The Orion Spacecraft as a Key Element in a Deep Space Gateway

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July 2017

Abstract

With the Orion exploration vehicle and Space Launch System (SLS) approaching operational status, NASA and the international community are developing the next generation of habitats to serve as a deep space platform that will be the first of its kind, a cislunar Deep Space Gateway (DSG). The DSG is evolvable, flexible, and modular. It would be positioned in the vicinity of the Moon and allow astronauts to demonstrate they can operate for months at a time well beyond Low Earth Orbit.

Orion is the next generation human exploration spacecraft being developed by NASA. It is designed to perform deep space exploration missions, and is capable of carrying a crew of 4 astronauts on independent free-flight missions up to 21 days, limited only by consumables. Because Orion meets the strict requirements for deep space flight environments (reentry conditions, deep-space communications, safety, radiation, and life support for example) it is a key element in a DSG and is more than just a transportation system. Orion has the capability to act as the command deck of any deep space piloted vehicle.

To increase affordability and reduce the complexity and number of subsystem functions the early DSG must be responsible for, the DSG can leverage these unique deep space qualifications of Orion. For example, Orion already contains sleep stations, a galley, and a toilet. Therefore, the DSG would not need those functions especially in its early stages of buildup (at most, one might choose to add two sleep stations to the habitat to increase personal space). This paper explores in more detail the many ways in which Orion can use its advanced capabilities to augment an early DSG, thereby decreasing complexity and improving affordability.

I. Introduction

Orion is a highly capable vehicle with unique features designed to meet deep space environments and keep crew members safe even given dangerous emergency scenarios. The investments made in Orion can be leveraged to reduce the cost, complexity and development timeline for a Deep Space Gateway (DSG).

With Orion operating as the command deck when crew is present, the DSG can be designed to a more affordable single fault tolerant architecture by utilizing the redundancy, performance, and safety built into Orion. Orion's robust fault tolerant design and capable avionics system enable it to provide the safe control and necessary interfaces for crew to interact with the DSG. Should an anomaly occur on the DSG, the crew can withdraw to Orion and use it as a safe haven while they continue to work to resolve the issue or safely return to Earth.

As technology matures and new mission capabilities are required in cislunar space, Orion will bring new systems in the form of Mission Kits to increase the capabilities of the DSG. NASA's goal to extend human presence in deep space can be accomplished affordably by integrating the existing investments in Orion with future development in the DSG.

II. Deep Space Gateway

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 Deep Space Gateway (DSG).[2] The DSG is a space platform in cislunar space which can support crewed missions of 30 – 60 days in length, with increased duration each mission. The DSG 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) element with an airlock for spacewalks and storage, and a cargo/logistics pod for supplies and trash disposal.

Lockheed Martin is currently working on a design of the DSG through the NASA funded NextSTEP Habitat program. The Lockheed Martin DSG concept can be seen in Fig. 1. The Habitat Element (HE) 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, propulsion and breathable air and is attached to the HM. The PPE is capable of operating autonomously for long periods of time while uncrewed and allows Orion to control the DSG 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 HE and provides astronauts the ability to assist in docking procedures and perform extra vehicular operations without leaving the DSG (i.e. inspection and tending to external science experiments). The final element of the DSG is the cargo and logistics pod which will allow supplies to be brought to the DSG as well as trash disposal. The DSG is designed to be robust and configurable, allowing for international partners to contribute to on-board science experiments or even major subsystems[3].

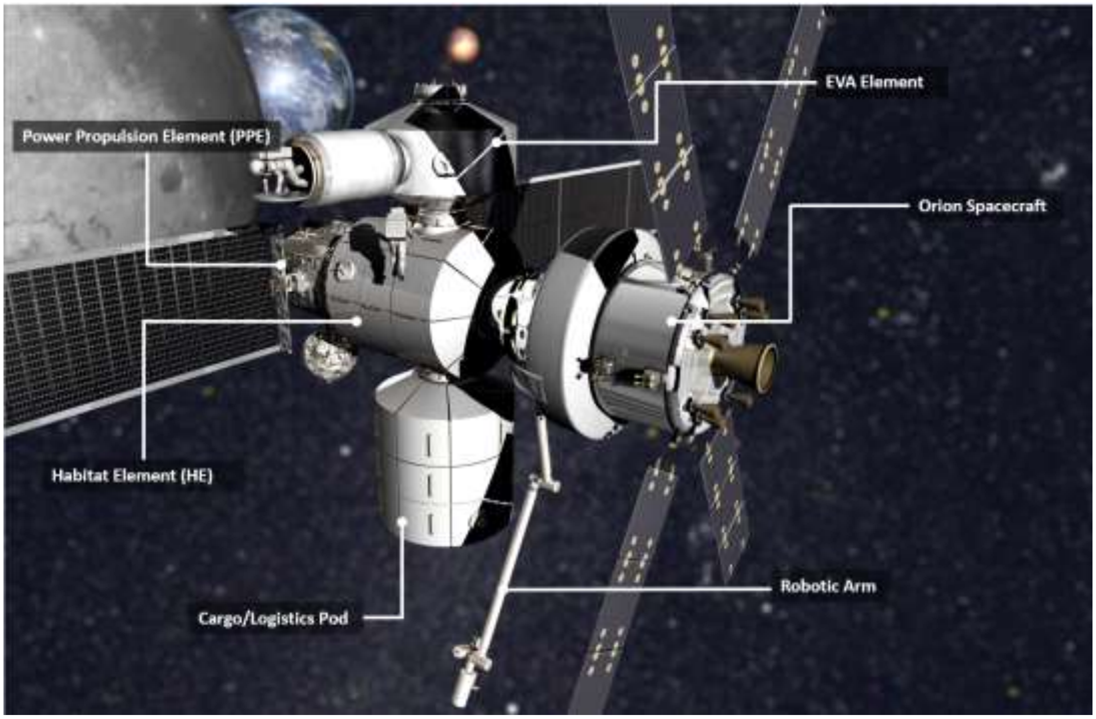

Figure 1. Lockheed Martin's Phase 1 DSG in Cislunar Space

III. The Orion Spacecraft

The Orion Spacecraft is a key element in NASA's human deep space exploration plans. NASA has designed the human rated Orion to meet deep space requirements and ensure it is robust from both a reliability and availability perspective. It can carry up to 4 astronauts on missions up to 21 days, limited only by consumables. During quiescent operations and/or while part of a larger architecture, Orion subsystems have the ability to support missions up to 1,000 days[1]. Orion is currently planning its next three test flights, Exploration Mission 1 (EM1), Ascent Abort 2 (AA-2) and Exploration Mission 2 (EM-2). For more detailed information on the upcoming Orion missions see reference[4].

Orion is comprised of three modules; the Crew Module (CM), the Service module (SM) which is composed of the European Service Module (ESM) and the Crew Module Adapter (CMA), and the Launch Abort System (LAS). Orion will be launched on the Space Launch System (SLS). The CM contains all the advanced subsystems to sustain a crew of four during deep space travel and provides safe reentry to Earth from deep space. The ESM is provided by the European Space Agency (ESA) and provides the in space propulsion capability, generates power, radiates excess heat, and carries the consumables (water, oxygen and nitrogen) to sustain the crew.

The CMA interfaces mechanically and electrically with the CM, and includes the separation mechanisms. The LAS protects the crew from the pre-launch, launch and ascent environments as well as provides the abort capability to remove the CM from any hazardous condition that may arise during these phases. The LAS also provides the propulsive capability for the LAS jettison.

Figure 2. The Orion Spacecraft Configuration

IV. Orion as the Command Deck of the Future

The most affordable way to send humans back to cislunar space in the near term is to leverage NASA's investment in current systems and technologies. Orion is a fully human-rated spacecraft designed to meet the strict requirements of deep space environments and challenging ascent and reentry environments. Aspects of the avionics, crew interface, life support, power, communication, and navigation systems on Orion can be utilized early on in the buildup of the DSG, to minimize duplication and rework and also provide a safe environment for astronauts to live and work. Using Orion as the command deck benefits the DSG without affecting Orion resource margins. This allows the DSG to become more independent in an evolutionary manner that aligns with affordability targets.

A. Command and Control

Command and Control of Orion was designed to cover critical functionality, availability and safety to meet key performance requirements. There are four redundant Flight Control Modules (FCMs) within the two Vehicle Management Computers (VMCs), shown in Fig. 4, which surpass the reliability requirements and ensure availability as Orion transitions through the challenging radiation environment of the Van Allen belts. As Orion prepares for reentry the vehicle transits through the Van Allen belts and the redundant FCMs are necessary to ensure sufficient radiation tolerance so that the crew is not waiting for computers to reboot when critical events such as thruster and pyro firings should be occurring. The FCMs provide a high integrity platform to house software applications, and have sufficient processing power to perform command and control of Orion as well as the Deep Space Gateway (DSG) without

Figure 3. Critical systems from Orion are leveraged by the Deep Space Gateway.

negatively impacting central processing unit utilization margins. Employing Orion as the command deck when docked with DSG enables a more streamlined approach to the avionics on the DSG. The planetary spacecraft utilized in New Frontiers and Discovery missions are a good model for the uncrewed portions of the DSG missions. The DSG command and data handling can be more akin to a deep space planetary mission with a single fault tolerant architecture because it relies on the reliability and availability built into Orion when crew is present. This allows DSG to work to similar cost and timeline constraints as planetary missions while maintaining a safe environment for crew through Orion.

Figure 4. Orion Vehicle Management Computer houses the Flight Control Modules that are the command source for the spacecraft and could minimize computing needed on the DSG.

The Orion Onboard Data Network (ODN) uses Time Triggered Gigabit Ethernet (TT-GbE) to provide data transfer within the vehicle as well as to interfacing vehicles. This is a triple redundant network capable of moving data at a rate 1,000 times faster than systems used on the shuttle and space station. This technology is built upon a reliable commercial data bus that has been hardened to be resilient to space radiation and proven on the Orion Exploration Flight Test-1 (EFT-1). The DSG will interface directly to the ODN via standard Ethernet. The redundant nature of the ODN ensures that critical commands leave Orion accurately and that essential telemetry from the DSG Command and Data Handling Unit (CDHU) is routed appropriately once onboard Orion. By selecting a standard Ethernet architecture, DSG is already compatible with NASA's Orion. Critical elements in the avionics network architecture are shown in Fig. 5.

In the unlikely event that something goes wrong with the primary flight computers on Orion, a dissimilar processing platform with dissimilar flight software is hosted on the Vision Processing Unit (VPU). The VPU provides a hot backup function to the redundant FCMs during critical phases of flight. This capability will also be utilized by astronauts aboard the DSG should emergencies arise in cislunar space.

Orion employs a wireless communication system to interface with cameras used to monitor critical events and crew activities. This system is capable of sending commands and receiving telemetry from end systems and is connected to a utility network that interfaces with the ODN. With the use of portable tablets and the Orion wireless communication system, the crew has flexibility to be in any area of the combined Orion/Deep Space Gateway and have insight into the critical systems of the cislunar station while having the ability to act on any urgent caution, warning or emergency alerts.

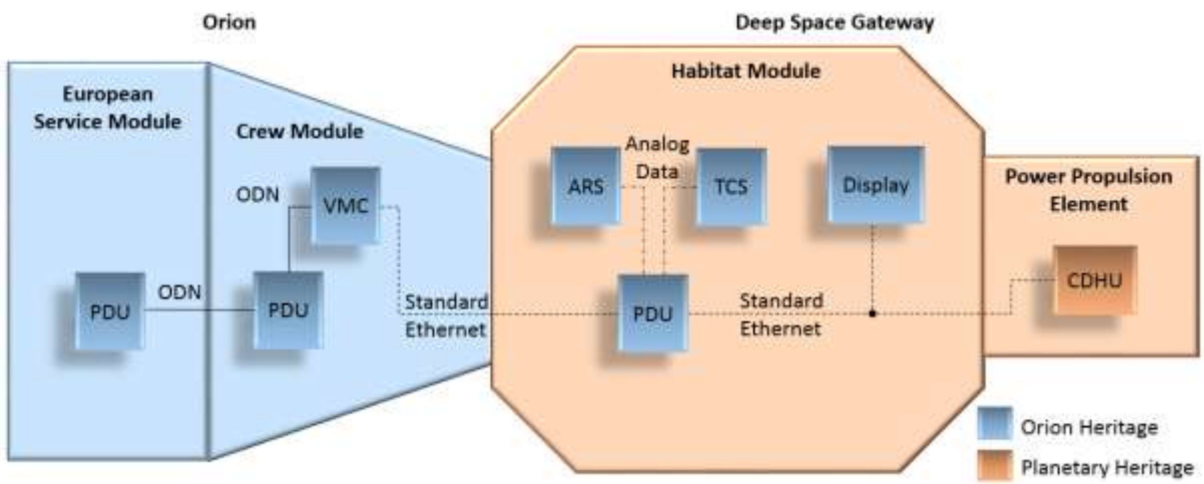

Figure 5. Significant Components in DSG Network Architecture

B. Crew Interfaces

The Orion Displays and Control equipment is the crew interface to the Orion systems. The Displays and Controls consist of three Display Units, seven Switch Interface Panels, two Rotational Hand Controllers, two Translational Hand Controllers, and two Cursor Control Devices, shown in Fig. 6. The Switch Panels and Hand Controllers hardware interfaces through serial interfaces to the Power and Data Units (PDUs) and then via the ODN to either FCMs within the VMC or the DUs for processing. The Display Units (DUs) utilize a variety of Display Formats to provide data to the crew for awareness and action when necessary.

The Orion Displays and Controls are designed for an intensive amount of crew interaction both in nominal and off-nominal scenarios. The Display Format Software Architecture enables streamlined addition of new formats via the Generic Display Engine; or, for more complex formats, via a library of reusable and common graphical elements. This library of graphical elements can be leveraged to facilitate development of unique formats for the DSG. The DSG formats will be displayed on the Orion DUs, a display within the habitat, or the supplemental wireless tablet. The DSG Display Formats allow the crew to interact with the DSG and provide insight into the health and status of the DSG systems.

Electronic Procedures have been developed for Orion that allow direct interaction with the Display Formats enabling reduced workload on the crew. The Electronic Procedures efficiently step the crew through planned tasks and reduce crew workload by highlighting various telemetry on a Display Format or queuing up commands. Additionally, the Electronic Procedures have built in links to the onboard Caution & Warning System which alert the crew when onboard faults and anomalies occur. The Electronic Procedures link provides the ability for the crew to bring up Electronic Procedures which communicate the urgent actions the crew need to take in order to address the Caution & Warning condition. This same methodology will be employed on the DSG to allow the crew more time for performing science and robotic missions by minimizing maintenance and sustainment tasks on the DSG. Utilizing a DCM within the habitat and similar display technology allows for seamless integration with the Orion displays and familiarity for the crew for operations.

C. Power

The Orion power system is capable of generating and supplying more power than is required for its on-orbit operations and surplus power can be shared with the DSG to supplement crew survival equipment and science experiments. Because Orion power margins are a critical resource, the DSG also supplements the Orion power with the PPE solar panels. The four Orion solar arrays generate about 11kW of power and spread 62 feet when extended. Orion’s batteries use small cell packaging technology to ensure crew safety when providing 120V power to the many systems on Orion.

Power is transferred between the solar arrays and batteries and to the end item loads via the Power and Data Units (PDU), shown in Fig. 7. This technology is leveraged to ensure a safe environment while the crew is onboard the DSG as well. The DSG power system is designed to support hardware that needs to be operational at all

Figure 6. Flexible Display Formats and electronic procedures enable extensive crew interaction with the Orion spacecraft.

times and crew specific items within the habitat such as life support systems and mission specific science experiments will use supplemental power from Orion.

D. Communications

The DSG communications architecture will also leverage the Orion S-Band architecture by utilizing similar components. The Orion Phased Array Antennas (PAAs) can be used to downlink telemetry from the DSG to the Deep Space Network (DSN) while Orion and DSG are docked. The science and video data collected by the DSG is most efficiently downlinked using Orion's optical communication system. Optical communication enables a significant increase to downlink bandwidth capability compared to traditional radio frequency (RF) communication, for example NASA's Lunar Laser

Figure 7. Power distribution, effector control outputs, and general input/output is accomplished with distributed Orion Power and Data Units which could also be used on the DSG to minimize new development.

Communication Demonstration (LLCD) demonstrated a record breaking moon to Earth download rate of 622 Mbps[5].

E. Guidance, Navigation and Control

Orion’s Guidance, Navigation and Control (GN&C) system will be utilized to minimize the cost and complexity of the DSG. During docking operations, the DSG will be the passive vehicle and Orion will use its Vision Navigation Sensor and Docking Camera to perform the piloted operations. Locating these sensors on Orion allows for use of Orion’s fully redundant systems and software architecture with robust control algorithms without having to fully duplicate this function on the DSG. During mated operations, Orion will control the attitude of the mated stack using thrusters. Orion’s propulsion system has sufficient fuel for station keeping of the mated stack; and, as elements are added to the DSG, the large inertias are more easily managed via thruster control than with reaction wheels. Orion has adequate control authority to meet mission needs for maneuvering and inertial hold.

F. Environmental Control and Life Support Systems

There is a symbiotic relationship between Orion’s Environmental Control and Life Support Systems (ECLSS) and what is needed on the DSG. These systems are designed to maintain a comfortable environment for four crewmembers for both short-sleeve cabin operations as well as suited operations under a variety of challenging external environments. It maintains a fully controlled cabin atmosphere and living environment while the crew performs their low-Earth and cislunar exploration missions.

Additionally, it is robustly designed to sustain critical functions for returning the crew safely home after a failure or catastrophic event, such as a toxic contamination or fire event or a breach in the pressurized cabin vessel. While the Orion ECLSS is designed for a reference mission of 21 days, the capabilities may be extended further when augmented with additional consumables and minimal equipment on the DSG to sustain the larger volume. Combined with a flexible layout configuration that utilizes standardized interfaces on the DSG, this approach allows for the streamlined implementation of an affordable and timely initial DSG capability that anticipates growth on the DSG as it transitions to a self-sufficient capability.

The Orion Air Revitalization System (ARS) is responsible for providing adequate ventilation for the crew, maintaining carbon dioxide, humidity, and trace contaminant concentrations at comfortable and safe levels, and maintaining the temperature at the desired crew selected setpoint. It includes two different types of fan packages, each redundant, that are optimized over a range of operating points.

Multiple heat exchangers remove heat from the air and transfer it to the Thermal Control System (TCS). A regenerative system continuously removes carbon dioxide and humidity, while a high efficiency particulate filtration system removes dust, fungi, and microbes from the air. Air monitoring ensures critical gases are within safe parameters and a suite of emergency equipment protects against fire and toxic contamination vents. The system accommodates for both low (sleep) and highly active (exercise) periods for the full four crew compliment. As such, many of these components are already sized to handle the DSG crew as-is or may be minimally duplicated within the DSG to accommodate the extended volume and mission requirements. The Orion ARS is the limited by the consumable based trace contaminant control system; thus, the DSG would retain that critical function to preserve the Orion capability.

The Orion TCS consists of both an active coolant network and passive heaters and insulation to protect the internal thermal environment from the extreme external temperatures and to collect and reject heat from internal components like avionics equipment. The TCS is sized for a high heat load capacity and utilizes both radiators and a regenerative Phase Change Material (PCM) heat exchanger to accommodate peaks of high thermal loads without relying on the use of expendable consumables. By leveraging Orion's capabilities and initially minimizing the internal components on the DSG, the DSG TCS can be simplified to primarily passive thermal control while scarring for an active coolant network. As the DSG architecture evolves in complexity and mission duration requiring more standalone capability, it can be upgraded with an active thermal control system as needed. Further, many of the same components and coolant fluids used on Orion can be implemented on the DSG for commonality.

The Orion Potable Water System (PWS) is a simple system of a pressurized storage tank water supply that is distributed to the crew for drinking and food rehydration via a water dispenser. The water dispenser is designed to be compact and modular, which allows for the option to upgrade with an adapter kit to interface it with water storage bags provided by the DSG. This offers mass and volume savings of water storage tanks, pressurant tanks, and avoids the duplication of a water dispenser on the DSG.

The Orion Waste Management System (WMS) features a full commode suitable for short to mid-length duration missions, offering both privacy and comfortable means for the astronauts to use the bathroom. It employs a small urine tank that is vented to space and replaceable canisters for solid waste storage. By utilizing Orion's WMS, the DSG only needs to provide the additional consumable materials for the extended mission duration while saving valuable mass and habitable volume. Additionally, there is potential flexibility to recover urine from the tank and store in bags for future processing as the DSG architecture evolves to include more advanced closed-loop ECLSS hardware.

V. Orion as a Safe Haven to the DSG

A facility placed in an orbit in the vicinity of the Moon is an ideal place to gain experience operating in deep space. To undertake human missions further into space, humans need to develop the technology, systems and capabilities required to live in deep space for extended durations. Employing a space proven Orion allows for a safe, practical approach to incremental build-up of capabilities on the DSG.

Orion is already designed to meet deep space requirements including the redundancy required for human-rating and ability to withstand radiation events. The reliability of the DSG increases when Orion is docked because Orion brings its quad redundant flight computers, triple redundant network and fault management software. This robust avionics architecture offers the necessary redundancy to ensure reliability and availability of the critical systems required when crew is present. In early missions to the DSG, the crew must perform many activities to advance human capabilities in deep space such as technology maturation of regenerative life support systems, practice tele-operation of rovers, and normal operations practice with simulated communications delays.[3]

In the event that an anomaly or emergency scenario occurs on the DSG, the crew can sequester themselves in Orion. The ECLS system on Orion offers commodities for crew survival which is significant in the event that Orion is acting as a safe haven while the crew troubleshoots any problems on the DSG. Orion also has the capability for crew to perform contingency EVAs from the crew module, which allows for more flexibility in troubleshooting scenarios. If those problems can't be resolved with crew onboard, the mission can be aborted and Orion will bring them back to Earth safely.

The ground can also continue to work to resolve the DSG anomaly remotely. There are uncertainties associated with the new techniques, technologies, and protocols needed deep space human explorations and the ideal location for gaining this knowledge is the space in the vicinity of Earth's moon, in cislunar space. It provides many of the hazards found in deep space and near Mars, while still being days, not months, from the safety of Earth. Fig. 8 highlights Orion as an element of the architecture of both the DSG and Lockheed Martin's Mars Base Camp (MBC) and how Orion serves as a safe haven capability for missions to cislunar space and Mars.

VI. Orion Enables an Evolvable Exploration Architecture

Utilizing Orion as part of the initial DSG architecture enables near term flight while allowing for an evolutionary path to a more self-sufficient Gateway. NASA has invested in Orion Systems that have surplus capability in many areas, from computer processing to system power to life support. Leveraging that excess capacity permits the creation of a leaner DSG in a shorter period of time. Continuity of human spaceflight is a key strategic principle in NASA's architecture for deep space exploration, and it is achievable when all elements of NASA's past investment are utilized to their maximum capacity. Over time and through subsequent missions that add key elements to enhance the DSG, its reliance on Orion can decrease as it becomes able to safely and independently support human missions. The evolution of the DSG towards the Deep Space Transport (DST) and Mars missions is shown in Fig. 9.

Orion provides the ability to transfer both pressurized and unpressurized cargo to orbit. This feature enables an evolutionary approach to the DSG through the use of Mission Kits. By leveraging the advanced systems and cargo capacity on Orion it is possible to fly an affordable

DSG earlier and add to its capabilities over time. Additionally, Orion has the capability to ferry cargo pods to the DSG that can be left behind or swapped out to enhance functionality, such as the ECLS system, in cislunar space. On early missions to the DSG, Orion's pressure swing amine beds are operational during docked operations and therefore reduce the load required for the DSG to handle. This translates to less hardware being flown on the early DSG missions; thereby reducing weight and cost of the initial DSG. As closed loop ECLS technologies mature, an advanced ECLS module can be flown aboard Orion as a Mission Kit to the DSG or within a cargo pod. This upgraded, stand-alone ECLS would remove the burden from a docked Orion to provide life support to the DSG crew. Another example of utilizing cargo pods to upgrade the DSG is the robotic arm. The robotic arm will be used to expand the DSG robotic capability for berthing, inspection, and maintenance tasks. By enabling an evolutionary path, Orion is an essential component in ensuring an affordable and near term launch of DSG.

Figure 8. Orion provides safe haven capability for the DSG and MBC.

As the DSG evolves, new capabilities are refined which are directly applicable to a DST for a Mars mission. Orion is key to this evolution and for a future deep space vehicle such as NASA's DST or Lockheed Martin's concept for the DST, MBC. For more on Lockheed Martin's MBC concept please see reference [1, 7] for the MBC Architecture. Orion is architected for long duration missions and can act as the Command Deck for the DST. The redundancy and robustness built in to the Orion avionics is leveraged to ensure crew safety whether in a moon orbit or at Mars. The same avionics hardware that Orion uses is easily integrated into a DST because of the network architecture that is the backbone of the Orion avionics.

The crew interface to the spacecraft will mimic what has been done on Orion through common Display Formats to give the crew members a familiar experience and reduce the amount of new training required. New Display Formats will be added that are specific to the Mars vehicle, it's associated hardware, and unique procedures that the crew need to run for Mars missions; however, the feel and use of the displays will be no different from what the crew used on DSG. The DSG also acts as a testbed to mature advanced ECLS technologies.

Orion currently operates as an open loop system, but the spacecraft that go to Mars will need to act as a closed loop ECLS system recycling and regenerating consumables such as oxygen and water. The DSG will evolve from an open loop system to a closed loop system via the addition of mission kits allowing astronauts to experiment and gain data on these new technologies that will flow into the design and implementation of closed loop systems installed on the DST.

The power and propulsion systems are another area where there is direct translation from the technologies used on DSG to what is needed for DST. Solar Electric Propulsion (SEP) is a low

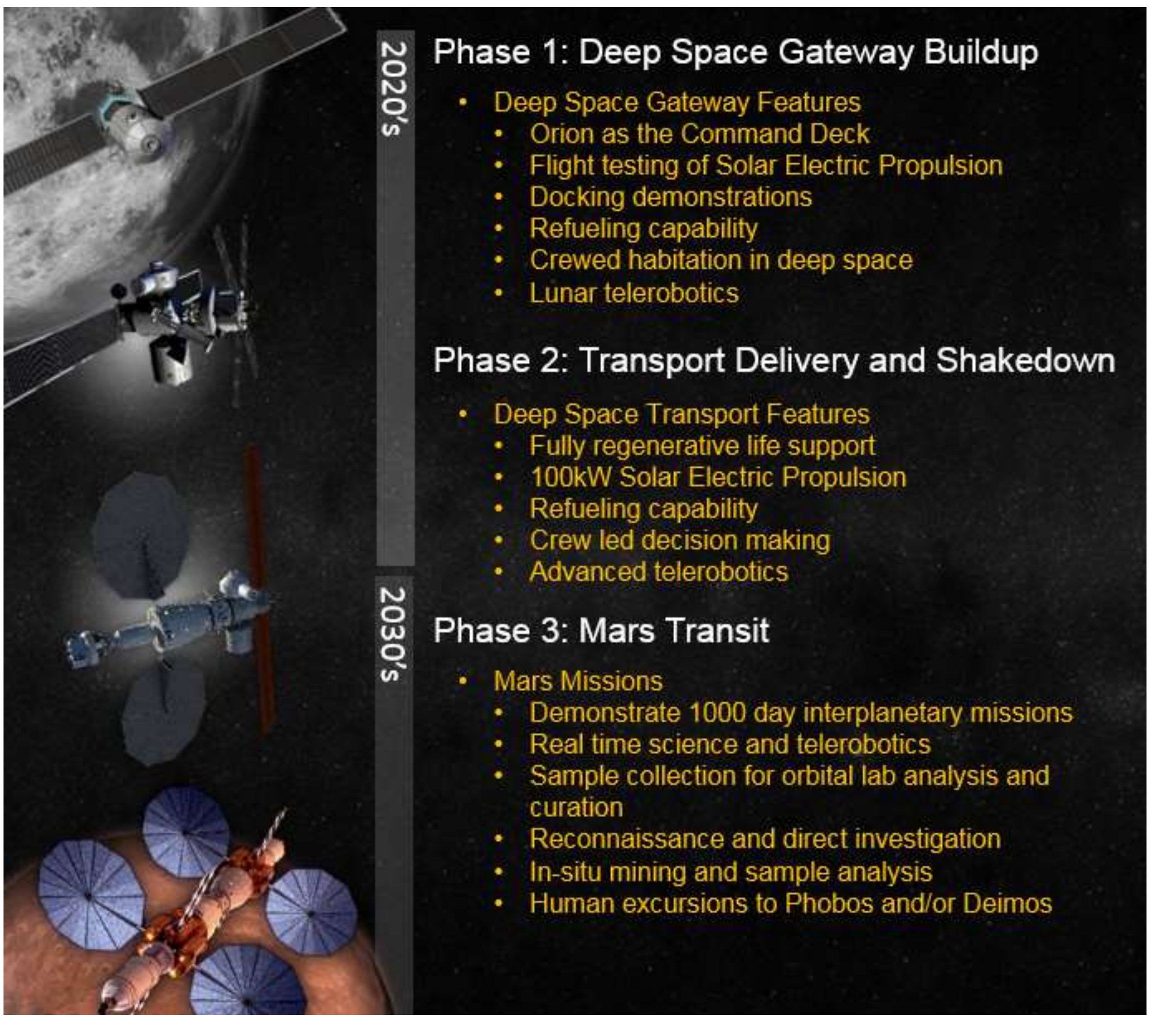

Figure 9. DSG capabilities are enhanced with each mission and evolve to become Mars Base Camp

thrust, highly efficient method for space transportation that will be employed by both DSG and DST. The DSG solar arrays are sized to support the electric energy required by the Hall Current Thrusters utilized in the SEP system. Humans will gain experience with a SEP system by using this technology to transport elements from LEO to cislunar space and while at the moon to move between different orbits. This technology is required for Mars missions to minimize the amount of fuel needed to transit between the moon and Mars to make mass available for other required logistics. The experience gained from living and working in cislunar space will be invaluable for the design and development of the systems needed for Mars missions.

VII. Conclusion

Leveraging NASA's investment in Orion minimizes development time and cost for the DSG. The DSG operates the majority of the time without crew presence which makes the planetary spacecraft utilized in New Horizon and Discovery missions a good model for this application. The DSG can follow the single fault tolerant architectures employed on planetary missions and work to similar cost and timeline constraints while creating a safe environment for crew by relying on the safety and reliability built into Orion. When docked to DSG, Orion is the command deck of the integrated stack and controls critical functions such as command and control, crew interfaces, life support, power and deep space communication necessary to support the crewed mission. Orion meets the strict requirements for human-rated missions in deep space flight environments, and not duplicating many of these capabilities facilitates an affordable DSG that enables continuity of human space-flight.

Orion also enables a gradual build-up of capabilities from both an operational and performance perspective. Operationally, Orion offers a safe haven capability that allows the crew to practice tasks and step through procedures necessary for missions beyond the moon. Should something go wrong in these simulations the crew can retreat to Orion and safely return to Earth. With respect to performance, Orion's cargo capability enables incremental improvements to the DSG through the use of Mission Kits. Mission Kits can be used to make improvements to the DSG such as upgrades to the life support systems or enhanced robotic activities. Utilizing Orion's advanced capabilities to augment an early Deep Space Gateway is one of the most affordable and safe ways to advance technologies and procedures to further human presence in deep space.

References

1. Cichan, T, Bailey, S.A., Norris, S.D., Chambers, R.P., Jolly, S.D., Ehrlich, J.W. Mars Base Camp: An Architecture for Sending Humans to Mars by 2028, 2017 IEEE Aerospace Conference, Big Sky, MT, 2017, 4 – 7, March.
2. W.H. Gerstenmaier, Progress in Defining the Deep Space Gateway and Transport Plan, Presentation to the NASA Advisory Council, 2017, 28 March
3. Pratt, W., Cichan, T., Drever, M., Fenoglio, F., and Hopkins, J. "Concept Study of a Cislunar Outpost Architecture and Associated Elements that Enable a Path to Mars," 67th International Astronautical Congress (IAC), IAC-16-A5.1.8x34596, Guadalajara, Mexico, 2016.

4. Norris, S., Marshall, P., Cichan, T., McNamara, R., Chambers, R. Orion EM-1 and Beyond Status. Global Lunar Exploration Conference, 2017.
5. Buck, J. and Washington, D. "NASA Laser Communication System Sets Record with Data Transmissions to and from Moon," *NASA News Release 13-309.* URL: https://www.nasa.gov/press/2013/october/nasa-laser-communication-system-sets-record-with-data-transmissions-to-and-from/#.WRONV2krLRY [cited October 22, 2013]
6. T. Cichan, S. Bailey, S. Norris, R. Chambers, S. Jolly, J. Ehrlich, Martian Moon Exploration Architecture, IAC-16,A5,2,10,x35709, International Astronautical Congress; IAA Symposium on Human Exploration of the Solar System, Guadalajara, Mexico, 2016, 26 – 30 September.