A Comprehensive Human Spaceflight Architecture for Exploration Beyond Low Earth Orbit

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Abstract - *There has been significant debate concerning whether the next major human spaceflight program should focus on exploration of the Moon, Mars, or Near Earth Asteroids. However, it is conceivable that Mars, asteroid, and lunar missions are not mutually exclusive, even within a limited budgetary framework. Implementation of near-term, affordable, multi-destination exploration architectures require the application of radical, cost-cutting approaches to human spacecraft development and mission execution. Small team developments for multi-mission spacecraft can be combined with US, international, and commercial launch assets to conduct human missions to near earth asteroids by 2025, land crews on the Moon within the next two years, and launch crews to Mars by 2035.*

Keywords: Asteroid, NEA, Moon, Mars, Phobos, Deimos, Distant Retrograde Orbit, DRO, surface, Constellation, Orion, MPCV, SEV, lander, habitat, rover, NSBE Visions for Human Space Flight Working Group.

1 Introduction

The Space Special Interest Group of the National Society of Black Engineers has commissioned a *Visions for Human Space Flight Working Group* to investigate technical challenges surrounding NASA human space flight and to identify an alternative path for the direction of United States human space flight. Research conducted by working group participants and documented in this paper represents volunteer labor executed on behalf of NSBE, a 501(c)3 nonprofit headquartered in Alexandria, VA. NSBE coordinates the inputs of aerospace industry experts to propose innovative solutions to complex technical challenges facing the United States. This paper, in coordination with six other Working Group papers, collectively encompasses the product of the Working Group's efforts. Recommendations, results, and conclusions in this paper do not reflect NASA policy or programmatic decisions.

1.1 Visions for Human Spaceflight

NASA recently been accused of lacking a vision for human spaceflight. [3], [9], [16], [21] However, it could be argued that this is a less than accurate assessment. In actuality, there is no lack of vision for human spaceflight. Instead, there are multiple, conflicting visions. There appear to be at least six primary competing interests from various governmental and non-governmental stakeholders with varying levels of decision-making authority or influence that have contributed to a state of conflict for the human spaceflight community in the present decade.

1.1.1 Human mission to an asteroid by 2025

In 2010, President Obama directed NASA to conduct a crewed mission beyond the Moon, specifically to reach a Near Earth Asteroid (NEA) by 2025. [13] Various options for asteroid missions have been examined by NASA, including options involving human travel to distant asteroids of various sizes or robotically capturing an asteroid or piece of asteroid and delivering it to a closer orbit for future astronaut visits. This mission has been promoted heavily by the White House and has support in the Democratically-controlled Senate, but is generally opposed within the Republican-controlled House of Representatives.

1.1.2 Human Lunar Exploration in the mid to late 2020s

The recently-cancelled Constellation program represented the latest in a series of NASA-initiated lunar programs dating back to cancelled programs created even during the Apollo lunar program. Arguably there has never been a time in the Agency's history where there were not official or unofficial works in progress to support potential lunar architectures. Lunar exploration has also enjoyed extensive support in the international community, with European, Russian, and even Chinese lunar ambitions.

1.1.3 Human Mars Exploration in the mid to late 2030s

Virtually all participants in human spaceflight express a long term desire for human Mars exploration. The Apollo program was originally intended by Wernher von Braun to be a precursor to Mars missions. Space entrepreneurs have established the Inspiration Mars foundation with the goal of conducting a manned Mars flyby and the company Space X was established based at least in part on founder Elon Musk's desire to see humanity reach the red planet.

1.1.4 Increase Human Spaceflight Operations Conducted by Commercial Operators

Musk is one of a growing cadre of spaceflight companies that believe they can accelerate the development of low (or at least lower) cost access to space. These operators seek to play an increasing role in space activity at all levels. Arguably at the lead of the pack, Space X and Orbital are now providing commercial cargo services to the International Space Station, while Virgin Galactic is on the verge of private suborbital flights and Bigelow Aerospace is steadily developing what may become the first commercial space station. At the extreme end of these visionaries are those who favor commercial development to the extent that in the future NASA will have no greater role in the development of spacecraft than the Department of Transportation has in the development of the next model of automobile.

1.1.5 Limit the NASA Budget to Current Levels and Reprioritize Focus as Needed

In general, Republicans in Congress are not in favor of increasing NASA budgets to accomplish new exploration agendas. Even Republicans from states such as Texas where prominent NASA centers are located favor seeing how NASA can handle the reduced budget brought on by sequestration. [11] They feel that new programs may require NASA to make hard choices, to the point that new programs may be at the expense of other programs. [4] It is a fundamental expectation that they want to see NASA make good steps and progress even without the desired budget. [2] They believe this can be achieved through a reprioritization of NASA, implying that earth and space science might be expendable in favor of manned spaceflight. [2]

1.1.6 Provide Sufficient Justification for NASA Expenditures

In comparison with their counterparts, Congressional Democrats tend to be more concerned with ensuring that sufficient justification has been provided for any spaceflight expenditure. North Carolina Representative Melvin Watt provided prophetic commends to this effect in 2002:

"That has to originate and the case needs to be made by NASA…they need to be telling us that and making the case for it and telling us what the potential is for discoveries that will be beneficial for us in our day-to-day lives…I want them to be constantly suggesting what the next frontier should be and making the case that that frontier is important to humankind. Without them making that case I think the level of support will diminish over time." [12]

1.1.7 The Silent Seventh Vision

A seventh vision exists that is described as silent because it is not strongly advocated by any decision making body, but instead permeates the NASA human space flight civil servant workforce. This vision is simply that rank and file NASA engineers must design, build, and operate spacecraft that travel into space. A significant initial internal NASA resistance to the commercial spaceflight development is directly attributable to this vision. The initiative was rolled out in a manner that created an atmosphere that was more competitive than complimentary, allowing NASA engineers to perceive the rise of companies such as Space X as a direct threat to their ability to serve as anything more than regulators and nontechnical managers. This resistance in actuality extends even to traditional contracting and predates NASA's existence, with a heritage stretching back to Saturn V designer Wernher von Braun's rocket team, who had an inherent philosophy dating back to the 1930s to rely almost exclusively on in-house capability for rocket development. Contractors were used by von Braun's team sparingly, only for specific components or with very close monitoring. [22]

1.2 Contributing Perspectives

These conflicting visions have competed essentially throughout the life of the Agency and have generally only been forced into harmony when overridden by national security issues. As a result, more than twenty human spaceflight programs have been cancelled since the Apollo program and the only human spaceflight programs that have actually made it to operational status since 1972 are Skylab, the space shuttle, and the International Space Station. The recent cancellation of the Constellation program triggered a wave of disruption throughout the Agency that led to two disconcerting reports.

1.2.1 OIG Report

The NASA Office of Inspector General recently assessed that the "limited number of small and mid-size projects in NASA's current portfolio allows too few opportunities for Agency personnel to gain experience managing a project's cost, schedule, and technical performance efforts." [15]

Making matters worse, even where projects exist, "increased reliance on contractors to design and build projects has led to a decline in Agency personnel with development experience…NASA engineers are primarily operating as overseers of work performed by contractors rather than gaining experience building instruments and spacecraft in-house…NASA will have an insufficient number of experienced project managers in the future to effectively manage the Agency's high-priority projects." [15]

1.2.2 National Research Council Report

The National Research Council was even more pointed in its critique of human space flight, articulating that there is "little evidence that the current stated interim goal for NASA's human Space Flight program – namely, to visit an asteroid by 2025 – has been widely accepted as a compelling destination by NASA's own workforce, by the nation as a whole, or by the international community." [1] The paralysis due to conflicting visions was fully evident and identified as a key source of the problems facing the agency. "The agency faces challenges in nearly all of its primary endeavors…and these challenges largely stem from a lack of consensus on the scope of NASA's broad missions for the nation's future." [1] Driving directly at the concerns raised by Representative Watt, they noted that "NASA's current vision and mission statements do not explain NASA's unique role in the government and why it is worthy of taxpayer investment." [1]

1.3 Overview of a Comprehensive Architecture

Much of the lack of progress in exploration beyond LEO is directly attributable to conflicting visions for human spaceflight that have pulled NASA in opposing directions. Most notably, three of these visions involve different destinations and many have felt that traveling to any one of these destinations must be at the expense of the other two due to the costs involved in developing unique architectures for each destination.

Unless there is a radical departure from traditional NASA mission architectures it will be impossible to move beyond Low Earth Orbit in any significant fashion. Any attempt to select and implement any one of the six primary competing visions meets with insurmountable resistance from advocates of the other five, as well as hidden resistance from the NASA workforce itself if they are not sufficiently included. Further, traditional NASA acquisition strategies have proven themselves incapable of developing the required space elements within the budgetary frameworks imposed by Congress. However, a possible solution may exist. The correct answer is not to choose any one of these competing seven visions, but to choose all of them. The obvious question is how is such an option possible? Imbedded within many of these visions is the assumption that they must be one or the other.

However, it is possible to reconcile these competing destinations through an architecture that develops a family of modular spacecraft, designed specifically to operate across all three advocated destinations (Moon, Mars, and asteroids) as well as the transits to reach each destination.

Prior NASA development efforts suggest that it may be possible to develop in parallel a collection of such multi-mission spacecraft families that can work together to reach multiple destinations, within the budgetary framework desired by Congressional Republicans, with sufficient justification desired by Congressional Democrats, and with both engagement of commercial space interests and significant NASA civil servant engineering engagement. This can enable near-term exploration of the Moon, Mars, and asteroids with nationally significant research objectives.

Among other paradigm changes, this breaks the design philosophy of highly optimized spacecraft designed to meet exacting requirements of a specific mission. Such a spacecraft may achieve a minimum mass or maximum performance in a given architecture, but it is generally prohibitively expensive to convert such a vehicle for any other use. Instead, a robust spacecraft family design with wide-ranging capabilities will be intentionally designed to function across a variety of space environments, recognizing that such a vehicle cannot be mass optimized. Such an architecture will be described in this and other Working Group papers.

The Working Group assumes that the following spacecraft will be operational by 2020 and that their development/sustainment is outside of the scope of the program proposed in this paper: MPCV, Soyuz, Asteroid Retrieval Vehicle, Dragon, Cygnus, ATV, HTV, Progress, and one or more commercial crew capsules. The Working Group also assumes that the following launch vehicles are also operational in this timeframe: SLS, Falcon Heavy, Falcon 9, Antares, Atlas, Delta, Arianne, Soyuz, and Proton family launchers. The Working Group also assumes that one or more manned space stations continue to exist in Low Earth Orbit.

2 Spacecraft Element Families

2.1 Power, Thermal, and Propulsion

All spacecraft require the generation and dissipation of energy to operate. A modular Power, Thermal, and Propulsion (PTP) spacecraft will serve as this central energy bus for human spaceflight applications, with both surface and in-space variants. This spacecraft must fit within mass and volume limits that enable delivery to a distant retrograde orbit (DRO) or Earth-Moon Lagrange point by the SLS or Falcon Heavy booster.

2.1.1 In-Space Propulsion

It is assumed that NASA, international, and commercial boosters will be capable of delivering spacecraft elements to assembly orbits in either DRO or elsewhere within Cislunar space. The PTP is required to transport spacecraft stacks from those assembly orbits to various orbital destinations. This includes transfer to and from Mars and to and from deep space asteroids. It also includes orbit maintenance at Cislunar destinations. Finally, it includes transfer of small asteroids from various orbits. The PTP must be reusable, implying a need to refuel, exchange propellant tanks, or be replaced with fresh PTPs, unless using an operational version of the currently in-development, propellantless quantum vacuum plasma thruster (QVPT) system, which by definition does not require refueling. [7] Given the mission durations, the PTP is likely to need a storable propellant if QVPTs are not used. It is likely that some form of electric propulsion will be required to fulfill this combined set of needs, but design trades beyond the scope of this study will be necessary for a final solution. When used in surface applications, the propulsion subsystem is not present.

2.1.2 Power

Power can be generated by means of small nuclear reactors or by solar arrays. Commercial small reactors in development [5], [6], [23] range in the 1-75 MW class. By comparison, exploration studies have explored 20-40 KW arrays for deep space propulsion. [10] Higher power solar systems are used aboard the International Space Station. Design trades beyond the scope of this paper will be necessary for a final solution. In addition to power generation, power may also need to be stored. For this purpose, batteries and PEM fuel cells come to mind and can also be traded. In order to fully satisfy the competing destinations of asteroid, Moon, and Mars, this power generation must operate in both microgravity and low gravity environments. It must operate in regions of constant sunlight, regions of constant shadow, and regions with periodic or irregular eclipse. It must operate at ranges from the sun of 1 astronomical unit to 2 astronomical units. The non-propulsive power requirements are generally the same in all of these varying conditions. If the PTP uses electric thrust, the power system must also supply its operating power.

2.1.3 Thermal

The PTP must also reject all of the heat generated by it and other modules within the spacecraft stack. The greatest head load is likely that generated by the propulsion system (in the case of electric thrust), but this load will operate in a variety of different locations (distant retrograde orbit, deep space, Mars orbit), which are different thermal environments with implications for heat rejection. Additionally, the Power-Thermal Unit (PTU – a PTP minus propulsion system) will operate on both the lunar and Martian surfaces, both unique thermal environments. Thus, the thermal system will need to be sized for this range of thermal loads and thermal rejection environments.

2.2 Microgravity Habitat (MH) and Planetary Habitat (PH)

A habitat is the living and working volume for a crew during long duration missions. The recommended habitat structure is based on the SLS upper stage liquid hydrogen tank, which has been advocated in several studies as a potential crew habitat. [19], [20] A PH is needed for lunar surface and Mars surface missions and a MH is needed for deep space asteroid and Mars transit missions. A separate physical element is used for each surface destination and for transit missions, but it is a common habitat design, with minor modifications to account for different gravitational environments. [18]

The SLS liquid hydrogen tank used as the pressure vessel for the habitat is 27 feet in diameter and 38 feet tall. This is slightly larger in volume than Skylab, which was 22 feet in diameter and 44 feet tall. [14]

2.2.1 Habitat Layout

A layout is provided in figure 1, based on recent NASA habitability concept studies. [14] The Habitat is organized into four decks, numbered 0 to 3, with 3 representing the uppermost deck, occupying the upper dome. In general, habitation functions are on the upper two decks and operations functions are on the lower two.

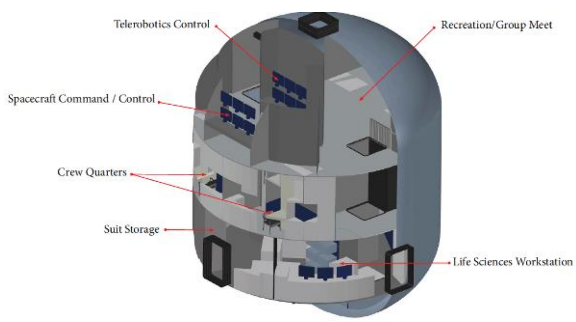

Figure 1. Habitat Layout

Deck 0 occupies the lower dome. This is primarily a subsystems equipment deck, containing most of the Habitat subsystems and crawlspaces to access each component as needed for maintenance. [14] In both the Mars Transfer Vehicle and Deep Space Vehicle versions of the MH, Deck

0 includes Vibration Isolation Systems for the crew exercise equipment, and provides accommodation for some of the exercise equipment hardware volume. In the Mars transfer version of the MH, the lower dome also includes a pressurized docking port for connection to the Three-Port Node described later in this paper.

Deck 1 is the primary operations deck. The deck includes a life sciences workstation, maintenance and fabrication workstations, crew exercise equipment, and spacesuit storage and maintenance. The four radial docking ports are also on this deck. [14] In the PH variants, the exercise equipment can be pushed further down into Deck 0, creating more volume on Deck 1 for physical science equipment.

Deck 2 is the private habitation deck. It contains four equally sized crew quarters. Each crew quarters includes a single bunk, work desk, shelf and counter space, and stowage lockers. The deck also includes a medical facility, hygiene and waste facility, and plant growth chambers.

Deck 3 is the public habitation and ops command deck. It occupies part of the barrel section and the upper dome. The docking port to MPCV is at the top of this deck for the MH configurations. It is not installed in the PH configurations as nothing docks to the top of the habitat on the surface. The deck also includes a galley, command workstation, teleoperations workstation, and a large open area that can be used as a wardroom, meeting area, and recreation area.

2.2.2 Radiation Shielding

Radiation shielding is an unaddressed problem in the microgravity configuration. Galactic Cosmic Radiation is potentially a cause for limiting mission duration and could invalidate some NEA and Mars transfers. Many spacecraft engineers fear that the only way to provide adequate shielding may be to provide excessive amounts of mass surrounding the Habitat. In a brute force application this could be accomplished by surrounding the habitat with small asteroids three to five meters in diameter. However, the mass of such a shield may make it impossible to move the habitat in any reasonable period of time. Solar Particle Events are much less of a concern, with the crew being able to obtain adequate shielding by rearranging mass within the spacecraft, or even retreating to radiation shelters designed into docked spacecraft.

The Planetary Habitat has an advantage over the Microgravity Habitat in that because it is a fixed facility it can take advantage of natural terrain for shielding from Galactic Cosmic Radiation. The habitat will be placed in a location providing tens of meters of shielding on as many sides as possible. This may involve placement in the bottom of a crater, inside a cave or lava tube, in a canyon, or adjacent to a cliff. Alternately or as a complement, ground moving equipment can create artificial terrain barriers surrounding the habitat. Thus, on the lunar or Martian surfaces radiation will not be a concern for the habitat.

2.2.3 Exterior Fixtures

In addition to the previously described docking ports, the habitat exterior will contain grapple fixtures for robotic manipulator arms to “walk” across the hull of the habitat. The exteriors of the lower and upper dome also contain mounting fixtures for payloads, including docking adapters and science instruments.

Additionally, the PH includes structural attach points for the surface mobility robots to lift and transport the habitat from the landing location to the outpost location. Finally, the PH includes deployable landing legs, stowed during launch in the interface shroud between the habitat and the SLS booster.

2.3 Scout Vehicle Cabin

A Scout Vehicle Cabin (SVC) is needed to enable crew activity away from the Habitat. This vehicle is based on the NASA prototype Multi-Mission Space Exploration Vehicle (MMSEV). The basic configuration of the MMSEV is a cylindrical pressure vessel with two side docking hatches. The aft bulkhead is sloped at a 10 degree angle and the forward dome contains eight windows for driving visibility. A low fidelity mockup of the MMSEV cabin is shown being used in an underwater test in figure 2. When used in applications requiring mobility a SVC variant is mated to a planetary or microgravity mobility system to enable transport, both of which are described later in this paper.

Figure 2. MMSEV Cabin

2.3.1 SVC Variants

2.3.1.1 Planetary Surface Rover (PSR)

The primary mission of the SVC is as a planetary surface rover. Deployed in pairs, two PSRs can enable excursions up to 480 kilometers from the Habitat. This variant of the SVC contains two suit ports on the aft bulkhead for EVAs. The side hatches are used for docking to the Habitat or to another SVC.

In the planetary surface rover configuration, the SVC can support two crew members for excursions up to 14 days in duration. In the event of a failure of either PSR, the other can recover the crew and return to the Habitat. The PSR configuration of the SVC includes structural attach points for the surface mobility robots to lift and transport the cabin.

2.3.1.2 Microgravity Scout (MS)

With minor modifications, primarily in the area of crew restraints and external hardware, the MS configuration of the SVC is used as an asteroid microgravity scout. The Deep Space Vehicle cannot be brought closer than several kilometers to the asteroid, so the MS is used to shuttle back and forth and conduct surveys of the asteroid surface. The crew will still ingress and egress via suit ports for EVA, but in this case the aft deck has a protected enclosure with a utility module aft of the aft deck, as shown by the MMSEV prototype in figure 3.

Figure 3. Aft deck of MMSEV with Protected Enclosure and Utility Module

The PS can be outfitted for up to 14 day operations, but during 30-day NEA missions, the PS will be used for 5-day excursions to the NEA before returning to the Deep Space Vehicle for a one-day refurbishment to return samples and exchange crew for the next excursion. This allows for five 5-day excursions at the NEA.

2.3.1.3 Planetary Lander Cabin (PLC)

The SVC can be used in a stripped down capacity as a planetary lander cabin, to transport the crew to and from the surface for both lunar and Mars missions. This configuration spins the vehicle around as shown in Figure 4 such that the aft bulkhead of the rover and scout variants is the front of the lander variant. It removes the internal stowage and crew systems, deletes the side hatches (though retaining the protrusions), replaces the suit ports with Display and Control Window Units (DCWUs), and replaces the cockpit with an aft hatch and dome. The dome, shown in Figure 5, becomes the primary ingress/egress path with subsystems equipment relocated to the side hatch protrusion volumes. [17]

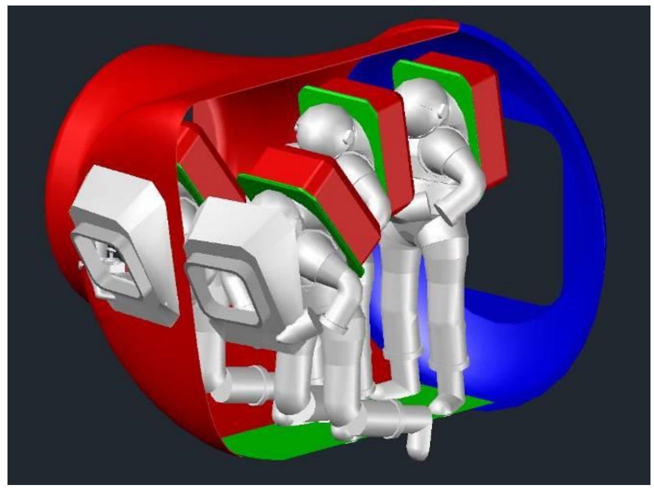

Figure 4. Cutaway View of Planetary Lander Configuration

The PLC is a “down and out” lander. It cannot sustain the crew for surface habitation. Upon landing, the crew must egress and transfer to some surface habitable environment and the PLC is deactivated or placed in a keep alive configuration for the duration of the surface stay. It is reactivated prior to ascent and used for crew transfer to a waiting orbital asset. It is essentially limited to use as a space taxi.

Figure 5. Notional aft hatch and dome replacing cockpit

2.3.1.4 Habitable Airlock (HAL)

The HAL configuration is a variation that can use any of the previous configurations as an airlock volume to some other space vehicle. It is intended for a microgravity configuration, though with some effort may be adaptable to a planetary operation. This configuration may feature the aft dome hatch, a cockpit, or a completely blank bulkhead. It may or may not include operable suit ports. And one or both of the side hatches may be deleted.

A test was conducted in neutral buoyancy at NASA Johnson Space Center as shown in Figure 6 that verified sufficient ingress and egress volume for two suited crew members. [8]

The intent of the HAL is primarily to provide a volume that can be depressurized without requiring a potentially larger or more critical pressure vessel to depressurize for EVA. However, it is also intended to provide limited habitation capability when not being used to support EVA. This may include crew hygiene, exercise, meal preparation, sleep stations, or operations workstations, though those facilities will by definition have to withstand vacuum or be easily removable to stow in another module during EVA.

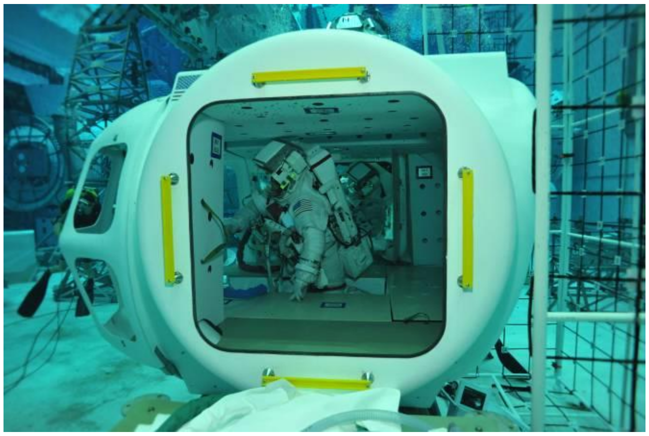

Figure 6. Neutral buoyancy test of ingress/egress for Habitable Airlock configuration

2.3.1.5 Three-or-Six-Port Node (3PN or 6PN)

The logical extension of the HAL configuration is to instead use the spacecraft as a node. This configuration retains both the side hatches and aft dome hatch. It may either retain or eliminate the aft enclosure behind the suit ports. If the aft enclosure is retained, it may provide an additional unpressurized docking port behind the aft enclosure attached to the utility module shown in figure 3. Two SVCs may be connected together by eliminating the suit port bulkheads and sealing the two pressure vessels together to form a six-port node. Like the HAL, some or all of the MS variant’s subsystem and crew accommodations functionality may be retained in the node configuration, as dictated by the needs of the overall space vehicle it contributes to.

2.4 Destination Propulsion

Destination Propulsion concerns the means of achieving mobility at the respective destination. It includes two main families – rocket propulsion, which is primarily high thrust chemical propulsion, and surface propulsion, which is primarily wheeled mobility.

2.4.1 Rocket Propulsion

Commonality is pursued for rocket engines, enabling a family approach of scaling or clustering rockets to achieve the necessary performance. A trade beyond the scope of this paper will down select between LOX-Methane, LOX-Kerosene, LOX-Ethanol, hypergolic, or other chemical propellants, with the same propellant to be shared by both main propulsion system (MPS) and reaction control system (RCS) thrusters. A key constraint is that this propellant solution must be storable for on-orbit mission timelines in excess of two years and potentially as long as five.

2.4.1.1 Propulsion Sled (PS)

The PS is a spacecraft bus augmented with four 5-thruster RCS pods. Various microgravity configurations of the SVC can mate with this sled to enable NEA sorties or other small spacecraft missions. The PS is equipped with deployable solar arrays and radiators and carries batteries for energy storage. It is responsible for power and thermal loads for both itself and a mated SVC. Payload bays on the PS can carry unpressurized cargo, including science equipment and resupply consumables. The PS is equipped with grapple fixtures to support robotic arm operations. The RCS tanks are capable of in-space refueling.

2.4.1.2 Lunar Ascent Stage (LAS)

The LAS is a PS bus modified to accommodate a single MPS engine embedded in the center of the PS, twin common bulkhead propellant tanks at each longitudinal end of the PS, landing legs, and RCS thrusters. The deployable solar arrays and radiators are replaced with body mounted arrays and radiators. The dorsal surface provides clearance to mate a PLC between the propellant tanks, with a deployable egress ladder leading from the PLC aft dome hatch to the surface. MPS and RCS tanks are capable of in-space refueling. The tanks and engine are sized to lift the LAS-PLC from lunar surface to low lunar orbit.

2.4.1.3 Mars Ascent Stage (MAS)

The MAS is a scaled up version of the LAS with additional tankage both above and below the PS bus and clustered MPS engines to reach Mars orbit. As such, it is a taller structure with accordingly greater ladder height.

2.4.1.4 Lunar Descent Stage (LDS)

The LDS incorporates elements of the PS and planetary scout chassis (described later in this paper) structural frames to mount multiple outrigger MPS engines analogous to the NASA Sky Crane, shown in Figure 7.

Figure 7. NASA Sky Crane

MPS propellant is stored in tanks above and below the structural frame. The LDS is used to lower cargo to the lunar surface for both manned and unmanned missions. For manned missions it will lower a LAS-PLC. Unmanned mission payloads include the PH, PTU, PSR/PSC, and other surface elements. Like the Sky Crane shown in Figure 8, the LDS will not directly land on the surface, but will lower its payload via cables to a soft touch down, then sever cables and fly away.

Figure 8. Sky Crane Lowering Payload

For cargo missions deploying the lunar outpost, a Lunar Cargo Vehicle is essentially the LDS plus whatever cargo it is delivering. For crew missions, a Lunar Crew Vehicle is essentially a LDS, LAS, PLC, and MPCV. The four vehicles may be launched in a lunar orbit rendezvous, earth orbit rendezvous, or all-in-one depending on the performance capabilities of the SLS or other available boosters.

2.4.1.5 Mars Entry, Descent, and Landing Stage (MEDLS)

The MEDLS contains a combination of systems to enable successful Mars landing. A disposable deorbit MPS engine provides initial deceleration to brake from orbit and is jettisoned shortly before entry interface. An aeroshell derived from the SLS shroud encapsulates the MEDLS/cargo configurations and is also jettisoned after atmospheric heating. Supersonic parachutes deploy next to further slow the vehicle. A shorter aeroshell is used fro crew configurations, with MEDLS-Short and MEDLS-Long used to differentiate the crew and cargo versions respectively.

Similar to the LDS, the MEDLS incorporates elements of the PS and planetary scout chassis structural frames to mount multiple outrigger MPS engines to provide landing thrust. The MEDLS engines are clustered above the payload, with propellant tanks above the engines. The need for a Sky Crane configuration of payload below the engines and tankage is even greater for the Mars lander than the lunar lander. NASA Constellation studies demonstrated an Altair lander plus surface mobility systems that could remove payloads from the top of a six-meter tall lander. However, such payloads on a Mars landing would require taller landers and even more complex cargo handling systems. Applying a common Sky Crane system for lunar and Mars payloads is expected to result in an overall less expensive architecture than two otherwise unrelated point design solutions. Landed cargo may include a PTU, MAS, MH, or other surface elements. Upon landing, the MEDLS flies off like the Sky Crane to crash a safe distance away.

2.4.2 Surface Propulsion

Once landing has been completed on either the Moon or Mars, additional propulsive capability is required on the surface to move cargo, personnel, and payloads to achieve mission objectives. This propulsion is achieved through a combination of wheeled and legged robotic locomotion.

The same minimum performance goals with respect to endurance, range, and speed apply to both Moon and Mars expeditions. Because Mars is expected to be the driving case for locomotive performance due to the increased gravity, the lunar variants may gain additional performance capability, given common motors and power supplies for both lunar and Martian PSCs and CMTRs.

2.4.2.1 Cargo Manipulation and Transport Robot (CMTR)

The ATHLETE (All-Terrain Hex-Legged Extra-Terrestrial Explorer) robot developed by the NASA Jet Propulsion Laboratory is the basis for the CMTR. This robot is capable of separating into two three-legged robots to attach to either side of a payload and carry it to any given destination. The ATHLETE prototype shown in Figure 9 is only half scale, with the full scale robot able to stand seven meters tall, enabling it to traverse virtually any terrain and to remove stacked payloads from lander packaged cargo assemblies. (Many cargo missions will consolidate multiple surface outpost elements into a single cargo delivery flight. These elements may be stacked vertically due to launch vehicle packaging constraints. Consequently, even though the payload is lowered from a Sky Crane-derived lander, the payload will be composed of individual elements that will need to be removed by the CMTR, requiring the unique capabilities of the ATHLETE configuration.)

Figure 9. Half-scale ATHLETE robot prototype carrying mockup habitat module

2.4.2.2 Planetary Scout Chassis (PSC)

The PSC is based on the chassis prototypes developed for the MMSEV. The PSC and CMTR will be designed to share common motors and wheels, as well as other subsystems (including power and avionics), software, and components where feasible. The PSC is intended to carry the PSR for excursions away from the Habitat. PSR/PSC excursions may last up to 14 days and traverse up to 480 km away from the Habitat. This requires a sustainable average driving speed of at least 20 kph (12.43 mph) to enable a one-day emergency return to base from the furthest point in its traverse. This constraint applies to both Moon and Mars applications and requires a common solution for both environments. Lunar and Martian gravitational, thermal, atmospheric, terrain, and lighting variances will impact the PSC design and it is likely that the chassis will be able to exceed this minimum performance constraint in certain environments, but must satisfy it in all of them.

2.5 Resource Utilization Element (RUE)

A variety of stationary or mobile RUEs will be developed for utilization of local resources. Depending on intended destination (NEA, Moon, or Mars) these may be free-flying, wheeled, legged, or stationary devices. Current resource utilization objectives include oxygen, concrete, aluminum, water, methane, pyroelectric power, and solar cell production. Generally, each resource will require one or more unique RUE configurations, though where possible they will share similar structural and utilities buses. (e.g. The oxygen production RUE will require a different outfitting of equipment than the solar cell production RUE but may have the same structural frame.)

2.6 Logistics Resupply Module (LRM)

A fundamental assumption of this architecture is that existing commercial and international cargo providers will be able to modify their spacecraft for deep space and planetary destinations. This includes modules such as the Cygnus, Dragon, ATV, HTV, and Progress. It is further assumed that any such logistics module will be outfitted by the commercial provider to fly with the appropriate docking interface to mate with the spacecraft or outpost it is supporting.

3 Comprehensive Architecture

The multi-purpose spacecraft described in the preceding section can be combined in different ways to produce human space flight mission architectures to near-Earth asteroids, the lunar surface, and Mars.

3.1 Captured NEA Architecture

The captured NEA mission involves sending human crews to an asteroid that has been placed in Cislunar space, presumably a Distant Retrograde Orbit (DRO). It should be noted that for purposes of this paper the Asteroid Retrieval Vehicle (ARV) is a conceptual spacecraft module. Various studies are currently underway in the aerospace sector to develop this spacecraft and this paper simply assumes that one such spacecraft is developed and that it will be launched in time to deliver an asteroid to a DRO by

2025. With this delivery completed, 21-day missions (including crew transit time to/from LEO) can be accomplished by flying a MPCV to dock with the stack. Figure 10 shows a notional configuration in PowerPoint art of MPCV docked to the aft of an ARV.

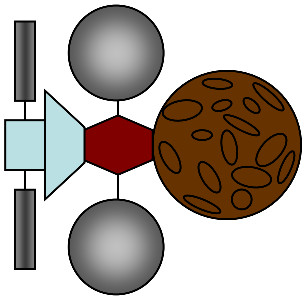

Figure 10. Captured NEA 14-Day Mission Configuration

Captured NEA missions of greater duration require additional spacecraft volume at the asteroid. For extended missions, the ventral side of a 6PN is docked to the aft of the ARV. The 6PN is two SVC pressure vessels, each with two side docking ports, docking ports in place of the cockpits and both suit port bulkheads eliminated to allow the two hulls to be sealed together at the bulkhead interface. They are mated to two PS, one on the dorsal side of the vehicle and the other on the ventral side. This entirely blocks the propulsion systems of the ARV and will also require retraction or jettison of ARV solar arrays, so it is necessary to fly a PTP to provide replacement power, thermal, and propulsion services. The PTP will mate to the dorsal side of the 6PN.

RUEs may be attached to the truss structure of the PTM or any of the open docking ports. This configuration, shown in figure 11, will allow MPCV, one or two logistics modules, and one to two MS/PS to dock with the captured stack. This enables the deployment of additional consumables and science equipment. The resulting NEA Orbital Spacecraft (NOS) enables extended scientific and engineering exploration of the captured asteroid. The NOS also permits simulation of the asteroid exploration portion of the deep space NEA mission.

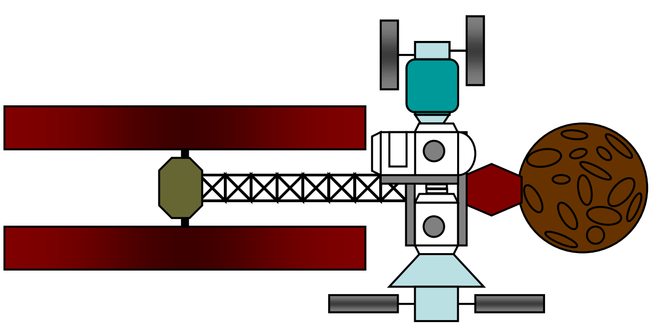

Figure 11. Notional NEA Orbital Spacecraft

3.2 Deep Space NEA Architecture

A deep space NEA visit requires the assembly of a Deep Space Vehicle (DSV). The DSV is notionally depicted in figure 12. The DSV includes the MPCV, shown in light blue docked to a MH, shown in gray. All of the four radial docking ports on the MH are occupied, two accommodating LRMs (shown in turquoise), one accommodating a HAL, and one accommodating a MS/PS. (The second LRM is not visible in the figure, but is on the docking port opposite the HAL.) The nadir MH docking port connects to the PTP. (This is an unpressurized docking port with no hatch present.) RUEs and any additional needed LRMs may be attached to grapple fixtures on the MH or on the truss structure of the PTM.

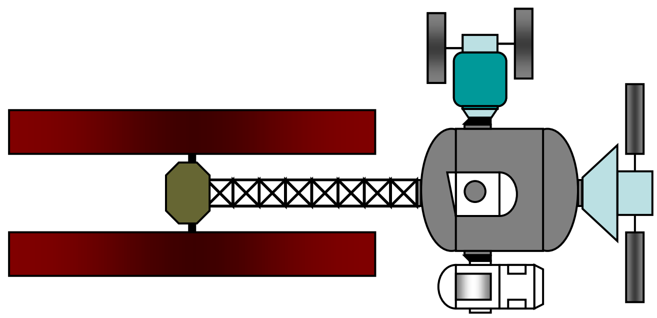

Figure 12. Notional Deep Space Vehicle

These spacecraft are launched into space by SLS and EELV boosters and robotically assembled in a distant retrograde orbit (DRO). MPCV arrives last with the crew. The DSV is reusable for multiple deep space NEA missions.

3.3 Lunar Exploration Architecture

Lunar surface exploration involves a single fixed outpost with mobile rover assets, depicted in figure 13. The architecture is centered around a PH. Its four radial docking ports are fully occupied, with two allocated to LRMs, one to a HAL, and the fourth to a 3PN. The 3PN in turn uses its two side hatches as docking ports for the two PSC/PSR rovers. The 3PN has two operable suit ports for local EVA or suit port transfer module operations.

The PTU is not physically docked to the outpost, but is connected by (buried) power and thermal cabling. It is physically separated to use local terrain for additional shielding. The two CMTRs are stationed in the vicinity of the Outpost but physical docking is not required for either robot. In the figure, one CMTR is depicted carrying a spent LRM away from the Outpost and the other is shown separated into its two halves. RUEs can be deployed in the Outpost vicinity or remote locations as appropriate to their specific purpose. Longer duration lunar missions may require additional LRMs, which will nominally be positioned in the Outpost vicinity and docked when needed.

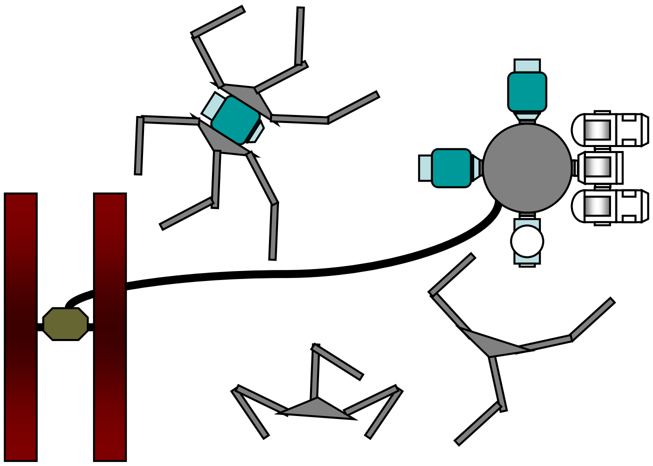

Figure 13. Notional Lunar Outpost

3.4 Mars Exploration Architecture

3.4.1 Mars Surface Outpost and Transfer Vehicle

The Mars outpost is identical to the lunar outpost and need not be repeated in this section. Transfer of the crew to Mars requires a very similar spacecraft to the Deep Space Vehicle. There are in fact only a few differences between the two. Most significantly, a PLC/MAS/MEDLS is docked to the upper (Deck 3) docking port of the MH in place of MPCV, which docks instead to the MH's fourth radial docking port. (The MEDLS remains on the planetary surface and the MAS is discarded in orbit, but the PLC returns with the stack to DRO for reuse. Additionally, a second MS/PS joins the stack. This requires the addition of a 3PN with suit ports and an unpressurized docking mechanism aft of the suit ports. The resulting Mars Transfer Vehicle (MTV) is depicted in figure 14. Like with the DSV, RUEs and additional LRMs may be attached to grapple fixtures on the MH or on the truss structure of the PTM. The MTV is reusable for subsequent crew expeditions to Mars.

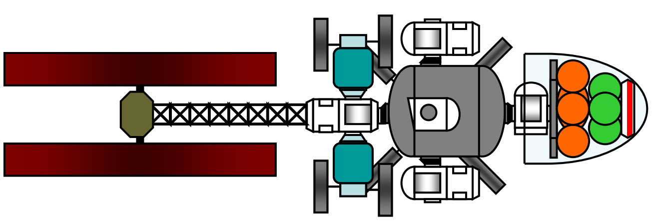

Figure 14. Notional Mars Transfer Vehicle

3.4.2 Mars Cargo Vehicle

Due to the distance between Mars and Earth, delivery of the surface outpost elements is significantly more challenging than for the lunar outpost. A PTP is mated to a MEDLS / cargo configuration to transfer Mars elements from Cislunar space to Mars orbit. Figure 15 shows three notional cargo configurations. Only the PTP is reusable. It will return autonomously to DRO after each cargo delivery.

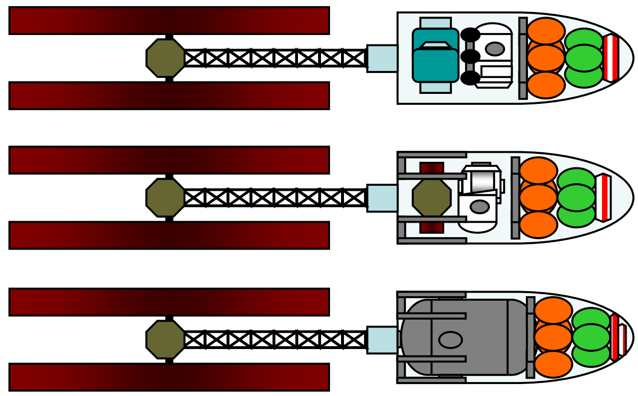

Figure 15. Mars Cargo Vehicle configurations

3.5 Recommended Mission Manifest Version 1.0

The previously described spacecraft integrate into a mission plan resulting in multiple missions to NEAs, the Moon, and Mars during the twenty-year period between 2025 and 2045. Table 1 shows the allocation of each spacecraft element to the composite vehicles used to implement the recommended exploration architecture.

Table 1. Spacecraft Element Allocation

	NEA Orbital Spacecraft	Deep Space Vehicle	Mars Transfer Vehicle	Lunar Surface Outpost	Mars Surface Outpost	Mars Cargo Vehicle	Lunar Cargo Vehicle	Lunar Crew Vehicle
MPCV	1	1	1	0	0	0	0	1
PTP	1	1	1	0	0	1	0	0
PTU	0	0	0	1	1	0	0	0
MH	0	1	1	0	0	0	0	0
PH	0	0	0	1	1	0	0	0
HAL	0	1	1	1	1	0	0	0
3PN	0	0	1	1	1	0	0	0
6PN	1	0	0	0	0	0	0	0
MS	1	1	2	0	0	0	0	0
PSR	0	0	0	2	2	0	0	0
PLC	0	0	1	0	0	0	0	1
PS	1	1	2	0	0	0	0	0
LAS	0	0	0	0	0	0	0	1
MAS	0	0	1	0	0	0	0	0
LDS	0	0	0	0	0	0	1	1
MEDLS Short	0	0	1	0	0	0	0	0
MEDLS Long	0	0	0	0	0	1	0	0
PSC	0	0	0	2	2	0	0	0
CMTR	0	0	0	2	2	0	0	0
LRM	1	2	2	2	2	0	0	0
RUE	Varies	Varies	Varies	Varies	Varies	0	0	0

Starting in 2029, multiple expeditions are planned to occur in parallel with each other. A first draft manifest is represented in table 2. Clearly as only a high level study has been conducted at this point, specific launch vehicle allocations cannot be credibly assessed. However, this recommendation does assume no less than four available SLS launches per year, along with availability of commercial and international launchers. It is not likely that this recommended exploration program would fully consume this composite launch capability, but SLS and Falcon Heavy usage are likely to dominate launch allocations, with most logistics and ISRU hardware potentially allocated to the smaller launchers (e.g. Delta, Falcon 9, Atlas, etc.). Crew launches are expected to rely primarily on MPCV/SLS, but may involve commercial or Russian vehicles. As noted in the introduction, this manifest does not describe NASA policy or programmatic decisions and no Agency endorsement of this manifest should be assumed.

Table 2. Recommended Mission Manifest

Year	Mission (includes transit times)
2025	21-Day NEA Expedition at DRO
2026	45-Day NEA Expedition at DRO
2027	95-Day Lunar Expedition
2027	45-Day NEA Expedition at DRO
2028	45-Day NEA Expedition at DRO
2028	365-Day Lunar Expedition
2029	730-Day Lunar Expedition
2029	45-Day NEA Expedition at DRO
2030	730-Day NEA Expedition in Deep Space
2031	730-Day Lunar Expedition
2033	860-Day Mars Dry Run at Lunar/DRO/NEA
2034	730-Day NEA Expedition in Deep Space
2035	730-Day Lunar Expedition
2035	860-Day Mars Crew Expedition
2037	730-Day Lunar Expedition
2038	730-Day NEA Expedition in Deep Space
2038	860-Day Mars Crew Expedition
2039	730-Day Lunar Expedition
2041	860-Day Mars Crew Expedition
2041	730-Day Lunar Expedition
2042	730-Day NEA Expedition in Deep Space
2043	730-Day Lunar Expedition
2044	860-Day Mars Crew Expedition

4 Conclusions

The spacecraft and architectures described in this paper are not particularly new – they reflect elements of exploration concepts that have been repeatedly visited in NASA exploration studies for the past forty years. What is unique is the attempt to harmonize these architectures in a manner that considers the unique drivers of each of the otherwise conflicting visions mentioned in this paper, as opposed to point solutions designed specifically for one and only one destination or mission. Issues related to reconciliation of the non-destination based competing visions fall within the scope of other Working Group papers, but if those can also be reconciled then it may be possible to see sustainable human space exploration beyond LEO begin within the next decade.

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