e., operators provide inputs to the spacecraft, which in turn affect the state of the spacecraft, such as the vehicle's position, orientation, or velocity. Depending on the level of spacecraft automation or whether in an emergency scenario, execution of these HAR tasks frequently requires direct manual input. For these HAR tasks, operators would likely interact with spacecraft systems such as attitude control and propulsion. For example, landing the Apollo Lunar Excursion Module on the Moon would be considered a Spacecraft Guidance HAR task. While there may be other dynamic HAR tasks that require hand-eye coordination, we limited Spacecraft Guidance tasks that control large space vehicles (typically pressurized vessels, but not necessarily).

In this assessment, the following HAR tasks are considered Spacecraft Guidance tasks:

- Ascent, which includes launching from Earth or from any other planetary body with a significant gravity well.
- Entry/descent, which includes re-entry to Earth or approaching another planetary body with a significant gravity well. It also includes descent to a planetary body with an atmosphere, such as Mars.
- Landing, the flight phase subsequent to entry and descent, including landing on Earth (on land or sea) or another planetary body with a significant gravity well.
- Docking/undocking, which includes attaching and detaching one spacecraft from another.
- Maneuver/reboost/rendezvous, which includes execution of finite, short dynamic changes in spacecraft attitude, typically when approaching other spacecraft or celestial bodies (e.g., asteroids) with very small gravity wells.
- Drive/navigate, which includes maneuvers on or near a planetary body that require continuous changes in spacecraft vehicle dynamics. This set of tasks could be considered a subset of maneuvers/reboost/rendezvous.

2.2 System Management Tasks

The HAR tasks identified under the category of System Management encompass Fault Detection, Fault Isolation, and Fault Recovery, or, collectively, Fault Detection, Isolation, and Recovery (FDIR). This task set, as the name implies, requires the monitoring of spacecraft systems, identifying system failures, isolating the root cause, and resolving or working around the off-nominal condition. FDIR is particularly important in complex, automated systems, and is viewed as a critical need for future human-robotic missions (Mishkin et al., 2007). Typically, FDIR is more akin to discrete-state process control and typically will have longer operator response times Spacecraft Guidance tasks (though not necessarily). On ISS, ground flight controllers are responsible for System Management tasks, monitoring and responding to sub-system issues as they arise, correcting and addressing them in a timely-manner. However, future human exploration missions may require astronauts to immediately address off-nominal failures during emergencies. Moreover, System Management HAR tasks are essential for pre-deployed spacecraft, subsystem, and robotic assets, as the automated checkout of habitats and vehicles is an assumed mission capability (Lowry, 2010). For these HAR tasks, operators would likely interact with spacecraft systems such as thermal, power, communications, command and data handling, and environmental control and life support systems (ECLSS).

2.3 Robotic Operations Tasks

Robotic Operations tasks focus on the operations of advanced automation and robotic agents. The NASA DRMs mention various types of highly autonomous systems, but tend to not be specific. Additional references were consulted to obtain a comprehensive set of Robotic Operations Tasks (NASA, 2015; Mercer et al., 2012; Mishkin et al., 2007; Pedersen et al., 2003). For instance, Pedersen et al. (2003) provide the following list of functionalities for future robotic agents: assembly, inspection, maintenance, human assistance, mobility, instrument deployment, and science planning and perception. Similarly, Mishkin et al. (2007) outline the functionality expected of robotic systems that will assist crew in assembly, habitat construction, sample return, science exploration, and human assistants.

The following are considered HAR Robotic Operations tasks:

- Complex assembly
  - Capture and berth: Assembly tasks that require a robotic agent to grab and hold a large spacecraft, vehicle, or module. Typically, capture is necessary before connecting two spacecraft.
  - Heavy lift: Assembly tasks that require a robotic agent to move a large spacecraft, vehicle, or module. As the name implies, the robotic agent must be able to lift significant loads, usually due to the size of the spacecraft, vehicle, or module and the gravity well of the planetary body. Robotic agents may be fixed in place or may translate with the heavy load.
- Site preparation assembly
  - Excavation: Assembly task that requires robotic agent to dig up and/or move large amounts of soil, regolith, or subsurface bedrock.
- Spacecraft support
  - System maintenance: Tasks that require robotic agents to conduct typically mundane and/or repetitive spacecraft maintenance,. Maintenance may be conducted on subsystems (e.g., a habitat filter system) while more complex maintenance may include servicing other robotic agents.
  - System preparation: Tasks that require robotic agents to build, repair, and/or conduct emergency care on spacecraft, vehicles, or other subsystems. These tasks would be the responsibility of robotic agents when the crew is unavailable (e.g., not on site) or because the task is too dangerous for the crew (e.g., nuclear power systems).
- Science and assigned activity support
  - Science/sample collection: Tasks that require robotic agents to collect and manipulate terrain samples. These tasks do not require the robotic agent to be in the same physical space as crew. Inherently, the robotic agent will be exposed to extreme environments.
  - Payload assistance: Tasks that require mobile robotic agents to autonomously transport items for the crew's use. The agent may or not may not be in direct contact with crew.
  - Crew assistance (physical): Tasks that require robotic agents to collect, hold, and handle specific items, such as tools. These tasks require the robotic agent to cooperate directly with crew. The crew and robotic agent team may be inside or outside a pressurized vehicle.
  - Crew assistance (cognitive): Tasks that require an autonomous agent to provide information and/or make decisions that will help crew complete and execute assigned tasks.
- Exploration
  - Scouting: Tasks that require mobile robotic agents to survey terrain of planetary body to enable scientific exploration. Exploration may be on the surface, from above the surface, or sub-surface (e.g., inside caves or lava tubes). Typically, scouting does not have a scientific objective.
  - Mapping: Scouting but with pre-determined science objectives. This implies the continuous use of scientific instruments and data collection.
  - Sampling/analyzing: Tasks that require mobile robotic agents to collect and analyze surface or sub-surface samples. This implies that the robotic agent is conducting in-situ science.

2.4 Mission Planning Tasks

Mission Planning HAR tasks enable mission operations (see also Mischkin et al., 2007), particularly those supporting the autonomy of crew from ground control, and that were not explicitly identified in the previous three HAR task categories. The following are considered HAR Mission Planning tasks:

- Staging operations: Tasks that support mission objectives involving pre-deployed precursor spacecraft systems.
- Strategic planning: Tasks that support the predicting and planning needed to maintain long duration mission operations. Examples of strategic planning tasks include determining whether sufficient power is available for upcoming payload; deciding deployment of robotic assets for scouting; projecting the number of extra-vehicular activities (EVAs) required next week; and determining maintenance schedules.
- Tactical activity scheduling: Tasks that support daily activity scheduling, which determines what the crew needs to accomplish and execute each day.
- Training: Tasks that support training needs, independent of ground control. These tasks may leverage automation or robotic assets.
- Medical Procedures: Tasks that support execution of medical procedures, independent of ground control. These tasks may leverage automation or robotic assets.

3. Human-Automation-Robotic Interactions

Each DRM makes various explicit and implicit assumptions with respect to the type of interactions between operators and automation or robotic agents. In order to consistently describe these assumptions, the expected interaction was reviewed and documented for each HAR task within each DRM. As a result, each task required an operator to only monitor, to only command, or to both monitor and command the automation/robotic agent(s). Other descriptions of HAR interactions, e.g., teleoperation, were not employed in order to maintain uniformity across the assessment.

4. Human-Automation-Robotic Factors

Based on the DRM assessment, HAR factors were determined. These HAR factors are critical elements that will significantly influence HARI. Essentially, future HARI designers and engineers will have to contend with these factors in their design of human-system interactions, because these factors will affect the type and frequency of interactions as well as the expected overall operational human-system performance. These factors were present in all DRMs, but are more prominent depending on the particular mission phases (e.g., Earth departure vs. Planetary surface operations). This set of HAR factors is summarized in Table 3.

Table 3. Human-Automation-Robotic Factors Descriptions

HAR Factor	*Description*	*Options*
Communication infrastructure	Communication availability between Earth and crew, as well as between crew and automation/robotic agent. This includes latency, quality, intermittency, and bandwidth of communication.	Three levels delineated according to latency: no communication latency, some communication latencies, long communication lags with limited bandwidth.
Spacesuit environment	Use of a pressurized spacesuit by crew while interacting with automation/robotic agent.	Suited and unsuited were the only conditions considered.
Gravitational environment	Gravity experienced by crew while interacting with automation/robotic agent.	Microgravity, partial gravity, and hyper-gravity.
Colocation (operator proximity)	Proximity of the operator to the automation/robotic agent when commanding and/or monitoring the system.	Operator inside or close to system, operator is outside or far from system, and operator is on Earth.
System diversity	Number and/or distribution of automation/robotic agents the operator will interact with at any given time.	One or many agents were the only conditions considered.

5. Generic Systems Classes

A challenge to developing a consistent and systematic assessment across multiple mission architectures was that each DRM is composed of different mission elements and systems. In order to have an assessment that would be useful for comparisons across the DRMs, a set of generic system classes needed to be defined. For this assessment, the systems specific to each DRM were first identified, and then each system was categorized according to generic system classes.

Moreover, to compare HAR task needs across different DRMs, generic names for spacecraft and robotic systems were used. This naming convention not only facilitated the identification of similarities across DRMs and unique needs for each mission type, but also allowed for an unbiased assessment. For instance, if a DRM mentioned using Robonaut but another mentioned robots fixing rovers, the assessment would focus on the dexterity capability—not the specific robot name. The system class definitions are:

- *Crew Capsule:* Earth ascent and Earth entry crew vehicle. Typically, the DRMs referred to the Orion Multipurpose Crew Vehicle (MPCV).
- *Crew Habitat Module:* Spacecraft module equipped for crew habitation (sleep, exercise, medical, etc.) and may enable EVA. For Deep Space Sortie, this is currently called the Exploration Augmentation Module (EAM); for Deep Space Habitation it is the Deep Space Habitat (DSH). For the Planetary DRM, the Crew Habitat Module and Crew Capsule together are currently called the Mars Transfer Vehicle (MTV).

- *Logistics Module:* Module that supports stowage for items such as food, spares, and trash. Typically, it is attached to a Crew Habitat Module (CHM).
- *Small Pressurized Exploration Vehicle:* A small, pressurized vehicle that can rove on a surface or navigate near/above the surface (like an asteroid). Capable of sustaining a small number of crewmembers from a few days to up to a month. Some DRMs call this vehicle the Multi-Mission Space Exploration Vehicle (MMSEV). The Lunar DRMs have both small and large pressurized exploration vehicles, where the large vehicle acts like a mobile habitat and could support crew for up to a month.
- *Unpressurized Exploration Vehicle:* A small, unpressurized vehicle that can rove on a surface with one or more crewmembers.
- *Descent/Ascent Vehicle:* A spacecraft that can conduct entry, descent, and landing on a planetary surface. Usually has an adjacent module that allows for departure from planetary surface. The Planetary DRM call this the Descent/Ascent Vehicle (DAV) while the Lunar DRM calls it a Lunar Lander, which also includes an ascent module.
- *Surface Habitat Module/Lander:* A spacecraft that supports crew habitation on a planetary surface. This is distinct from the CHM because the Surface Habitat is intended to operate on the surface. For the Mars/Planetary DRM, the Surface Habitat operates in transit from Earth, on Mars orbit, as well as the planetary surface.
- *Power Surface Asset:* An asset that provides an additional power source, particularly for long duration, planetary missions. This is a fixed-location surface nuclear power plant for the Planetary DRM and a portable, solar one for the Lunar DRM.
- *In-Situ Resource Unit:* An asset that uses materials from the destination and outputs useful products for crew. For the Lunar DRM, options include oxygen, hydrogen, and other volatiles to supply life support, fuel-cell replenishment, and propellant. For the Planetary DRM this also includes production of water, and inert breathing gases (nitrogen and argon).
- *Communication Surface Asset:* A dedicated communication system asset on a planetary surface that facilitates communications to Earth. For the Lunar DRM, this asset is portable. For the Mars DRM this includes a high-powered communications terminal adjacent to the habitat in conjunction with an orbiting Mars network of satellites.
- *Science Instrument Station:* Science instrument assets expected to be deployed on the planetary surface.
- *Integrated Multi-System:* An integrated system of multiple surface assets connected and operated as one system. An example of this is an integrated system that includes Crew Capsule, CHM, and Logistics Module (LM), as outlined in the Deep Space DRMs.
- *Asteroid Robotic Retrieval Vehicle:* Uncrewed spacecraft that travels into deep space to retrieve either an asteroid or a boulder from an asteroid, and returns it to a different orbit. This spacecraft is unique to the Deep Space Sortie DRM.
- *Robotic Large Manipulators:* Large robotic arms or manipulators that can carry/lift heavy items (either in place or transporting), capture other spacecraft, and dig/excavate large amounts of regolith. This robotic class may include large drilling machines.
- *Robotic Dexterous Manipulators:* Generally, smaller dexterous robotic arms that are on a mobile platform. They are intended to conduct maintenance, emergency repairs, help construct space assets, help crew in procedure/task execution, and maintain other robots.
- *Robotic Surface Explorers:* Mobile robots that can be on or fly above the surface. They may be used for scouting (goal is not science-oriented), mapping (goal is science oriented), sampling/analyzing (using science instruments), drilling or subsurface exploration, and/or payload assistant (transporting, collecting, following).

- *Autonomous Intelligent Systems:* Augmented intelligence, decision support, or artificial intelligence that will interface with crew to help provide state information as well as decision-making. Autonomous Intelligent Systems are always locally resident with the crew.

6. Design Reference Mission Descriptions

For each exploration DRM (Deep Space Sortie, Deep Space Journey/Habitation, Lunar Visit/Habitation, and Planetary Visit/Habitation), requires different systems. The subsequent sections describe each DRM and the types of HAR tasks within each exploration mission.

6.1 Deep Space Sortie

The Deep Space Sortie DRM involves a robotic spacecraft retrieving an asteroid or asteroid material from deep space and delivering it to a Distant Retrograde Orbit, where an assembly of habitable spacecraft will dock with it, enabling human missions to an asteroid (ARCM Team, 2015). The Deep Space Sortie DRM is set in Cislunar space, the region of space roughly coinciding with the Moon's orbit, but not including lunar surface activity. The crew sizes considered by this DRM are two or four crew, with most concepts based on this DRM focused on four crewmembers (ARCM Team, 2015). Mission concepts have ranged from durations as short as a few days to as long as 30–60 days, and even as great as 300 days at the destination. This is in addition to transit times to/from Earth, which vary anywhere from 6 to 5 days each way.

Several spacecraft assets are associated with this DRM. The DRM assumes completion of the NASA heavy lift space launch system (SLS) and the Orion MPCV termed the Crew Capsule in this report. The DRM also assumes a supplemental habitable volume to add capability beyond that provided by the Crew Capsule. This is a conceptual spacecraft referred to in some studies as the EAM, but is referred to by other names in other studies and may be a single module or composed of multiple modules. For purposes of this report, this element is referred to as the CHM. The DRM further assumes some capability to resupply consumables and remove trash/waste. In this report, this element is referred to as the LM. Finally, the DRM assumes a robotic vehicle used to capture asteroid material, known in many studies as the Asteroid Robotic Retrieval Vehicle (ARRV) and this report will use the same name (ARCM Team, 2015). The ARRV is always uncrewed.

The ARRV launches first, an uncrewed mission to retrieve asteroid material from beyond Cislunar space. While the ARRV is performing its mission, the crew is launched in a Crew Capsule accompanied by the CHM on a mission to deploy the CHM to Cislunar space. Following this mission, a second crew launch consisting of a Crew Capsule and a LM delivers supplies to fully outfit the CHM. After this mission but prior to the next one, the ARRV arrives with the asteroid and docks to the currently uncrewed CHM/LM pair. Then, a third crewed mission delivers the crew in a Crew Capsule with another LM with supplies to the stack (the initial LM departing autonomously prior to the new LM's arrival).

6.1.1 Spacecraft Guidance

For the Deep Space Sortie DRM, crew and/or ground teams need to monitor and/or command four types of spacecraft systems in key dynamic phases of operations: Crew Capsule, CHM, LM, and ARRV.

Crew Capsule: For the critical phases of ascent, entry/descent, and landing, crew is expected to monitor and command the spacecraft while suited in both microgravity and hypergravity conditions. For docking/undocking and maneuvers/rendezvous events, crew is also expected to monitor and command the spacecraft. They may be suited for docking/undocking events. The frequency of interaction ranges from continuous to intermittent.

There is no mention of crew having to remotely operate the Crew Capsule—crew will always be onboard or in a docked spacecraft. Crew may be expected (while onboard the Crew Capsule) to remotely monitor and issue commands to the ARRV, CHM, and/or LM during approach, rendezvous, docking, undocking, and separation operations. These tasks will primarily be limited to subsystem configuration and do not include dynamic piloting of these vehicles. The crew will only perform piloting operations for the Crew Capsule.

Crew Habitat Module: Crew is only expected to directly interact with the CHM after the Crew Capsule docks with the CHM. There is no communication lag for the crew by virtue of the crew being physically onboard the spacecraft. The DRMs are not specific as to whether the crew will exclusively command the CHM directly when docked or if they will remotely command the CHM from a workstation inside the Crew Capsule. The availability of both options opens the possibility for command location to be a crew preference. When the Crew Capsule is docked to the CHM, there should be no perceived difference to the crew if monitoring/commanding the CHM from inside the Crew Module or onboard the CHM. The frequency of interaction ranges from continuous to intermittent.

Logistics Module: Similar to the CHM, crew will only directly interact with the LM after the Crew Capsule docks with the CHM. Ground team will monitor and command the LM docking to the CHM and the LM will not undock until after the crew have already departed the CHM. The crew will need to be able to seamlessly command the LM without distinction as to whether the crew is onboard the LM, CHM, or Crew Capsule. The docked vehicles will be considered a single spacecraft system—much like the ISS is one spacecraft composed of multiple modules.

Asteroid Robotic Retrieval Vehicle: For dynamic events, the crew is not expected to interface with the ARRV. See the subsequent Ground Team section for more details.

Ground Team: For all the aforementioned spacecraft, plus the ARRV, the ground team is expected to be able to monitor and send commands to the spacecraft for all phases of flight. The command frequency may be intermittent or continuous. For all events beyond LEO, the ground team will have to manage with some communication lag. In Cislunar space, this lag is in the vicinity of 1.3 seconds. For trajectories between Cislunar space and a deep space asteroid this lag will increase but the maximum delay cannot be determined until a specific asteroid with a known orbit is selected. Assuming that an asteroid destination is closer than Mars, ground team are likely to contend with communication lags that are no shorter than 1.3 seconds but no greater than 3 to 4 minutes.

6.1.2 System Management

Crew Capsule: There is little discussion in the documentation regarding FDIR due to the early state of these mission concepts but it is assumed that crew will have to monitor and command FDIR of the spacecraft's subsystems. Crew will execute these interactions while unsuited or suited, in microgravity or hypergravity. The crew will also have to monitor and command for FDIR when aboard other spacecraft such as the CHM. They will have limited FDIR capabilities when on EVA.

Crew Habitat Module: Crew is expected to monitor and command FDIR for CHM subsystems while onboard the spacecraft (always in an unsuited microgravity environment). Crew can also monitor and command CHM FDIR while onboard another spacecraft such as the Crew Capsule.

Logistics Module): Crew is expected to monitor and command FDIR for LM subsystems from onboard the CHM or if necessary from the Crew Capsule. LM itself has no crew interfaces to spacecraft subsystems.

Asteroid Robotic Retrieval Vehicle: Crew is not expected to interface with the ARRV for any subsystem/vehicle management tasks. See subsequent Ground Team section for more details.

Ground Team: For all the above-mentioned spacecraft, the ground team is expected to monitor and command for FDIR for the spacecraft's subsystems with either none or some communication lag (depending on mission phase). The ground team configuration is unclear and has not been defined in Deep Space DRMs. Historically, Mission Control has operated under one of two configurations. For instance, Mission Control devoted one flight control team to the International Space Station and a separate team to the Space Shuttle. However, during the Apollo missions, Mission Control devoted a single flight control team to monitor the Saturn V, Apollo Command and Service Module, Apollo Lunar Module, and Apollo Lunar Roving Vehicle.

6.1.3 Robotic Operations

The primary robotic asset in the Deep Space Sortie DRM is the ARRV, in particular its manipulation systems used to grapple the asteroid material. For purposes of its robotic activity, the ARRV is monitored and commanded exclusively by the ground team and the robotic systems are only active prior to the arrival of crew. Due to the time delay involved and limited bandwidth, it is expected that the ground team will have some level supervisory control of the ARRV's manipulators and will not directly teleoperate the asteroid capture sequence.

Many of the dexterous manipulators and surface explorer robots in other DRMs do not have a direct role in this DRM. However, there is the possibility that lunar-based robots may be controlled by crew in the CHM but that is not yet an official part of this DRM.

Intelligent systems have not been defined for this DRM but may be present in some or all of the following: spacecraft, EVA suits, surface explorers, and ground team. Crew may experience some communication lag when querying robotic assets with intelligent systems that are not co-located (e.g., surface explorers). Similarly, the ground team will experience some communication lag when querying with intelligent systems that are not co-located (e.g., spacecraft, EVA suits, surface explorers).

6.1.4 Mission Planning

One of the noteworthy characteristics of the Deep Space Sortie DRM is that its architecture assumes multiple missions, both crewed and un-crewed, each building capabilities at the Cislunar presence over time.

Staging Operations: Staging operations have not been finalized for this DRM and may be either autonomous or crew supported. The primary driver is whether modules are launched as secondary payloads along with a Crew Capsule or are launched independently. Astronauts are expected to perform staging operations during any crew assembly mission that may include delivery of the CHM, LM, and Crew Capsule. Crew will not be responsible for staging operations during any uncrewed assembly mission. The ground team is expected to support all staging operations.

Strategic Planning: For both the crew and ground team, strategic planning is not expected to be significantly different from ISS.

Tactical Activity Scheduling: For both the crew and ground team, tactical activity scheduling is not expected to be significantly different from ISS.

Training: The DRM does not specify training activity. Training activity is likely to be computer based, performed individually by each crewmember. The limited communications lag will not prevent voice and video communications so typical ground-to-space exchanges can still take place. However, the lack of mention of any crew training strategies does suggest that these exploration missions, which range in duration across DRMs from as short as 5 days to as great as 300 days, will be very prescriptive, implying that most mission planning is assumed to be the ground team's responsibility. Longer duration missions may be viewed as an opportunity to prepare for human missions to Mars and hence these missions may provide opportunities to test and evaluate mission planning performed by the crew instead of the ground.

Medical Procedures: Medical procedures are not expected to be significantly different from ISS and crew will perform them in coordination with the ground. These procedures will include the use of telemedicine systems.

6.1.5 Limitations of Assessment

The Deep Space Sortie DRM does have some limitations with respect to identifying future HARI needs. Since the DRM is still in work, many of the research and mission objectives are still in flux, producing significant uncertainty as to human-automation/robot interactions that will be the required. Thus, there may be other HARI needs that do not presently exist in any documented form. Further, both presently identified and unidentified needs may change numerous times before program implementation. However, while the DRM is still subject to change, the documentation available was sufficient to understand the main elements for this mission's architecture. Most human-automation/robot interactions identified were recognizable, however, some were assumed or extrapolated from the mission description. Also, there is no mention in the reviewed DRM documentation of the envisioned concept of operations for providing crew more autonomy.

6.2 Deep Space Habitation

The Deep Space Habitation DRM involves traveling to a near-Earth asteroid (NEA) and exploring it. The mission consists of four crew members and three SLS launches (ESD 10012 document and Generic Human Exploration Design Reference Missions slides):

- SLS1: Pre-deployment of Deep Space Habitat (termed CHM in this document);
- SLS2: Pre-deployment of Space Exploration Vehicle (termed Small Pressurized Exploration Vehicle (SPEV) in this report) and possibly the Logistics Module (LM);
- SLS3: Launch of crew in Multi-Purpose Crew Vehicle (termed Crew Capsule in this report).

First, the CHM is launched into Low Earth Orbit (LEO). One year later, the SPEV and possibility the LM launch and rendezvous with the CHM in High Perigee-High Earth Orbit (HP-HEO). The following year, the Crew Capsule launches and rendezvous with the CHM, SPEV, and LM at a staging point in either HEO or Earth-Moon Lagrange Point 1 (E-M L1). After the stack assembly is complete, the crew transfers into the CHM for deep space travel. When the Crew Capsule is docked with the CHM, the Crew Capsule is the active vehicle. Upon arrival at the NEA, the Crew Capsule and CHM station keeps at a safe standoff distance. The crew conducts 28 days of exploration with SPEV excursions to several sites around the NEA. For the return trip, the SPEV is left at the NEA while the rest of the integrated vehicle travels back to Earth. When nearing Earth, the Crew Module is fully powered and the crew transfers back into the Crew Module. The Crew Module separates from the CHM to return to Earth (ESD 10012 document and Generic Human Exploration Design Reference Missions slides).

6.2.1 Spacecraft Guidance

Crew Capsule: For the critical phases of ascent, entry/descent, and landing, crew is expected to monitor and command the spacecraft while suited in both microgravity and hypergravity conditions. For docking/undocking and maneuvers/rendezvous events, crew is also expected to monitor and command the spacecraft. They may be suited for docking/undocking events. The frequency of interaction ranges from continuous to intermittent. Crew will have to remotely command the Crew Capsule while aboard the CHM.

Crew Habitat Module: Crew is only expected to interact with the CHM after the Crew Capsule docks with the CHM. Thus crew is expected to monitor and command the CHM with no communication lag during the dynamic phases (maneuvers/rendezvous and docking/undocking). The frequency of interaction ranges from continuous to intermittent. Crew will have to remotely command the CHM from either the Crew Capsule or the SPEV. From the CHM, crew will have to remotely command the Crew Capsule and the SPEV. The CHM is expected to have docking/undocking capabilities.

Logistics Module: The DRMs have not fully resolved whether crew will be onboard the LM during dynamic phases of the mission. Some scenarios may call for jettisoning one or more LMs during the mission. If crew interaction is required, they may have to remotely command the LM from the Crew Capsule, CHM, or SPEV.

Small Pressurized Exploration Vehicle: For dynamic events such as docking/undocking, navigating around a planetary object (asteroid), and soft "landing" (e.g., grappling, orbiting) onto the surface of a planetary object with very small gravity field, crew is expected to monitor and command the SPEV, experiencing no lag. Crew may be in the SPEV cabin unsuited, or suited while at the suit ports. The command frequency will range from continuous to intermittent with no lag. Crew may also be expected to remotely command the SPEV from the CHM or Crew Capsule if other crewmembers within the SPEV are incapacitated or if the SPEV is uncrewed.

Ground Team: For all the aforementioned spacecraft, the ground team is expected to be able to monitor and send commands to the spacecraft for all phases of flight. The command frequency may be intermittent or continuous. For all events beyond LEO, the ground team will have to manage with some communication lag. This DRM's communication lags will be longer than Deep Space Sortie mission, hence, but relatively short compared to Mars transit.

6.2.2 System Management

Crew Capsule: Crew is expected to monitor and command FDIR of the Crew Capsule's subsystems. These interactions are completed while crew is unsuited or suited, in microgravity or hypergravity. Crew will have to still monitor and command the Crew Capsule's FDIR when onboard the CHM and SPEV. Crew will have limited FDIR capabilities while performing EVA.

Crew Habitat Module: Crew is expected to monitor and command FDIR for the CHM's subsystems while onboard the CHM (always a microgravity, unsuited environment). Crew can also monitor and command FDIR while onboard the Crew Capsule and SPEV.

Logistics Module: Crew is expected to monitor and command FDIR of the LM's subsystems from onboard the CHM, or if necessary from the Crew Capsule or SPEV. There are no crew interfaces to spacecraft subsystems on the LM itself.

Small Pressurized Exploration Vehicle: Crew is expected to monitor and command FDIR of the SPEV's subsystems while onboard the SPEV. This includes both unsuited crew in the cockpit and suited crew in the suit port. From the Crew Capsule and CHM, crew may monitor and command SPEV's subsystem's FDIR. Crew will have limited FDIR capabilities while on EVA.

Ground Team: For all the spacecraft mentioned above, the ground team is expected to monitor and command FDIR for the spacecraft's subsystems with none, some or long communication lag depending on the mission phase. This DRM's communication lags will be longer than Deep Space Sortie mission, but relatively short compared to Mars transit.

6.2.3 Robotic Operations

No heavy robotic manipulators have been identified for this DRM. The SPEV will have a robotic arm that can do a variety of robotic tasks: penetrate the surface to set anchors, surface sampling, drilling operations, and collecting samples (ESD 10012 document). Once the SPEV is left behind on planetary object as a robotic asset (Generic Human Exploration Design Reference Missions slides), crew is expected to remotely command and monitor the robotic asset with various communication lag (depending on the relative distance between them). No information was found to indicate that surface explorers other than the SPEV are expected.

Noteworthy is that documentation identifies new technologies in the area of robots working side-by-side with suited crew (Generic Human Exploration Design Reference Missions slides). However, it is unclear how the crew is expected to interact with the SPEV while suited, conducting EVAs.

While intelligent systems have not been defined for this DRM, they but may be present in some or all of the following: spacecraft, EVA suits, surface, and ground team. Crew may experience some communication lag when querying robotic assets with intelligent systems that are not co-located (e.g., surface explorers). Similarly, the ground team will experience some communication lag when querying intelligent systems that are not co-located (e.g., spacecraft, EVA suits, surface explorers).

6.2.4 Mission Planning

Staging Operations: Staging operations have not been finalized for this DRM and may be either autonomous or crew supported. The primary driver is whether modules are launched as secondary payloads along with a Crew Capsule or are launched independently. Crew is expected to perform staging operations during any crewed assembly mission that may include delivery of the CHM, LM, and Crew Capsule. Crew will not be responsible for staging operations during any uncrewed assembly mission. The ground team is expected to support all staging operations (crewed and uncrewed).

Strategic Planning: For both the crew and ground team, strategic planning will likely be very similar to ISS. However, the increased time delay will likely encourage other asynchronous communication protocols, such as more the use of text-based planning tools than voice communication. The communication delay is unlikely to have a significant impact on strategic planning.

Tactical Activity Scheduling: For both the crew and ground team, it is unclear to what extent, if any, tactical activity planning will be altered from ISS processes. The increased communication delay may make direct vocal communication challenging but is not likely to impact the use of text-based communication.

Training: The DRM does not specify training activity. Any such activity is likely to be computer-based training, performed individually by each crewmember. Interactive training with the ground is possible but communication delay may decrease the effectiveness of voice and video communication.

Medical Procedures: Crew will still perform medical procedures in coordination with the ground team. More research is needed to determine the impact of communication delay on telemedicine.

6.2.5 Limitations of Assessment

One of the limitations of the DRM's documentation is the lack of information about the level of automation for the spacecraft, especially for the CHM, LM, and SPEV, including its robotic capabilities. In addition, there is not sufficient information about crew tasks such as training and medical procedures. The DRM documentation also lack information about the various elements of mission planning.

6.3 Lunar Visit/Habitation

The Lunar Visit/Habitation DRM extends beyond the capabilities of the Apollo program. While the basic architecture for this DRM is generically described in summary slides (NASA, 2012), two published documents were referenced for additional information about the Lunar DRM. The first publication (Mazanek et al., 2009) delineates the lunar exploration architecture as it was proposed during the Constellation Program. The Human Spaceflight Architecture Team (HAT) expanded on Constellation plans, as documented in a second publication (Mueller, Connolly, and Whitley, 2012).

A distinguishing factor of the Lunar DRM is that it is described as a series of missions to the Moon, both crewed and un-crewed – not just one monolithic mission. The DRM leverages several short lunar sortie missions with four crewmembers, building upon a series of pre-deployed surface assets to extend mission durations. This campaign of lunar missions would culminate in missions lasting 28 days, during which crew will live and operate for two weeks in full sunlight and two weeks in full night. Since each mission in this DRM builds on previous missions, presumably only one site will be explored. This implies that surface mobility systems will be emphasized to maximize lunar science exploration.

The Lunar DRM discusses several types of surface assets. While mentioned, in-situ resource utilization (ISRU) is not significantly highlighted as an essential key surface asset. In addition to a pre-deployed surface habitat, logistics modules, and a power/communication asset, there are several robotic assets. Robotic assets are meant to help in the assembly of the habitat, to scout new terrain, and allow astronauts to travel beyond the habitat outpost. Both Mazanek et al. (2009) and Mueller et al. (2012) describe concepts of operations that are very dependent on extravehicular activities (EVA), where astronauts explore the lunar surface via reconfigurable mobility systems.

Many of the systems described in the Lunar DRM have specific names that are tied to previous or existing NASA projects. The DRM assumed utilizing up-and-coming space systems, such as heavy lift launch (SLS) and crew vehicle (Orion). For the purposes of this assessment, all assets were given generic terms. For example, the lunar lander is identified as a Surface Lander, not Altair, and surface rovers are classified as pressurized or unpressurized. While lunar communication infrastructure has also been by HAT and/or the Constellation Program), communication bandwidth is assumed to be akin to ISS capabilities, with latencies assumed to be greater than ISS but not much than 10 seconds.

6.3.1 Spacecraft Guidance

For the Lunar DRM, crew and ground teams need to monitor and/or command three types of spacecraft systems—the Crew Capsule, Lunar Lander, and Rovers (both pressurized and unpressurized)—during key dynamic phases of operation. It is assumed that crew would interact with the Crew Capsule and Lunar Lander while suited for any operations that exposed them to high gravity loads (e.g., ascent) or a risk of depressurization (e.g., docking/undocking). Crew will certainly drive the unpressurized rovers on the lunar surface while suited.

The ground team is also expected to command and not just monitor the Crew Capsule and Lunar Lander. Unlike the Apollo Program, which left an astronaut on board the Crew Capsule, all astronauts to go to the surface on future lunar missions, leaving an uncrewed return-to-Earth vehicle orbiting the Moon. Under these circumstances, ground team will have to monitor and if necessary, command the orbiting spacecraft. The Lunar DRM also requires landers to pre-deploy assets on the surface. While Mueller et al. (2012) suggest this will be done completely autonomously, ground teams will have to monitor this operation, and possibly intercede, by sending commands to the landers. While ground teams will have to contend with some communication issues, including some lag, for any of the spacecraft, there is no mention of crew having to remotely operate either the Crew Capsule or the Lunar Lander.

There are elaborate plans for remotely operating one or more of the pressurized/unpressurized rovers by crew and ground. It is expected that ground teams will monitor and remotely operate the rovers because these assets will be delivered and autonomously deployed before crew arrival. Moreover, crew is expected to monitor and operate these rover assets while on the way to Moon, while on the lunar surface, and while "riding" the rover vehicles. Hence, the human-robotic interaction design will have to include mitigations for communication lag, not just for ground but also for crew. For example, remote rover operations by crew will involve commanding the mobile chassis to "dock" (or mate) with pressurized modules.

The inclusion of different types (pressurized and unpressurized) of rovers suggests that the human-automation-robotics interaction should be designed consistently across both systems in order to minimize training and system development. However, this may be a challenge due to significantly different "ride on" interaction modes with one system necessitating interaction while wearing a pressurized space suit.

6.3.2 System Management

For the Lunar DRM, crew and ground teams will need to monitor fault detection, manage fault diagnosis, and command fault recovery. There is little discussion of FDIR in the documentation, but it is assumed that crew and ground will have some role in system management as it is a fundamental HARI task for any system with automation. The Lunar DRM presents a number of mission assets including Surface Habitat modules, rovers (pressurized & unpressurized), Lunar Lander, Crew Capsule, and surface stations that will require system management by crew and/or ground teams: for Power, Communication, In-Situ Resource Utilization and Science Instrument.

Compared to ISS missions, the number of DRM systems to manage will be higher because it includes individual, unique spacecraft vehicles such as landers and rovers. ISS flight controllers manage the space station while other ground teams support visiting vehicles; this was the case for Space Shuttle and continues for other visiting vehicles that dock with ISS. Presumably, the variety of Lunar DRM mission assets signifies an increase in the number of ground controllers with specializations for each system. The current concept of operations does not describe the role allocations between ground and crew with respect to the management of these systems. Therefore, the HAR interactions assessed here assume the worse case scenario that both crew and ground team will need to monitor and command all systems. Crew may also have to contend with the emergency scenarios where they will need to do both FDIR commanding and dynamic spacecraft guidance.

Two particular systems are worth noting. First, there is one exception that does not require crew HAR interaction. The Science Instrument Stations will be deployed by crew but operated only by ground teams (Mueller et al., 2012). This is the only system that was described to exclusively require ground control. Second, the DRM describes an architecture where multiple modules combine (e.g., Pressurized Rover and Surface Habitat) and operators are expected to interact with an integrated multi-system as well as each system in a standalone fashion (Mazanek et al., 2009). There is an inherent assumption of common interfaces and system-automation architecture across these systems.

In order for ground teams to conduct system management, they will have to contend with some communication issues for assets en route to and from the Moon, on lunar orbit, and on the lunar surface. The DRM requires the Crew Capsule to be left uncrewed in lunar orbit. The DRM also describes EVAs that require all crewmembers, which means that the Surface Habitat/Lunar Lander will also be left uncrewed. On the other hand, the crew may want to monitor (and perhaps command) mission assets while en-route or while conducting EVAs, especially during emergencies. This would introduce some communication latencies and require novel HAR interactions while commanding on EVA. It is assumed that most of the HAR interactions on the lunar surface will not have to contend with significant communication latencies as crew will be either in the spacecraft (e.g., Crew Capsule, Surface Habitat) or close by (e.g., Power and Communication Stations).

6.3.3 Robotic Operations

Aside from the unpressurized and pressurized rovers, the Lunar DRM emphasizes the use of two main classes of robotics: Heavy Lift and Surface Explorers. There is mention of Dexterous Manipulators (NASA, 2012; Mueller et al., 2012), but it is not emphasized. It is assumed that both ground teams and crewmembers will monitor and command these robotic assets.

Heavy Lift robotic assets are critical for lunar surface operations in this DRM. Notably absent is the mention of large robotic arms (categorized as Heavy Lift in this assessment) while en-route or in lunar orbit. However, stationary and/or mobile cranes are necessary to assemble lunar outpost. Additionally, the Constellation Program was aiming for a heavy-lift mobility system (Mazanek et al., 2009). While similar to space robotic operational experience (i.e., robotic arms), the differences are not insignificant and new HAR interfaces will be needed. Moreover, HARI design will have to consider the need to remotely operate Heavy Lift robotic assets both from within a pressurized cabin and while crew is on EVA. Mazanek et al. (2009) also indicate that there will need to be a "manual override" capability for contingencies that will have to be used by suited astronauts. While communication latencies will not likely be part of the HARI design, the required interaction between ground teams and these robotic assets will be subject to some communication issues (Mazanek et al., 2009).

The Lunar DRM emphasizes the use of Surface Explorers, which are robotic scouts that explore and map terrain while completing science objectives along the way. Mueller et al. (2012) goes as far as calling them "a fleet of small rovers". These robots are in addition to the unpressurized rover, which is essentially a large Surface Explorer. What is unique about the Surface Explorers in the Lunar DRM is the number of small robots crew and ground are expected to monitor and command. HARI design for these Surface Explorers will have to manage some communication latencies, not just for ground team, but for also crew who are expected to command these robots while on low lunar orbit (Mueller et al., 2012). While operated from a pressurized module (like the Habitat Element), it is likely the crew will have to contend with some communication latencies if the Surface Explorers are not in direct line of sight. Additionally, while not directly mentioned, it is assumed that a suited astronaut may want to command and control these robotic scouts. If these requirements persist, it may necessitate commanding these robots through supervisory control methods instead of direct teleoperation.

Dexterous Manipulators are mentioned in the Lunar DRM as robotic systems attached to the larger rovers. A small, dexterous robotic arm manipulator attached to the Pressurized Rover is expected to assist in completing science objectives, allowing astronauts to interact with the lunar surface without conducting an EVA. Robots will also handle "servicing operations" and other outpost setup functions in preparation for astronauts landing (Mueller et al., 2012). It is assumed that dexterous robotic manipulators will be necessary to accomplish these tasks. While ground teams will be the main operators for these precursor robotic operations, it is not unreasonable to assume that crew will also utilize these robotic systems. Similarly, crew and ground teams will need interfaces to operate Dexterous Manipulators what will have to address the same HARI design issues as the Surface Explorers.

It is worth noting the underlying assumption that ground teams and crew to a certain extent are able to easily teleoperate these lunar robotic surface systems subject to the given communication latencies and bandwidth restrictions. Direct, constant interaction with robotic agents, i.e., teleoperation, under these communication limitations is known to be challenging and nontrivial for HARI design implementation. Making supervisory control, with inherently less frequent human-system interaction into a viable HARI solution, will require significantly larger investment in robotic and automation technologies. .

The increase in the number of types of robotic agents ground teams and crew will have to contend with brings to the forefront the HARI design challenge of monitoring and commanding heterogeneous robotic agents. While ground will have the advantage of multiple specialized teams to assign to each each type of robotic agent, the lunar outpost crew will not themselves have the local numbers to do so.

The Lunar DRM does not discuss any Intelligent Systems (automated, computer systems) that would provide crew with support if they were to operate more autonomously from mission control.

6.3.4 Mission Planning

A unique characteristic of the Lunar DRM is that it is an architecture assumes multiple missions, both crewed and uncrewed, each building capabilities and the lunar outpost over time. There are numerous precursor missions for staging operations. Presumably, ground teams will manage these pre-deployments, including depositing many of the surface assets (both stationary and roving), setting up and maintaining the outpost between crewed missions, and implementing robotic scouting missions. Additionally, ground teams will have to attend to spacecraft such as the lander (Descent/Ascent Vehicle) and Crew Capsule when they are uninhabited. There will be many HARI design requirements for ground teams. These requirements will have to address the previously described communication limitations.

One area of HARI design is of interest for the Lunar DRM is robotic medical procedures and/or automated medical assistance. Although there is one habitat illustration that includes a medical operations space neither medical procedures nor automated medical assistance are mentioned in the documentation reviewed. Presumably, medical procedures will not significantly differ from ISS operations.

The Lunar DRM documentation reviewed does not mention the envisioned concept of operations for enhancing crew autonomy. Specifically, there is no discussion of planning strategies (strategic and tactical activity planning) or training on the lunar surface. Possibly, the distance to the Moon is not far enough to significantly change current ISS-like role allocations between ground teams and crew. However, the lack of mention of any crew training strategies indicates that these exploration missions, which will be at most 28 days, may be very prescriptive. This implies that most mission planning will be the ground team’s responsibility.

6.3.5 Limitations of Assessment

With respect to the Lunar Visit/Habitation DRM, the documentation available was sufficient to understand the main elements for this mission's architecture. Most human-automation-robotic interactions identified were recognizable, however, some were assumed and/or extrapolated from the mission description. These assumptions were stated in the previous section.

Absent in the DRM documentation is any lengthy discussion about the lunar outpost location on the Moon. Exploring the poles is mentioned (e.g., Shackleton Crater), but not highlighted. Polar lunar locations impose challenging environmental constraints on HAR interactions, as there are some extreme lighting conditions (e.g., areas in permanent shadow). Other lunar outpost locations could have substantial HARI implications as a function of location. Exploration on the far side of the Moon would impose longer communication latencies and stricter bandwidth restrictions since this destination would require a communication architecture that does not depend on line-of-sight to Earth.

The Lunar DRM could have been assessed more thoroughly for HARI design and interactions if there were documentation of a concept of operations. This would have been key for shedding light on the role allocations between ground and crew, and hence understanding where crew-centric HARI challenges reside. On the other hand, the Lunar DRM describes a great variety of spacecraft and robotic assets, particularly surface systems. This is not surprising considering that some of the documentation reviewed came from the Constellation Program's Lunar Surface System Project.

The Lunar DRM assessment is limited with respect to the identification of future HARI needs because the documentation reviewed instead focuses on the mission elements that would enable the incrementally development of a lunar outpost. In turn, the DRM documentation does not significantly consider automation and/or robotic elements that would facilitate crew productivity and science return.

6.4 Planetary Visit/Habitation

The architecture and underlying design trades for the planetary DRM are described in NASA's Human Exploration of Mars Design Reference Architecture 5.0 (Drake, 2009). In order to avoid confusion, this report will reference this as the Mars DRM 5.0 (as opposed to DRA for architecture). Mars DRM 5.0 is the most recent publically available detailed planetary-exploration DRM document available; it was in fact used by the National Research Council (2014) in their evaluation of different approaches to developing a U.S. human space exploration program that would culminate in a mission to Mars.

The fundamental distinguishing feature that shapes the Mars DRM is the long stay on the planetary surface. This surface stay is driven by the need to minimize crew transit times and costs, which in turn constrains departure dates and intervals to and from Mars. The long-duration planetary stay necessitates delivery of significant infrastructure, including a surface habitat, a Mars ascent vehicle for departing the planetary surface, a nuclear fission reactor to power surface operations, and an ISRU capability to generate consumables (oxygen, water, as well as inert nitrogen and argon for breathing) for ECLSS and propellant (methane and oxygen) for the ascent vehicle. This infrastructure is to be established on Mars before crew arrival. These infrastructure elements are significant undertakings for a number of reasons. First, all of these elements entail substantial payload up-mass and, thus, will depend on multiple heavy-lift launches from Earth and automated rendezvous and docking to assemble nuclear-thermal-rocket equipped transit vehicles in low Earth orbit (LEO) before departure to Mars orbit and the planetary surface. Second, remote operation from Earth of any uncrewed systems in the vicinity of Mars will contend with round-trip communication delays up to 44 minutes (Fong, Zumbado, Curie, Mishkin, & Akin, 2013). Finally, many of these Mars-specific infrastructure elements will be untested in off-Earth operations on other interim (e.g., lunar and/or asteroid-redirect) missions (National Research Council, 2104).

This pre-deployment architecture demands that the planetary DRM be conducted in two distinct phases. The second phase begins with the remote assembly of the Mars transit vehicle in LEO over a year after the first phase during which the aforementioned infrastructure assets were positioned in Mars orbit or on the planetary surface. The six-member astronaut crew will travel to Mars in the habitat on their transit vehicle, dock with the orbiting surface habitat, and then descend in the habitat to the Martian surface while the transit vehicle remains in orbit. While on the surface, crew will conduct a variety of exploration and scientific activities with the aid of different robotic devices, including at least two pressurized and two unpressurized rovers, and, at minimum, an automated drilling platform. At the end of their 500+ days on Mars, the crew will leave the habitat behind on the surface and launch on the ascent vehicle to dock with the transit vehicle and then depart for Earth without the ascent vehicle.

While the DRM employs generic acronyms such as MTV, DAV, and SHAB to describe key mission vehicles, respectively, the Mars Transfer Vehicle, Descent Ascent Vehicle, and Surface Habitat, Drake (2009) names others from current and recent NASA programs. For example, while Mars DRM 5.0 designates the heavy-lift launch vehicle as the Constellation Program's lunar mission Ares-V, the National Research Council (2014) report revises it to the current Space Launch System (SLS). Moreover, astronauts will launch from Earth in one Orion crew delivery capsule, which docks with the Mars Transit Vehicle and is jettisoned prior to trans-Mars injection, while a second, long-lived and quiescent Mars-block-upgrade Orion capsule remains attached to the transit habitat until Earth entry, descent, and landing (EDL) by the crew at the end of the mission (Drake, 2009).

6.4.1 Spacecraft Guidance

Mars DRM 5.0 describes a series of flight and surface vehicles and assemblies of vehicles that astronauts will occupy (Drake, 2009). As detailed below, these vehicles and assemblies will be controlled and monitored by astronauts and/or ground.

The various planetary EDL, habitat, and surface departure vehicles that will be occupied by crew upon arrival at Mars, as well as the interplanetary crew transfer vehicle will all be launched from Earth in segments separate from their respective propulsion modules and assembled into their respective Earth-Mars transit vehicle systems in LEO. Initially, a series of heavy-lift launch systems will carry components for the Mars descent-ascent vehicle, the surface habitat, and the logistic infrastructure (for in-situ resource utilization). Subsequent heavy-lift systems will later launch the elements for the MTV, including crew capsules, transfer habitat modules, and planetary surface rovers (both pressurized and unpressurized).

The DRM states that assembly of the various transit vehicles segments will be conducted via automated rendezvous and docking (Drake, 2009, pp. 3, 22). Given that astronauts will not be launched until their Mars transfer vehicle is ready, all LEO assembly activities will be monitored and controlled by ground with low latencies (less than 10 seconds round trip) and varying intermittency. Control and monitoring for the uncrewed transfer vehicles will be handled by ground with latencies increasing to 44 minutes round trip and growing intermittency as the different vehicle systems progress from LEO to Mars orbit and towards the planetary surface. At Mars, communication intermittency with ground will depend on the established deep space and Mars communication network infrastructure (Drake, 2009, p. 9); without the appropriate infrastructure, communication may be cut off when assets are on the opposite side of Mars from the Earth or during solar occlusion (i.e., when the Sun blocks the line of sight between the two planets).

Astronaut crew arrival at the MTV will enable direct-contact interaction with near-zero latency while monitoring and controlling various MTV systems, such as propulsion and power components, the transit habitat, and the long-lived Earth-return capsule. The frequency, or conversely, the intermittency, of such interactions will both depend on and inform the degree of automation and autonomy these future systems. Crew will be able to interact with the SHAB, DAV, and infrastructure on Mars orbit and the planetary surface with decreasing latency as they approach Mars and near-zero latency once they dock and transfer over from the MTV to these other systems. Crew will then land on Mars near the pre-deployed DAV and other surface assets. On the return trip, crew leaves Mars on the ascent vehicle that will interact with MTV with diminishing latency as they near it. Once crew has launched from Earth, monitoring and health checks for all vehicle and habitat systems will be performed both by ground and crew (Drake, 2009, p. 30).

On the planetary surface, the Mars DRM adopts a “commuter” strategy, where a stationary, centrally located base habitat operates with two pressurized and two unpressurized rovers for mobility and science (Drake, 2009, pp. 5, 36, 39). Surface mobility is essential to meet the science objectives laid forth in this Planetary DRM. Drake (2009, p.70) notes that both unpressurized and pressurized rovers assist scientific discovery by extending the range of human explorers on the Martian surface. The unpressurized rovers could be considered as extensions or multipliers crew EVA suit capabilities in that they could share or offload suit functions such as power, ECLSS, navigation, communication, and carrying experiment packages (Drake, 2009, pp. 39). Interactions between crew and an adjacent rover would be direct, e.g., manually driven with direct visual observation of the immediate environment, with varying frequency of interaction depending on rover automation, autonomy, and the specific task being executed.

The role of the pressurized rovers would be to extend crew range from the fixed habitat, enabling a total travel distance of 100 km to place crew within easy EVA walking distance of features of interest. The on-board habitation and science capabilities of the pressurized rovers would be modest, with support for a crew of two, for up to two weeks without resupply, and carrying only the minimum of essential equipment. The types (i.e., latency, frequency) of interaction between unsuited crew and the pressurized rovers will be depend on the degree of rover automation and autonomy for the particular task at hand. For activities such as manual driving with direct steering and speed control input of the pressurized and unpressurized rovers, crew interaction will be frequent and generally continuous because of the need to navigate and avoid surface obstacles in a largely unstructured environment.

6.4.2 System Management

System Management will require significant advances in automation and autonomous systems as all the previously described space assets will require at least some level of monitoring and FDIR. Many of the spacecraft assets will require “automated operations mode” because they will be monitoring and controlled by Earth ground team (Drake, 2009, pp. 4). Effective human-automation integration will be essential for managing the large number of pre-deployed spacecraft assets. These assets will have to be “checked out” before crew can even launch from Earth and then depart to Mars.

Autonomous pre-checkouts for verification of system functions will be required in order to help ground teams assess completion of critical tasks such as the creation of all the propellant needed for crew-return. With ground supervision, automation may also work through any anomalies that arise. Additionally, astronauts in transit will checkout these pre-deployed assets prior to landing.

While not as safety critical as environmental or ECLSS monitoring, science stations will be deployed by astronauts but autonomously operated from Earth. Such scientific stations are integral to fulfilling science and mission goals set forth by the Mars DRM 5.0. Remote operations of multiple stations, under communication time-delays, will be a new challenge for ground teams, necessitating the use of more highly autonomous FDIR.

The National Research Council (2014) assessment of Mars DRM 5.0 observes that the Mars mission will comprise more primary elements, e.g., vehicles, power, propulsion, infrastructure systems, etc., than the lunar or deep space DRMs or than are currently associated with ISS. Extrapolation from the number of ground team members supporting ISS and the vehicles that visit it suggests a significant growth in the number of ground controllers required to support a Mars planetary mission unless a new paradigm for ground control of long-duration, deep-space operations is developed.

Because ground and astronaut crews will both be involved in monitoring for Mars DRM vehicle and habitat system health (Drake, 2009, p. 30), a highly automated system architecture could substantially mitigate the operational impact of system health monitoring and space-based system maintenance (Drake, 2009, p. 74). Improved system efficiencies and reliability are anticipated for the Mars DRM, from increases in ground and surface operations automation, in-space system autonomy, improved fault tolerance of system operations, and automated FDIR (Drake, 2009, p. 64). These improvements are especially critical given the unavoidable communication latencies and intermittencies between ground and vehicles in transit or on the remote planetary surface. The specific augmentations needed for autonomy will depend on the specific mission phase, vehicle, and the presence of crew on board.

6.4.3 Robotic Operations

A uniquely important aspect of crew activities in the Mars DRM is their operation of a variety of robotic systems on the planetary surface. Crewed exploration will bring human perception, motor dexterity, and intellectual acumen to the planetary surface, removing limitations that constrain remotely operated, time-delayed precursor robotic missions. Robotic operations on the surface will be subject to communication lags ranging from tens of milliseconds to tens of minutes depending on operator distance from Martian worksite, i.e., on Earth, during transit, or on Mars. Specifically, once on the surface, crew may be suited or unsuited during interactions and have some to near zero communication lag depending on proximity and on the communication infrastructure on the surface. The ground team, while potentially acting as a backup to the crew, will monitor and possibly command the robotic agents with round-trip latencies as high as 44 minutes.

Though acknowledged as a key future challenge (Drake, 2009, p. 64), detailed information is not available on the number and types of dexterous or large, heavyweight manipulators and how exactly they might assist the crew in the execution of procedures. Based on NASA’s space robotics experience on ISS and the Martian surface, planetary exploration will likely require large and dexterous manipulators (e.g., Fong et al., 2013). One new robotic capability repeatedly mentioned in Mars DRM 5.0 is surface drilling. This drilling equipment, which will be carried or towed by the pressurized rovers, will enable subsurface science exploration at depths up to 1000 meters. While drilling robots will be largely autonomous, it is acknowledged that astronauts intervention will be needed in order to ensure successful task completion (Drake, 2009, p. 38).

Robotic agents will be used for site preparation before astronauts arrive, or even in lieu of crew. Mars DRM 5.0 discusses the pre-deployment and use of nuclear power, ISRU facilities, and their corresponding radiation shielding. Pre-deployment of an above ground reactor and shielding will require robotic deployment, all commanded and monitored from Earth. Dexterous robotics will also be required to maintain or repair nuclear power assets that crew cannot approach due to radiation hazards. Additionally, it is likely that robotic agents will facilitate establishing the underlying infrastructure. For example, such equipment could be pre-deployed to excavate for piping or electrical conduit, or to build berms for radiation shielding. Though not selected, Mars DRM 5.0 considers robotic deployment of solar/regenerative fuel cell power systems (Drake, 2009, pp. 70).

Similar to NASA's current Mars rover missions, the DRM envisions use of mobile science robots to collect samples at specific areas the crew should avoid in order to prevent biological cross-contamination. Significantly different from current robotic operations, these robots will be teleoperated by astronauts on Martian surface. The DRM specifically mentions teleoperating robots from within the pressurized rover. It is likely that astronauts, with the support from ground teams, will command and control these science robots with and without spacesuits.

Small mobile robotics agents will also be used as scouts (see also Fong et al., 2013), which is a paradigm shift from current space robotics operations. Mars DRM 5.0 emphasizes science exploration, and hence, the importance of mobility/crew-transport and an increased number of surface EVAs. Teleoperated robots will play a key role in science exploration preparation by scouting terrain, i.e., providing reconnaissance information about traversability, hazardous zones, and higher resolution data to inform science objectives. Although not specified in the Mars DRM, some mobile platforms could fly through the Martian atmosphere to efficiently carry out scouting and mapping operations. Rovers (small robots and/or larger assets) will pre-position supplies in caches for crewmembers exploring the surface at a distance from the habitat base. These caches would contain commodities for life support and power, extending and maximizing the range of scientific surface exploration. Operators will monitor and command surface robotic assets with various communication lags, depending on their location and the communication infrastructure available. It is unclear the exact role the ground team is expected to have, but they may need to manage some mobile robots if the task or the number of robots, and consequently the workload, becomes overwhelming to the limited number of onsite astronauts.

There will be up to four pressurized and unpressurized rovers for this DRM (previously described in the Spacecraft Guidance subsection), which will be used for payload operations, e.g., transporting, collecting, and following, and conducting surface and subsurface exploration. These robotic activities may be carried out autonomously or under teleoperation.

As noted in the System Management subsection for this DRM, highly automated system architectures could substantially mitigate the operational impact of monitoring systems health and conducting space-based system maintenance (Drake, 2009, p. 74). Thus, while specific augmented-intelligent systems have not been defined in the Mars DRM, it is likely that these decision-support systems will interface with the crew, helping them by providing state information on systems such as power, ECLSS, or navigation, as well as more general aids for decision-making. Crew, to a certain degree, will have to be self-sufficient. Given the number of envisioned surface EVAs, some level of autonomous support will be desirable. These augmented-intelligent systems may be present while crew is suited, under various gravity conditions, unsuited, and within a pressurized mobile environment. These systems are not meant to eliminate conventional control techniques in that the crew will always be able to use the intelligent system as a "backup" interaction method. Increases in ground and surface operations automation, in-space system autonomy, improved fault tolerance of system operations, and automated FDIR are expected to yield improved system efficiencies and reliability (Drake, 2009, p. 64).

Because such augmented-intelligence decision-support systems will always be resident with the crew, their use will not typically involve communication lags. Ground interactions with these Intelligent Systems, other than updating software or providing data, have not been defined in the Mars DRM. However, the ground team, if engaged, may want to monitor crew interactions with these systems.

6.4.4 Mission Planning

While the ground team is expected to support all crewed and uncrewed operations, they will have complete responsibility for uncrewed assembly and deployment phases. Priori to crew launch from Earth, the ground team is expected to conduct and complete all staging, assembly, checkout, and monitoring operations for an unprecedented number of pre-deployed assets. These include a variety of Mars surface stationary and rover assets, the Descent/Ascent Vehicle prior to being occupied and the Crew Capsule and MTV, which remain in Mars orbit while crew is on the surface. These operations will be subject to various communication lags, from short (hundreds of milliseconds) to very long (tens of minutes) (Drake, 2009, pp. 5–6).

Strategic planning by the crew will likely be similar to ISS. The increased time delay will likely encourage use of more text-based planning tools than voice communication with ground. Unless there are long and unanticipated communication disruptions with ground, delays are unlikely to be significant enough to disrupt planning,. It is assumed that ground will conduct all strategic planning but that crew will work with the ground in developing plans. The mission outlines will contain detailed activities to ensure that crew safety requirements and mission objectives are met. Nevertheless, because many specifics of these plans will be based on initial findings on the surface, the crew will play vital role in determining the specific activities needed to meet general mission objectives (Drake, 2009, p.4).

While some level of crew autonomy will need to be supported from ground for the Mars DRM, how that will be accomplished operationally is still undetermined. It is unclear to what extent, crew tactical activity planning will be different from existing ISS processes. As noted above for strategic planning, increased time delay that would make direct vocal communication challenging is not likely to impact of text-based communication, unless there is extended and unanticipated loss of communication with the ground. While there is no explicit indication in the Mars DRM, it is assumed that ground will do some tactical activity planning while still giving the crew some autonomy for tactical planning as well.

While there is no explicit indication within the Mars DRM, it is assumed and highly likely that crew, though they will have been extensively trained before launch, will have to train in-transit and on the surface to maintain (refresh) competencies and develop new unanticipated ones, such as for new activities to be executed and learning science payloads. Training will be accomplished through specific devices but also may be embedded as a special training mode within existing userinterfaces. As the transit vehicle approaches the planetary surface and the communication delays decrease, some types of practice operations with surface assets will be possible. These conceivably could even transition to the conduct of some actual operations before arrival. The ground team is expected to support training throughout, but with lengthy communication delays (Drake, 2009, p. 67).

Because of the crew's remoteness and isolation during transit and on the planetary surface, they will have to conduct a greater variety medical procedures than currently planned for ISS, including diagnosis, laboratory analysis, anesthesia, and surgery (Drake, 2009, p. 66). These procedures will have to be executed with significant autonomy because of the generally long (up to 44 minutes) round-trip communication delays with Earth. Astronauts will likely have to leverage augmented intelligent systems for medical procedures. Though not mentioned directly, the use of specialized physical tools and medical robots within the pressurized volumes is likely. Hence, specialized manual and robot-like tools will need to be developed to meet the unique medical challenges of extended planetary habitation. The ground team is still expected to monitor and conduct telemedicine, particularly for diagnosis and treatment (Drake, 2009, pp. 64-66).

6.4.5 Limitations of Assessment

It is important to note that while many HAR interaction situations were identified, the documents (Drake, 2009; National Research Council, 2014) reviewed in this section emphasize higher level programmatic and architecture design issues and trade analyses (e.g., candidate Earth-Mars-Earth transit trajectories, surface power solutions, science exploration and objectives, etc.) that were considered in the formulation of the Mars DRM. Because of the breadth of the architectures involved, the cited documents do not delve to a level of detail sufficient to depict all robotic and automation systems or all of the specific HARI use cases that can be expected to arise to during a mission. Rather, the Mars DRM merely lists space vehicles such as heavy-lift launch systems, crew vehicles (e.g., Orion, MTV, etc.), and surface systems such as habitats and rovers, and states whether these elements will be deployed before the crew launches. Documentation on concepts of operations (ConOps) would have helped better identify HARI use cases across the full spectrum of exploration tasks. Such specific identification would provide a more concrete understanding of where the mission HARI challenges reside.

Although the Mars DRM does not explicitly describe controls and displays for HAR interactions, the document, in general does emphasize the advantages of commonality across different Mars mission elements, and between elements of different missions from the standpoint of development costs, system redundancy and the number of systems that ground and astronaut crews will need to learn to operate and maintain (Drake, 2009, pp. 34, 67). When brought to bear on HAR interaction design, commonality principles could be expected to yield similar cost, redundancy, and ease-of-use benefits (e.g., Fong et al., 2013). Additionally, it was presumed that HARI methods and designs available for a mission twenty or more years in the future will parallel or be directly based on those for current related crewed and uncrewed space mission systems (e.g., Fong et al., 2013).

7. Summary of Evaluation Limitations

Because of the breadth of the architectures involved, the cited documents do not delve to a level of detail sufficient to depict all robotic and automation systems or all of the specific HARI use cases that can be expected to arise during a mission. For example, our HAR tasks analysis was not detailed enough to extrapolate HAR integration needs based on individual automation and robotic capabilities that would be expected to result from a specific system, such as the Asteroid Robotic Retrieval Vehicle. Most notably, the Asteroid Robotic Retrieval Vehicle is only present in one DRM. However, that is not to say that the technology development from such a system could not benefit other systems in other DRMs.

While many human-automation/robot interactions were directly identifiable from the DRMs, some had to be inferred or extrapolated from the mission description. The DRMs are still in work and many of their objectives are still in flux, which leads to significant uncertainty about the human-automation/robot interactions that actually will be required. There still may be other HARI needs that have not yet been identified and that therefore do not exist in any documented form. Further, regardless of whether they have yet been identified, needs may change numerous times before mission is implemented. Thus, this assessment comprises our best guess of future HARI design needs at this point in time.

One lesson learned from this assessment is that the DRMs are inconsistent with their description of expected interactions between operators and automation/robotic system. Additionally, there was little mention of the type of interaction, i.e., whether crew or ground was expected to have intermittent or continuous communication (or both) with these automation and robotic systems. In the absence of documentation on ConOps to better identify HARI use cases across the full spectrum of exploration tasks, it is difficult to provide a more concrete understanding of where the mission HARI challenges reside. Short of ConOps documentation, it would be beneficial for the DRM development community to use a consistent categorization of the expected type of human-automation-robotic interaction. Our assessment was based on a very simplistic categorization (monitor, command, or both). Potentially in future DRM development, HAR tasks could be described relative to how frequently operators are expected to interact with a given subsystem or robotic agent (e.g., must command this system once a day).

Assessing the NASA DRMs limited the types of HARI tasks that could be identified. At least three types of HAR tasks were included in our assessment: tasks that enable other mission objectives, tasks that support crew autonomy, and tasks that alleviate crew time. Nonetheless, these task types were not fully employed within the DRM documentation that the team obtained. Consequently, additional resources, like the NASA Technology roadmaps and published reviews of future human-automation-robotic integration needs were leveraged for a more complete view of potential HARI tasks.

Most of the DRM documentation focused on major components of the respective mission architectures with very little discussion of the automation/robotic systems that could enable other mission objectives. For example, telemedicine will be critical in future planetary missions, likely requiring new automated systems and/or medical robotics. Another example is the control of robotic agents that support surface EVAs such as a supply-carrying robot to replace Apollo's Module Equipment Transporter (MET). Specifically, mission objectives will require crew to interact with other automation/robotic systems that will need to be designed specifically to support science, telemedicine, and training.

Additionally, the DRMs did not explore or delineate the types of automated and/or robotic systems required to adequately support the crew's autonomous execution of mission tasks (i.e., autonomous from ground control). At this time, it is still unclear which systems will be necessary to accomplish this goal. Hence, future NASA technology development roadmaps in this area could benefit from evaluating current and future automated/robotic systems.

Similarly, the DRMs did not elaborate on automation/robotic systems that could increase available crew time or make it more efficient. While the DRMs identified robotic systems that increased surface capabilities (e.g., heavy lifting robotic arms), mention of robotic systems that increase available crew time are absent. A significant issue with current ISS space operations is the limited amount of time astronauts have available for the conduct of onboard research. A recent study suggests crew will have even less time for science in future missions (Mattfeld et al., 2015). By completing repetitive tasks, automated, intra-vehicular robotic systems could offload crew time. For example, robotic agents could be assigned maintenance tasks. Surface DRMs will necessarily increase maintenance chores simply due to the greater number diverse assets (from habitat to robots and rovers). In turn, the deployment of such robots suggests emphasizing the development of Earth-bound operator-control HAR interfaces for remote robotic agents. Further evaluations of current and future systems will be required before determining the scope of these HAR tasks.

8. Discussion and Future Work

Four DRMs (Deep Space Sortie, Lunar Visit/Habitation, Deep Space Journey/Habitation, and Planetary Visit/Habitation) were assessed according to the procedure described above. The first step was to determine the distribution of system classes across the DRMs. Though details are not included in this paper, our team also identified which HAR task categories (Spacecraft Guidance, System Management, Robotic Operations, and Mission Planning) were expected for each system class. Not all task categories were attributed to all system classes. For each HAR task category (per system class), our team determined or inferred the type of human-automation-robotic interactions and the human-automation-robotic factors that would dominate the HAR integration design. Overall, this assessment provided insight as to which are the most critical future HAR integration design needs from the DRM perspective.

One result evident from this study is that the distribution of systems requiring human-automation-robotic integration across DRMs is unbalanced between surface and Deep Space DRMs. Many more systems are required for surface than for Deep Space DRMs. Similar to a recent National Research Council report, each DRM builds upon its predecessors, with a growing need for more systems and elements as missions become more complex.

The four types of HAR task categories received unequal consideration across the DRMs. Spacecraft Guidance and System Management tasks were most prevalent with very little emphasis on Mission Planning tasks. Discussion about Robotic Operations tasks was unevenly distributed across the DRMs. We noted that many of the assumptions about the capabilities of future of automation and automated vehicles is beyond current NASA human spaceflight operational experience and will therefore require new human-automation integration design and verification methods. Moreover, while many of the Robotic Operations tasks are conducted remotely (i.e., telerobotics), there are a variety of new robotic systems for which novel human-robotic integration design will be necessary.

The Human Exploration Architecture Team (HAT) evaluates a wide range of DRMs such as missions to Phobos and the Earth-Moon Lagrange Points. Most recently, the Evolvable Mars campaign (Craig, Herrmann, and Troutman, 2015) has gained prominence. Evolvable Mars includes several destinations, with each program advancing the necessary technology to reach farther into our solar system, with the ultimate goal of landing on Mars. Principally, our assessment has evaluated each of the campaign's stepping-stone destinations, from cislunar, Moon, asteroid, and deep space habitat, to Mars. Thus, the implications of our assessment will likely extend and apply to the Evolvable Mars campaign as a whole.

Future work will focus identifying promising technologies to perform the HAR tasks required for future human exploration missions, evaluating the human integration and HARI design challenges of these systems, and identifying the near term research needed to develop these technologies and evaluate their feasibility.

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