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Concept of Operations for the Gateway

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Abstract

NASA has outlined a phased approach to expand human presence deeper into the solar system starting with the Moon. Phase 1 of this plan begins in the 2020s, with missions in cislunar space and assembly of the Lunar Orbital Platform-Gateway. The Gateway is an evolvable, flexible, and modular space platform in lunar orbit. It can support crewed missions 30 to 60 days long, with increasing duration each mission. When the Gateway is uncrewed, robotic science missions will be performed. The Gateway allows astronauts to practice the skills and test technologies needed for months and years beyond Low Earth Orbit. A key to success for these deep space missions will be carefully coordinated operations by ground support, flight crew, and autonomous spacecraft.

Lockheed Martin Space is designing Gateway concepts as part of NASA's NextSTEP study contract. Additional operational considerations will be made to accommodate science payloads that would use the Gateway as a communication relay, platform for in-space or remote robotic missions to the lunar surface, and remote experiments during untended periods. The Gateway is modular in design to incorporate international cargo and logistics modules, additional habitat modules, and perhaps crewed lunar landers. These operational considerations are also being designed into the system. Working through the operational practices and relationships between the crew and ground control at the Gateway will provide the groundwork for future missions to Mars requiring more autonomy, such as Mars Base Camp missions. For example, robotic operations on the lunar surface, conducted by scientist astronauts, are directly translated to the exploration of the Martian surface by rovers and Unmanned Aerial Vehicles from a Mars orbital platform. As preparations are made for missions to Mars, more autonomy will be required and the interactions between the crew, ground and autonomous spacecraft systems need to be refined.

I. Introduction

NASA has been working with United States industry partners and International Partners to define the next step in human space exploration, the Gateway. Lockheed Martin Space (LM Space) is currently working on a design of the Gateway through the NASA funded NextSTEP Habitat program. As NASA looks to expand human presence deeper into the solar system, new operational concepts and considerations need to be developed, leveraging the past experiences in industry and agency such as the International Space Station and interplanetary robotic spacecraft, while focusing on the future where communication delays may drive more automation and crew involvement in operations. This paper will discuss an overall operations concept for the Gateway, how the different ground operation centers could interact as well as operations occurring at the Gateway itself, both autonomous and crew involved.

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II. Gateway Overview

The Gateway is a space platform in cislunar space which can support crewed missions of 30 to 60 days in length, with increased duration each mission. For the remainder of the year, there are opportunities to continue lunar science as well as other deep space science and operations without the crew present. The Gateway is comprised of several elements which provide key capabilities for cislunar exploration; a habitat where the crew would live and work, a self-sufficient power and propulsion bus with docking capability, an extra-vehicular activity (EVA) with an airlock for spacewalks and storage, and a cargo/logistics pod for supplies and trash disposal.

The LM Space Gateway concept can be seen in Fig. 1. The Habitat Element provides the Orion crew with additional living space and contains the science stations which can be configured for specific missions. The Power and Propulsion Element (PPE) is the primary source of power and propulsion and is attached to the habitat. The PPE can operate autonomously for extended periods of time while uncrewed and allows Orion to control the Gateway when astronauts are present, providing robust crew safety. The Extra Vehicular Activity (EVA) Element allows for the crew to exit for space walks and consists of an airlock and equipment bay for spacesuit storage. The Robotic Arm is operated from inside the habitat and provides astronauts the ability to assist in docking procedures and perform extra vehicular operations without leaving the Gateway (i.e. inspection and tending to external science experiments). The final element of the Gateway is the cargo and logistics pod which will allow supplies to be brought to the Gateway as well as trash disposal. The Gateway is designed to be robust and configurable, allowing for international partners to contribute to on-board science experiments or even major subsystems.

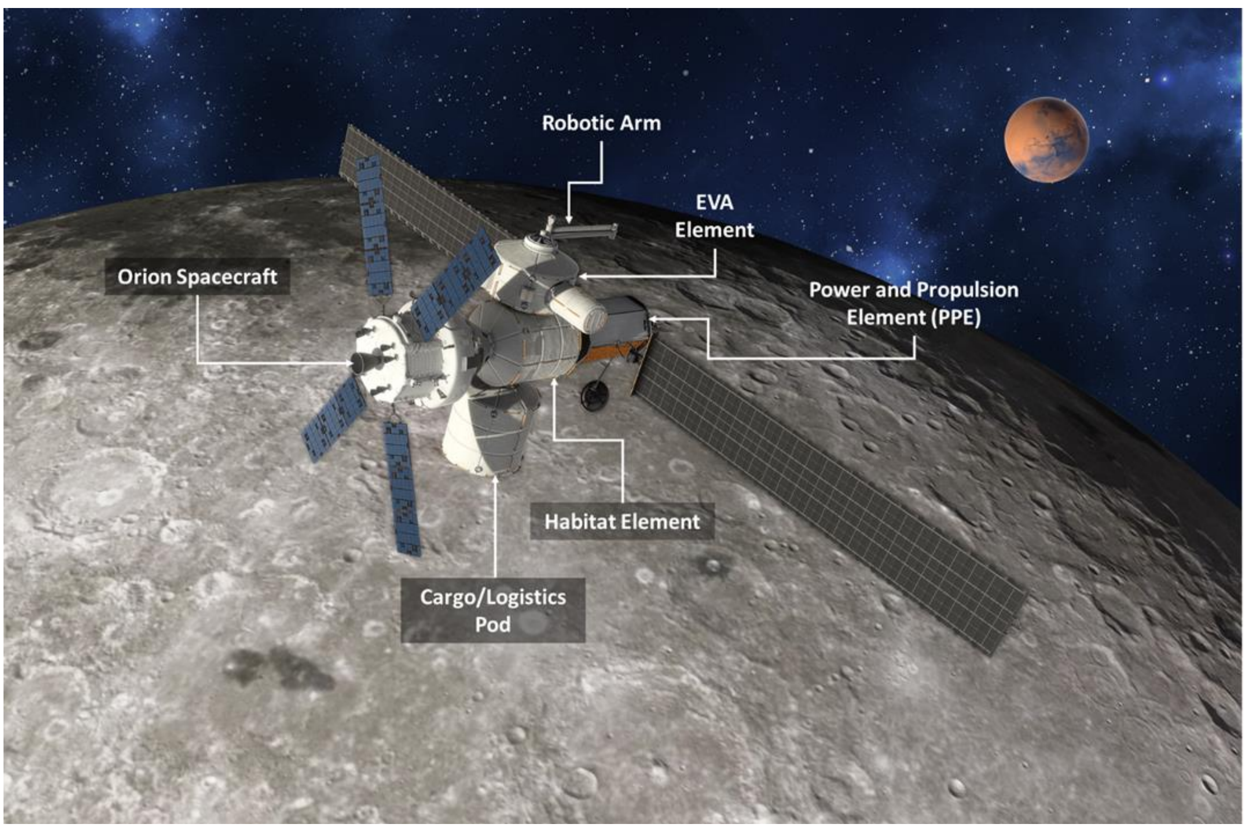

Figure 1. Lockheed Martin's Gateway Concept.

III. Operations Overview

As the next step in the progression of human spaceflight into deep space, the Gateway provides the unique opportunity to merge the strengths of human and robotic spaceflight missions. The Gateway could capture an optimal balance point of the human-machine interface by finding and implementing that ideal combination of crewed and uncrewed capabilities. This optimization can be achieved in part through a symbiotic relationship between the Gateway and the Orion crew vehicle. Because of this integration with Orion and this symbiosis between human and robotic capabilities, a large portion of the workload for maintaining the Gateway will be shared across multiple automated and remote systems. The more-complex Orion systems can be replaced or refurbished on Earth, and the simpler Gateway systems will mostly be maintained remotely and robotically with minimal astronaut servicing. As a result, the astronauts will have more time to spend on science objectives and mission support. And when the Gateway is uncrewed, its systems will be sufficient for operating as a remote robotic spacecraft.

From a ground control center perspective, the operations teams will need to coordinate between an array of ground facilities. For 11 months, while the gateway is uncrewed, the gateway can be operated as an interplanetary spacecraft until preparations for crewed operations begin. A few weeks before crew arrival, gateway systems checkouts will occur, and the gateway will be configured for crew occupancy. A crewed Gateway control center could be brought online at the MCC, where specialist console positions for the crewed portion of flight can be staffed. At this point, the primary command path would be transitioned and the uncrewed Gateway control center would act similar to the mission evaluation room (MER), and provide engineering support as well as be the backup control center in case of any problems or emergencies. As the Gateway systems are being checked out, the Orion spacecraft will be launching to bring the crew to the Gateway. At this time, the Orion control center in Houston will be brought online and perform as the primary control center for Orion. From a Gateway perspective, the Orion control center will support Gateway coordination for crew arrival. After completion of that mission and departure of the Orion, the mission authority transfers back to the uncrewed Gateway control center for remote uncrewed operations. At this point, the crewed Gateway control becomes a support control room that provides access to mission data for mission managers and science planners as well as act as a backup control room. During all crewed and uncrewed phases of operation, the crewed and uncrewed Gateway control centers will interface with payload control centers to coordinate and command science, relay, and telerobotics operations. Figure 2 shows the mission authority timeline and transfer of responsibilities between the different ground control centers and Fig. 3 shows the Orion Mission Control Center at NASA JSC.

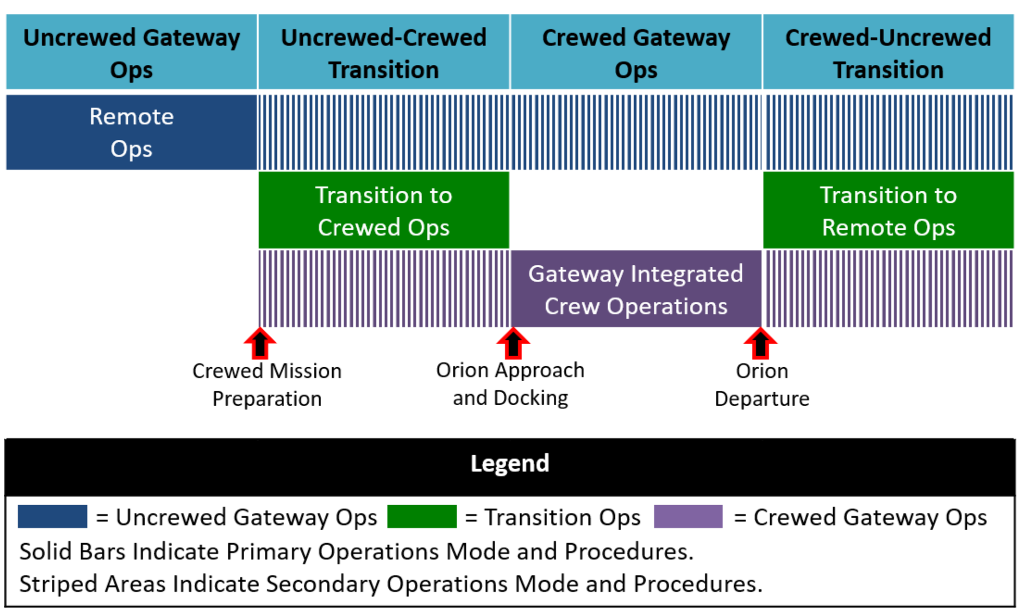

Figure 2. Mission Authority Timeline. *Definition of transfers of mission authority throughout mission phases ensures the safety of the crew.*

Figure 3. Orion Mission Control Center at NASA JSC [7]
(Image courtesy of NASA)

IV. Configuring The Gateway For Crew

The Gateway will be operational in both crewed and uncrewed modes. In each mode, the space platform will behave in different ways. With humans onboard, the Gateway will provide limited autonomous capabilities, leaving humans as the primary sources for executing decisions. The onboard autonomy will mainly provide telemetry and data analysis, with recommended actions for certain subsystems such as hardware health monitoring and maintenance. A limited subset of non-critical subsystems such as the lighting controls might reside within its autonomous capabilities, but the humans would always have override capabilities and insight into all of its actions. Per NASA JSC's FLOAAT (Function-specific Level of Autonomy and Automation Tool) scale, crewed autonomy would be rated between levels 1 and 6 across the four defined categories of functionalities (observing, orienting, deciding, and acting). A majority of the system and subsystem tasks would hover around levels 3 and 4, allowing the computer to be the primary source for data analysis and prioritizations and the human to be the primary source for decision execution [1,2].

Prior to crew arrival to the Gateway, several largely autonomous operations will need to be performed to transition to a crewed configuration. The first of these is a proper insertion of the Gateway into the needed operational cislunar orbit. The scope of this operation could range from a routine orbit maintenance maneuver prior to arrival to a multiple week SEP burn to insert the Gateway into a different cislunar orbit optimized to the mission goals of that particular crewed segment. In either case, the burn would be preceded by a slew maneuver with fine control required through the burn duration. The mission would be timed to rendezvous and dock at the most favorable position in the orbit. In the case of an NRHO orbit, this is likely immediately following the perilune orbit maintenance maneuver and burn.

The space environment within the pressurized segments of the Gateway would need to be brought up to crew standards and verified prior to opening the hatch between Orion and the Habitat. Again, the degree of change levied on the autonomous operations of the Gateway would vary depending on the relative state between uncrewed and crewed operations. If biological experiments had been included in the preceding uncrewed segment, these adjustments might be subtle. Regardless, the Gateway environment will need to be set and maintained at the prescribed habitable internal pressure and temperature limits. This transition may require the activation and checkout of previously offline ECLSS equipment.

In preparation for docking with the Orion spacecraft, the Gateway will need to be positioned so that Orion will approach in the tail-to-sun orientation. The Gateway reaction wheel subsystem will maintain attitude during the coarse approach operations of Orion or another visiting vehicle. The PPE will then shift into "idle mode" during the final approach portion and docking. Upon verification of a complete and successful docking operation, the Gateway will resume control of the increased stack making autonomous updates to compensate for changes in mass, moments of inertial and center of mass.

Once docked, the Gateway will transition to a crewed configuration control state. This includes an avionics mode switch enabling Orion console and tablet connectivity, display and commanding. While the PPE avionics will continue to provide primary command and control capability, crew interaction and override capabilities will be appropriately extended before the hatch to the habitat is opened. Gateway telemetry will be available to the crew via S-band communication throughout docking operations. Another transition that will be made upon arrival is in regards to the Fault Management System. This FMS crewed mode will be coupled with the Orion fault management and will also extend as needed to any element that is co-manifested with Orion with the intent to extend the Gateway. Other autonomous state updates will need to be made to reflect the now extended state of the Gateway including mass properties, thermal and ECLSS updates.

Finally, in preparation for a crewed segment, science platform preparations will likely be needed. These could include the installation or swap out of either internal or external science instruments. This will also be the opportunity for any scheduled refurbishing, maintenance and calibration. The operation of existing collectors will likely need to be incremented to reflect changes in geometry and field of view. The autonomous collection of data requiring precision pointing may need to be integrated with crew operations to work around exercise or other potentially disrupting activities. The specifics of these and many of the other stated transitions will be mission specific. Gateway flexibility and agility will be essential in the regular, largely autonomous transitions between a crewed and an uncrewed Gateway.

V. On-Orbit Crewed Operations

A. Control Center Interactions

Crewed operations need coordination between an array of ground facilities and staff in multiple centers that interact for real-time operations. Communications networks and many ground facilities support crewed and uncrewed operations on the International Space Station (ISS). For ISS, a network of NASA, International Partner, and commercial ground stations direct crewed and uncrewed vehicles. They drive robotic arms, operate science payloads, and deploy CubeSats at or near the ISS. Figure 4 below shows the distribution of the ISS centers spread across the Earth.

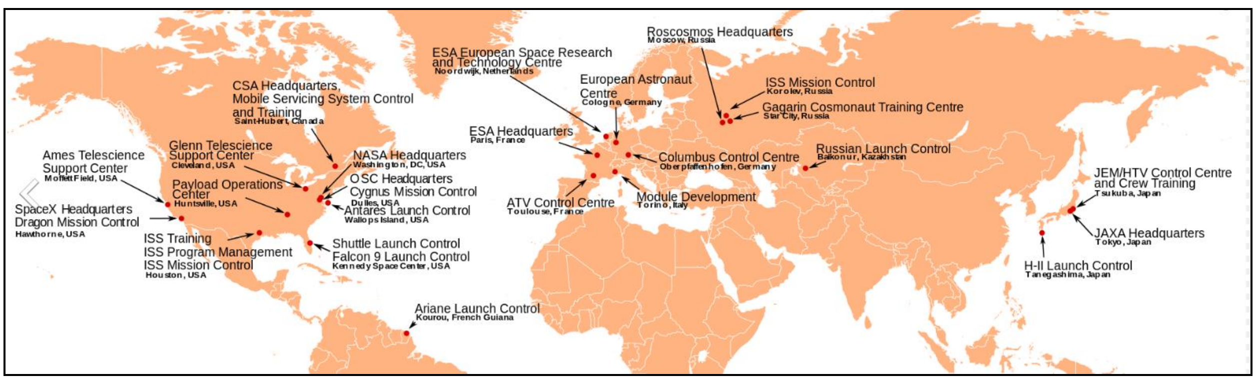

Figure 4. International partners perform ISS operations from an array of mission support facilities spread across the Earth. *Many of these sites will enable deep space exploration.* (Image courtesy of NASA)

This same dynamic is expected for lunar exploration. For lunar exploration some sites will perform pre-launch testing, using a test-like-you-fly approach. This pre-launch testing also informs flight and ground crew training at the different facilities. Support sites also enable on-board refresher training for astronauts in space during missions. Sites spread around the Earth provide continuous communications relay and storage of data produced by each mission. Different operations centers control launch vehicle, crew spacecraft, and cargo spacecraft. Figure 5 shows a sample of mission phases that ground sites conduct. Ground sites also support the Gateway, monitoring the station and its subsystems when crewed or uncrewed. Like ISS, these activities may include remote Gateway robotic arm use and control of future free-flying robotic units near the Gateway.

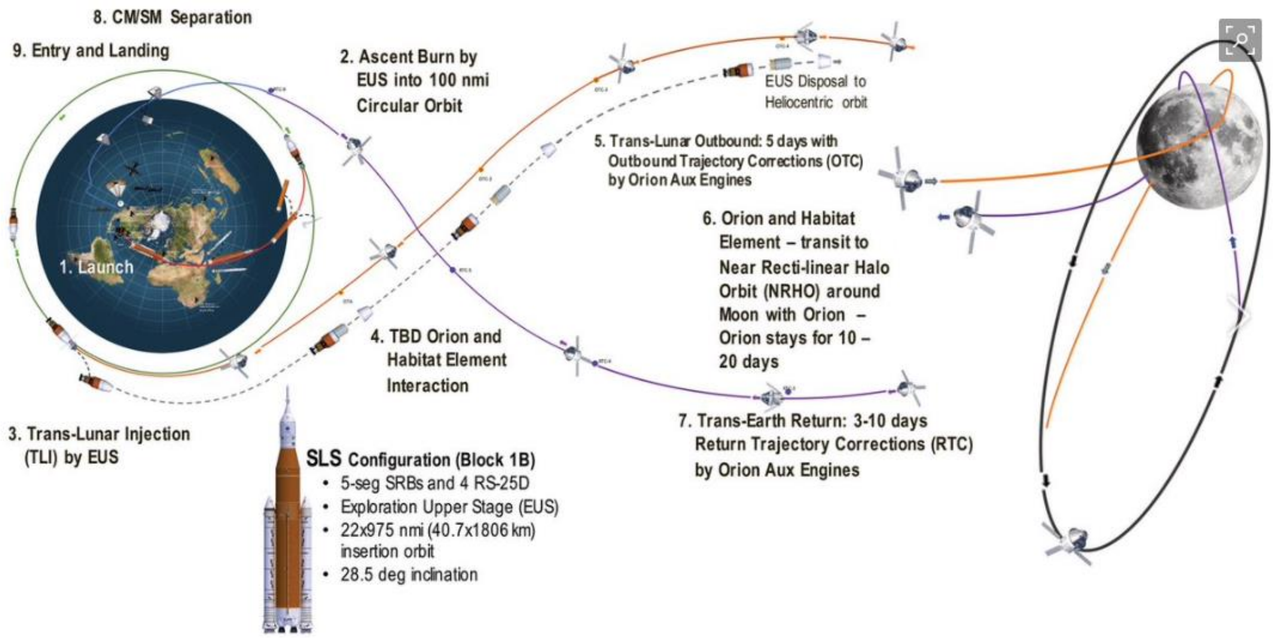

Figure 5. **Ground sites direct launches and spacecraft flight to and from lunar orbit.** (Image courtesy of NASA)

A new element may be needed for deep space exploration which is the command and control from the Gateway of other robotic elements. From a Gateway workstation, astronauts may control nearby CubeSats and SmallSats. They may monitor satellites in lunar orbit, track landers, hoppers and ascent stages, and teleoperate robotic vehicles to explore the lunar surface. This would be excellent practice for Mars exploration, where Earth mission support centers have long time-delays in communications during real-time operations.

VI. Payload And Science Operations

A. Payload Operations Concepts

The Gateway offers numerous capabilities in support of payloads, summarized in Table 1. These capabilities can support operations both internal and external to the habitat, thereby allowing for a diverse set of payloads to be hosted or remotely linked to the Gateway. A variety of payloads can be hosted on free-flying CubeSats, launched from and commanded by the Gateway. For payloads with limited communications range or obstructed line-of-sight, the Gateway can serve as a communications relay between the payload and control centers and operators on Earth. The Gateway could also provide local telemetry processing and data storage to: supplement payload instruments with limited on-board processing capability, enable store and forward data transmission, and provide an opportunity for autonomous commanding. Instrument payloads hosted internal or external to the Gateway can directly interface with the Gateway systems and be commanded by astronauts in the habitat or operators in the control center on Earth. Internal to the habitat, the crew set up, monitor and collect samples from experiments. External to the habitat, the crew deploys and maintain instrument payloads via extravehicular activities or through teleoperation of the external robotic arm.

The Gateway can also support robotic or human exploration of the lunar surface. Robotic landers and rovers are teleoperated by astronauts on the Gateway or by an operator on Earth using the Gateway as a communications relay. Crewed surface missions are executed with a lander docked with the Gateway, allowing astronauts to deploy new payloads, service existing payloads, and return samples from the surface. The lander could use the Gateway as a communications relay between the crew on the surface and a control center on Earth, including transmission of high data rate telemetry like video. Samples returned to the Gateway can be stowed by astronauts or robotically and are isolated from the rest of the Gateway environment.

Table 1. Gateway Payload Capabilities.

Gateway Payload Capability	Internal/External	Possible Features
Environments	Internal	• Radiation and Micrometeorite/Orbital Debris Protection • Pressurized and Climate-Controlled Environment • Unpressurized Cargo
	External	• Cislunar Space • Lunar Surface
Deployment/Maintenance	Internal	• Robotic Arm • Habitat Crew
	External	• Cubesat Launcher • Robotic Arm • Extravehicular Activity
Communications	Internal	• Wireless or Wired Ethernet
	External	• Spacecraft Crosslink • Deep Space Network Uplink/Downlink • Crew Radio Communications
Planning, Commanding, Processing and Storage	Both	• Support for CFS-compliant Applications • Telemetry Data Processing • Buffer and Archive Data Storage
Physical Interfaces	Internal	• Power/Data/Consumable Connections • Modular Instrument Bays
	External	• Power/Data Connections • Standard Mounting Fixtures
User Interfaces	Both	• Device Control Panels • Tablets • Telerobotics Workstation • Virtual/Augmented Reality
Lunar Surface Lander	External	• Robotic • Crewed
Sample Return	Internal	• Refrigerated Storage • Crewed Sample Collection • Robotic Stowage Transfer
	External	• Science Airlock • Extravehicular Activity • Robotic Capture/Stowage Transfer

The payload support capabilities of the Gateway enable operations of instrument payloads conducted locally or remotely, autonomously or by a human operator. Table 2 identifies the operations types and actors provided by the Gateway.

Table 2. Gateway Operation Types and Actors.

Operations Type	Operations Actor	Operations Description
Remote	Control Center	Telerobotics Remote Commanding of instrument payloads
Remote	Gateway Astronaut	Telerobotics Remote Commanding of instrument payloads
Local	Gateway Astronaut	Operations internal to the habitat Extravehicular activities
Autonomous	Gateway Computer	Pre-defined program execution Machine learning for closed-loop anomaly control

The diversity of operations types supported by the Gateway are critical to meeting its science and exploration mission objectives during both crewed and uncrewed phases. To illustrate this, Table 3 maps some of the anticipated mission activities to the operations types and actors that the Gateway supports.

Table 3. Gateway Mission Operations.

Mission	Suggested Activities	Operations Type - Actor
Astrobiology, Life Sciences	Set Up Experiment	Local - Gateway Astronaut Remote - Control Center
	Monitor Experiment	Local - Gateway Astronaut Remote - Control Center Autonomous - Gateway Computer
	Collect Samples/Results	Local - Gateway Astronaut Remote - Control Center Autonomous - Gateway Computer
Astrophysics, Heliophysics, Planetary Science	Instrument Deployment	Local - Gateway Astronaut Remote - Gateway Astronaut Remote - Control Center
	Instrument Commanding	Remote - Gateway Astronaut; Control Center Autonomous - Gateway Computer
	Data Processing	Remote - Control Center Autonomous - Gateway Computer
Lunar Science	Robotic Exploration	Remote - Gateway Astronaut; Control Center
	Crewed Exploration	Local - Gateway Astronaut Remote - Control Center
	Sample Return	Local - Gateway Astronaut Remote - Gateway Astronaut; Control Center
Preparation for Deep Space Exploration	In-situ Aggregation, Assembly and Servicing	Local - Gateway Astronaut Remote - Gateway Astronaut; Control Center
	Spacecraft Duty Cycle	Local - Gateway Astronaut Remote - Control Center Autonomous - Gateway Computer
	Technology Demonstration	Local - Gateway Astronaut Remote - Gateway Astronaut; Control Center Autonomous - Gateway Computer
	Proximity Operations, Rendezvous and Docking	Local - Gateway Astronaut Remote - Gateway Astronaut; Control Center Autonomous - Gateway Computer
	Resupply and Disposal	Remote - Gateway Astronaut; Control Center Autonomous - Gateway Computer
	Crew Health	Local - Gateway Astronaut Remote - Control Center Autonomous - Gateway Computer

B. Robotics Operations

Both internal and external robotic arms will be used to augment Gateway activities including crewed and uncrewed tasks. The internal robotic arm will be used for repetitive tasks while the crew are present, like removing CTBs and cargo from the Logistics Module as well as packing the module with trash. When the crew are not present the internal robotic arm can be used to monitor, start, and stop science experiments remotely. Such experiments might be starting vegetable germination prior to crew arrival, and even potentially assist in harvesting crops. When preparing for crew arrival the internal robotic arm is also used to clean and test the habitat module surfaces for bacteria growth. Additionally, when combined with robotic operations of the external robotic arm the two can be used in conjunction to remove experiments from the exterior of the Gateway, place them in the science airlock and prepare them for return to Earth once the crew arrive. These robotic arms can work both autonomously, telerobotically from the science workstation in the Gateway, as well as from the Gateway control center. The external robotic arm can also be used to assist with Extra-Vehicular Activities (EVAs) and for berthing of cargo/logistics modules; rendezvous and docking may occur autonomously or by berthing using the external robotic arm.

Figure 6. Notional Internal Robotic Arm.
(Image courtesy of Universal Robots)

Table 4. Crewed vs. Uncrewed Robotic Tasks.

Un-Crewed Robotic Tasks	Crewed Robotic Tasks
A/T: Routine & Maintenance inspection and tasks	A/T: Routine & Maintenance inspection and tasks
A/T: Pre-Crew-Arrival/Post-departure stage and configure	A/T: Off-shift (crew idle-time) stage and configure
A/T: Experiment tending and support • Sample placement and change out • Sort / Stow • Micro-greens germination and plant tending • Habitat spatial surveys – environment/stowage/etc.	A/T: Experiment tending and support • Sample placement and change out • Sort / Stow • Micro-greens tending and plant harvesting • Habitat spatial surveys – environment/stowage/etc.
A/T: Debris, Lost/Found Items, Collection and Containment	A/T: Debris, Lost/Found, Refuse Collection and Containment
---	A/T: Crew Assist – fetch/return/hold/retrieve/clear-clean
A/T: RMRA Experiments • Capability development	A/T: RMRA Experiments • Capability development • Device training with Crew
T: Contingency Support • Issue Localization and Isolation • Repair/Make-Safe	T: Contingency Support • Issue Localization and Isolation • Repair/Make-Safe, Enable ops with minimal crew risk
A: Autonomous T: Tele-operated (distant operator when un-crewed, distant or local crew operator when crewed)	

VII. Extra-Vehicular Activities (EVA)

There are three basic use cases identified for EVAs at the gateway in cislunar space. Assembly EVAs are used during build-up and construction of the gateway and include activities such as making umbilical connections, performing inspections, and deploying mechanisms. Utilization EVAs are focused around science and functionality of the gateway and include retrieving external science experiments and assembling large-scale external structures. Maintenance EVAs help to ensure the health and safety of the habitat and crew and include performing preventative maintenance and repairing external damage. The need for many of these EVAs may be diminished due to the autonomous design of modern spacecraft, however EVAs are a critical part of ensuring long-term success of the gateway. EVAs are especially important for troubleshooting anomalies and they provide the needed flexibility to expand or add science experiments that were not conceived as part of the original gateway design. While EVAs at the gateway in cislunar space will be different than EVAs at ISS in LEO, it is important to note that about half of the EVAs performed on ISS included tasks that were not planned as part of the original design.

One major difference between EVAs at the gateway compared to EVAs at ISS is the number and frequency of EVAs will be lower at the gateway. ISS is a large and complex spacecraft that has had 18 years of continuous crew presence in LEO. Over 200 EVAs have been performed at ISS to date with many those falling in the assembly and maintenance categories. In comparison, the gateway will be a much smaller and more autonomous spacecraft, and it will only be crewed for 30-60 days per year. Therefore, there will be fewer opportunities to perform EVAs at the gateway and a larger percentage of those EVAs will fall into the utilization category. Over time, maintenance EVAs will become more frequent as the robotic systems that enable the gateway to operate autonomously require more servicing. The need for more frequent maintenance EVAs as the gateway ages will be exacerbated by the harsher radiation and thermal environments at cislunar space compared to LEO. Additionally, since the gateway is intended to be a "port of call" instead of a "final destination" in space, EVAs will be needed to assemble and service visiting vehicles, such as a robotic lunar lander or Deep Space Transportation (DST) to take humans to Mars. This will be an entirely new type of EVA in the utilization category and will drive new procedures and support equipment.

A new, advanced EVA suit is being developed for use at the gateway, but the overall process for executing EVAs at the gateway will be largely the same as the process currently in use at ISS [3]. The first step is to prepare crew members and EVA suits in the equipment lock. The equipment lock containing the crew and suits is then isolated from the habitat and pressurized while the crew undergo a three-hour pre-breath and the suits are purged for 30 minutes. When the purge and pre-breathe are complete the crew don the suits, conduct checkouts, and move to the airlock with tools and equipment. The airlock is isolated from the equipment lock, suit tethers and umbilicals are connected to internal connection points, and pressure in the airlock is gradually reduced. When pressure in the airlock reaches 1.5 psi the hatch is opened and the crew egress the airlock into space. The suit tethers and umbilicals are moved to the external attachment points and tools are secured. The crew move to the worksite and conduct the scheduled activity for up to 5.5 hours. When work is complete, the crew enter the airlock, move the tethers to the internal connection points, and close the hatch. Pressure is slowly equalized with the equipment lock before the crew opens the hatch, enters the equipment lock, and doffs their suits. The equipment lock pressure is slowly equalized with the habitat before the hatch is opened and the crew enter the habitat, completing the EVA operation.

VIII. Cargo Modules And Visiting Vehicles

Cargo modules, sometimes referred to as logistics modules, and visiting vehicles are core elements of the gateway. As the name implies, cargo modules bring supplies to the gateway. Cargo modules are considered disposable, meaning they are not permanent elements of the gateway and are disposed of after fulfilling their purpose. Visiting vehicles are usually used to bring crew to and from the gateway, such as Orion, but can also include uncrewed and robotic vehicles.

A. Cargo Modules

During build up and assembly of the gateway, cargo modules will bring critical components, like ECLSS pallets, to the gateway that will be installed into the permanent habitation elements. Once gateway assembly is complete, cargo modules will supply the gateway with consumables and science equipment. Some cargo modules will be disposed of shortly after being offloaded, while others may remain at the gateway for extended periods, up to several years, collecting trash and providing pressurized storage volume. As with all gateway elements, cargo modules are equipped with International Docking System Standard (IDSS) compliant docking ports and the gateway can accommodate multiple cargo modules simultaneously due to its modular design. The gateway's external robotic arm will be used to manage potentially complicated configurations that may arise when multiple cargo modules are present.

Cargo modules, pressurized or unpressurized, may be launched co-manifested with a crewed vehicle, such as with Orion on NASA's Space Launch System (SLS), or supplied by a commercial or international launch partner. When co-manifested with a crewed vehicle, the vehicle's propulsion and docking system will be responsible for delivering the cargo module and docking it at the gateway. When launched by a commercial or international partner, the cargo module will be delivered to cislunar space by a propulsion element and berthed to the gateway using the external robotic arm. Pressurized cargo modules are relatively easy to accommodate at the gateway since they are accessible by crew nearly immediately after docking, while unpressurized cargo modules require special accommodations. Equipment can be extracted from an unpressurized cargo module by the robotic arm or by crew during EVAs.

B. Visiting Vehicles

One major function of visiting vehicles is to bring crew to and from the gateway. Orion will be a frequent visitor and the gateway will also accommodate visiting vehicles from international partners. Other crewed vehicles such as lunar landers, will typically provide their own propulsion and will be responsible for rendezvous and docking operations with the gateway. Preparations for crew arrival will be made in advance and since the visiting vehicle and gateway are both pressurized, the crew will be able to disembark the visiting vehicle and enter the habitation elements of the gateway quickly and easily after docking. While the modular design of the gateway will allow for multiple vehicles to visit simultaneously, this scenario presents complications and simultaneous visits will likely be transient in nature. One potential complication is conflicts between the multiple solar array systems. Another potential complication is the ability of the Power and Propulsion Element (PPE) support the increased loads from multiple vehicles simultaneously.

IX. Virtual And Augmented Reality

The emerging technologies of Virtual and Augmented Reality (VR and AR) have the potential to revolutionize human space flight operations. VR technology completely immerses users within a computer-generated simulation of a real-world environment, such as the Gateway, allowing them to physically interact with a photorealistic replica from a safe, remote destination. Whereas VR requires the user to inhabit an entirely virtual realm, AR bridges the gap between the digital and physical world by overlaying computer generated data onto the user's field of view. The following section explores some of the ways existing AR and VR technologies can be leveraged to enhance Gateway mission operations both on the ground and in-space.

A. Ground Training Operations

AR and VR technology can be applied to nearly all aspects of a mission lifecycle, beginning with astronaut training. Using VR, the entire mission crew can be fully immersed into a shared environment where they can practice both routine and emergency mission scenarios from the safety of the ground. Within the full scale digital simulation, astronauts can work as a team and identify areas for workflow improvements, leading to more streamlined procedures. Lessons normally learned in space can be identified in advance, reducing the probability of human error. As VR technology improves, it can potentially become a viable substitute for physical prototypes, leading to costs savings in the mission development phase. For the NextSTEP program, Lockheed Martin has already developed a VR prototype that allow users to interact with a full-scale Gateway. The unique VR simulation allows engineers to experience the exact dimensions and layout of each Gateway module, helping them identify opportunities to optimize the design to support anticipated mission operations.

Figure 7. Practicing On-Orbit Maintenancein a VR Simulation.

B. In-Space Operations

The combined capabilities of AR and VR can be used to enhance crew productivity and reduce errors during deep space missions. Using AR smart glasses, astronauts can remain cognizant of their physical surroundings while visualizing digital data that helps them quickly and efficiently make decisions and execute tasks. Instead of consulting a 2D list (paper or digital), AR can compile the necessary data and overlay it into the user’s field of view. For example, during an on-orbit repair, AR can display step-by-step instructions, overlay relevant health and diagnostic data, and grant the user “X-ray” abilities to visualize internal hardware. Visualization can also be used to guide astronauts during Extra-Vehicular Activities (EVA) by superimposing the optimal walk-path to their destination.

AR can also reduce the need to physically interact with components by allowing users to remotely control knobs and buttons through virtual touchscreens, voice commands, or gestures. From the ground, support teams can use the latest diagnostic data to generate a nearly identical VR environment to help troubleshoot during unexpected emergency scenarios. VR can also be used to perform telerobotic mission operations from the safety of orbit. VR can utilize video feeds from the rovers to virtually transport astronauts to the surface of an extraterrestrial environment, such as the moon.

Figure 8. Utilizing VR for Enhanced Telerobotic Mission Operations.
(Right image courtesy NASA/JPL)

X. Mars Extensibility

Operating at the Gateway prepares scientists, astronauts, and the exploration community for living and operating around Mars. As the International Space Station is protected within the Van Allen Belts and only a 45 min emergency return time, the Gateway provides a platform to transform and adapt operations to a deep space mindset, which will be the foundation for operations at Mars.

There are many challenges to living and working in deep space. The most obvious challenges come from distance from Earth. With a communication delay (two-way light time) of 2.5 seconds [6] for the Lunar nearside, astronauts will need to be more independent with respect to emergencies, EVA support, and lunar operations. Telerobotic operations from Earth to the lunar surface or the Gateway are still manageable. With a two-way delay at Mars ranging from 6 minutes to 44 minutes [6], only course navigational corrections for rovers, as seen with Curiosity and Opportunity, is possible. Additionally, these time delays would require the crew to be more self-reliant and incorporate redundancy into the architecture and operations. This is particularly important when planning for maintenance and repairs regarding bringing spare parts. 3D printed parts, made from materials that can be recycled, allow for a reduction in the number of spare parts that are required. Additionally, the Digital Twin health monitoring can pre-emptively warn crew if potential failure is statistically probable, so crew can 3D print new parts. Virtual reality or augmented reality allows the crew to learn on the job how to install and repair a specific part.

There are many challenges from a physical and psychological standpoint to living and working in deep space. Operations at the Gateway allow scientists and doctors to determine signs, mitigations, and treatments for long-term voyages, such as a trip to Mars.

XI. Conclusion

NASA's Gateway will be an evolvable, flexible, and modular space platform that will provide payload and science operations in lunar orbit with the support of crewed missions that last 30 to 60 days. Operational efficiencies and cost savings can be realized by an operations concept that incorporates the autonomy of an interplanetary spacecraft to operate the Gateway during uncrewed periods. Additionally, internal and external robotics will enable ground-controlled payload, science, and relay operations during both crewed and uncrewed periods. While crewed, the Gateway will utilize virtual and augmented reality to enhance crew operations and maximize the utility of crew time. A focus on efficient, modern operations and an increase in autonomy and robotics will be key parts of making the Gateway missions successful, and mature the capabilities needed for future Mars operations.

XII. References

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