A Multi-Gravity Docking and Utilities Transfer System for a Common Habitat Architecture

Robert L. Howard, Jr.[1]
NASA Johnson Space Center, Houston, TX, 77058, United States of America

The Common Habitat architecture, a study architecture based on a large habitat derived from the SLS Core Stage Liquid Oxygen tank and designed to operate in microgravity, lunar surface, and Mars surface environments, requires a pressurized docking and berthing system that also works in all three domains. Prior flown docking systems have only been designed for microgravity, but a prototype suit port-derived docking system was developed under the Constellation program for the lunar surface. This system employed an active-active mating adapter approach consisting of a simplistic passive docking system on all spacecraft and a pressurized mating adapter with active systems on each end to form the docking connection. Derived from this approach, the Common Habitat architecture will use a multi-gravity active-active mating adapter (MGAAMA) to perform this function on the Moon, Mars, and in microgravity, connecting the various pressurized elements needed for surface base camps or deep space habitation. Design aspects and open trades of the MGAAMA system will be described. In addition to forming a structural connection and enabling the transfer of crew and equipment, the MGAAMA must also transfer utilities in the form of gases, fluids, power, and data. The MGAAMA is also designed with a degree of articulation in order to accommodate significant angular misalignment. Due to the environmental conditions the MGAAMA will experience, dust and thermal protection systems are discussed. Because the MGAAMA involves docking to spacecraft with different docking systems of different sizes, the MGAAMA is a family of docking systems with interfaces compatible with current and legacy spacecraft docking systems.

I. Nomenclature

AAMA = Active-Active Mating Adapter
ACBM = Active Common Berthing Mechanism
APAS = Androgynous Peripheral Attach System
ASTP = Apollo-Soyuz Test Program
CBM = Common Berthing Mechanism
CM = Command Module
CSM = Command Service Module
DIR = Docking Interface Ring
DRATS = Desert Research and Technology Studies
DSEV = Deep Space Exploration Vehicle
DSSV = Deep Space Science Vessel
EVA = Extra-Vehicular Activity
IDSS = International Docking System Standard
ISS = International Space Station
LEO = Low Earth Orbit
LIDS = Low Impact Docking System

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[1] Habitability Domain Lead, Human Systems Engineering and Integration Division, AIAA Senior Member.

LM = Logistics Module
LM = Lunar Module
MGAAMA = Multi-Gravity Active-Active Mating Adapter
MPLM = Multi-Purpose Logistics Module
NDS = NASA Docking System
NEA = Near Earth Asteroid
PCBM = Passive Common Berthing Mechanism
PCTM = Pressurized Crew Transfer Module
PEM = Pressurized Excursion Module
PMA-1 = Pressurized Mating Adapter 1
PR = Pressurized Rover
R&R = Rendezvous and Recovery
RCS = Reaction Control System
SIP = Suitport Interface Plate
SPR = Small Pressurized Rover
TDA = Target Docking Adapter

II. Introduction

This docking and utilities transfer system is created for and is applicable to space architecture studies involving the Common Habitat. The Common Habitat is an SLS-derived pressure vessel, where a SLS core stage liquid oxygen tank is manufactured for use as the habitat primary structure. This is referred to as a “dry hab” construction, roughly analogous to the Skylab space station, whose primary structure was a Saturn SV-B liquid hydrogen tank. [1] With a crew size of eight, the Common Habitat is being developed with the design goal that multiple copies of the same element can be used on the lunar surface, Martian surface, and in microgravity – with little to no destination-specific variation. On the surfaces of the Moon or Mars, the Common Habitat is docked with other elements to form a long-duration base camp. [2] In microgravity, the Common Habitat is docked with other elements to form a Deep Space Exploration Vehicle (DSEV) which primarily provides interplanetary transportation to and from Earth while conducting microgravity exploration and research. [3]

This docking system is also applicable to the Deep Space Science Vessel (DSSV) study. The DSSV is a much larger spacecraft than the DSEV and is intended to support human exploration of the inner solar system with a much larger crew, generally between the solar orbits of Mercury and Ceres. The DSSV is envisioned as a potential follow-on program after the initial series of Mars human landings. The current configuration of this forty-eight-person spacecraft includes ten pressurized modules, of which there are two 10-meter diameter modules and eight 4.5-meter diameter modules. [4]

Neither the Common Habitat nor the Deep Space Science Vessel are currently part of any active NASA reference mission or human spaceflight program. This paper is part of an ongoing a feasibility study to assess the viability of the Common Habitat, DSSV, and associated architectures, elements, and operations. Should such feasibility be determined, NASA would then be positioned to make a programmatic decision about whether to incorporate any aspects of these studies into current or future programs.

This docking system is being developed in order to ensure proper translation paths for crew and hardware between elements and to establish means for utilities connections between docked elements. This concept defines a common approach that can be shared across the surface base camp and DSEV, while also remaining compatible with other spacecraft concepts such as the DSSV.

III.History of Prior US Docking Systems

Gemini was the first US human spaceflight program to involve docking. The Gemini docking mechanism consisted of a Rendezvous and Recovery (R&R) section mounted in the Gemini capsule and a Target Docking Adapter (TDA) mounted on the Agena Target Vehicle or the Automated Target Docking Adapter. [5] This non-androgynous cup and cone system, shown in Fig. 1, does not allow for crew transfer, providing only structural and electrical connection between the two spacecraft. [6]

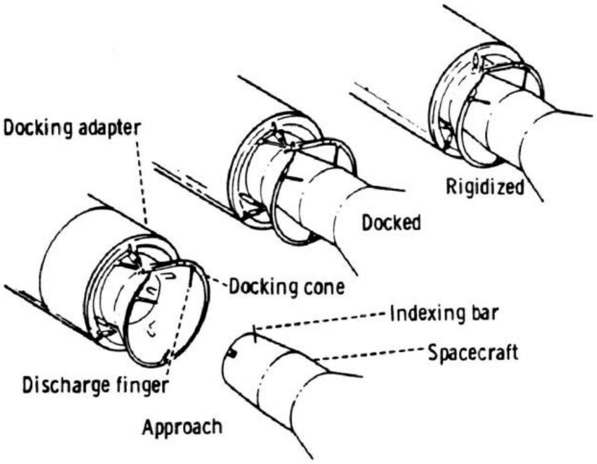

Fig. 1 Gemini Docking Mechanism

Apollo used a probe and drogue mechanism to dock the Command Module (CM) to the Lunar Module (LM), shown in Fig. 2. [6] The CM and LM dock twice. The first docking occurs when the CM extracts the LM from the Saturn S-IVB upper stage in Low Earth Orbit (LEO). Here, the CM is the active spacecraft and the LM is passive. The second docking occurs in lunar orbit when the LM ascent module returns from the lunar surface. In this case the LM is the active spacecraft and the CM is passive. [6] The probe can be removed by the crew to allow for crew transfer between the spacecraft. This same docking system was also used on Skylab.

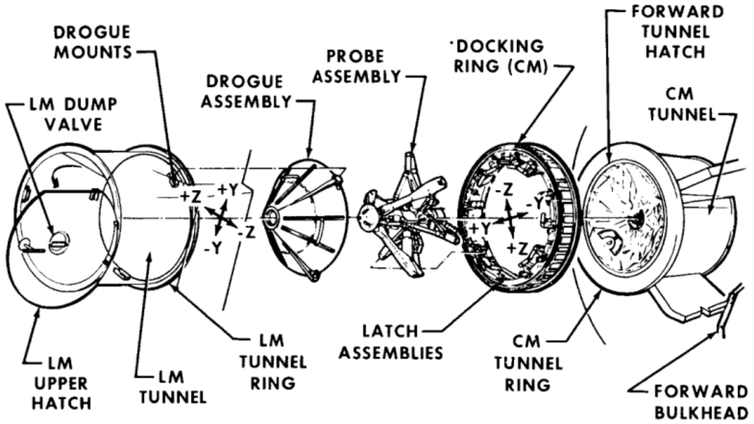

Fig. 2 Apollo Docking Mechanism

The first androgynous docking system was developed for the Apollo-Soyuz Test Program (ASTP). The ASTP featured a docking module launched with the Apollo Command Service Module (CSM). Jointly designed by NASA and Soviet teams, [7] the Androgynous Peripheral Attach System (APAS) contained docking systems on each end, one intended to dock with Soyuz and the other to dock with Apollo. Both systems could serve as either active or passive. [6] The US end is shown in Fig. 3. The active side extends prior to docking and the APAS uses spade-shaped petals on both active and passive sides to perform a gross alignment, with shock absorbers dissipating the residual impact energy. The active unit then retracts to bring the docking collars together. Alignment is completed by guides and sockets in the docking collars. [8] APAS was also used on the shuttle's Orbiter Docking System and on the International Space Station (ISS) between Pressurized Mating Adapter 1 (PMA-1) and the Russian FGB module. [6]

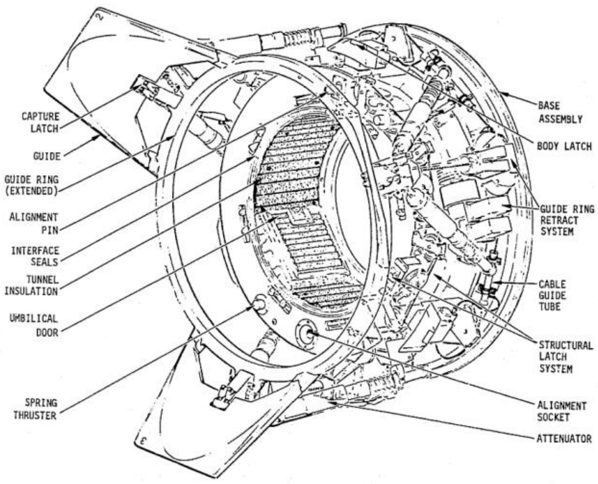

Fig. 3 US Portion of the APAS

The Common Berthing Mechanism (CBM) was used on the ISS as the primary connection between pressurized elements on the US segment. As the name implies, the CBM is a berthing system instead of a docking system. Shuttle or ISS robotic arms are used to position passive CBM (PCBM) elements for berthing. The CBM is not androgynous – pressurized elements are equipped with either active or passive CBMs, shown in Fig. 4 and 5. [9] Coarse alignment guides constrain roll and translation as the PCBM is guided towards the active CBM (ACBM). Capture latches then draw the PCBM into fine alignment with the ACBM. When ACBM fine alignment pins are seated in the PCBM's fine alignment sockets, structural attachment is achieved by advancing sixteen powered bolts on the ACBM into sixteen nuts on the PCBM. [6]

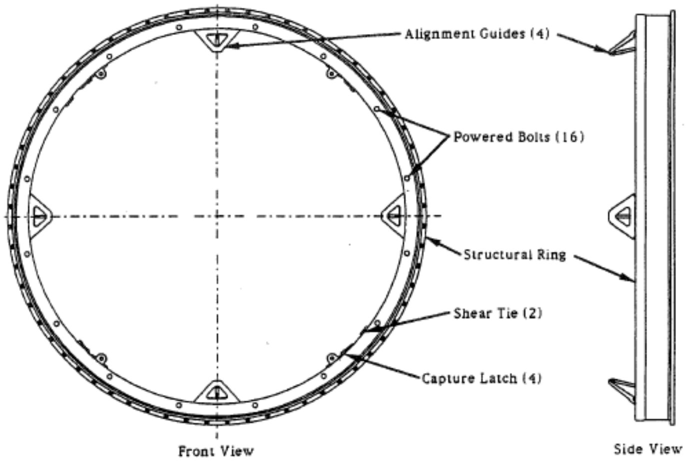

Fig. 4 Active CBM

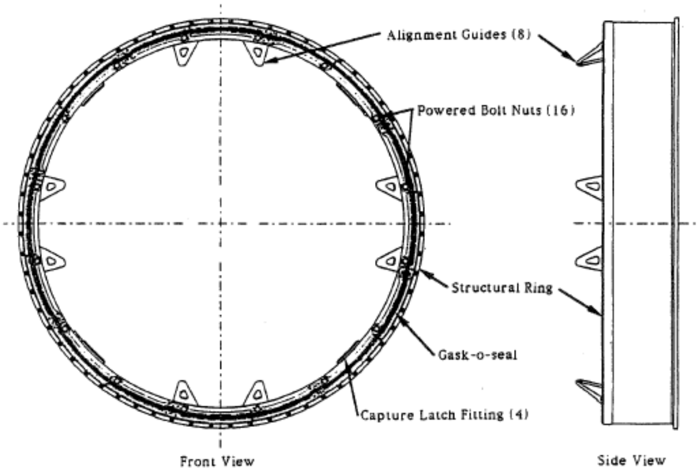

Fig. 5 Passive CBM

The most recent US docking system is the NASA Docking System (NDS). NDS was developed to comply with the International Docking System Standard (IDSS), which is developed based on both the APAS and an internal NASA study – the Low Impact Docking System (LIDS). [6] NDS, shown in Fig. 6, includes an APAS-derived hard capture system and a LIDS-derived soft capture system. [6] NDS Is intended for both LEO and exploration missions and can perform capture, structural attachment, power/data transfer, and undocking. [10] An innovation of the NDS over predecessor docking systems is that it eliminates the need for post-contact thrust, with the docking system mechanisms maneuvering the two vehicles to hard mate. [10]

Fig. 6 NASA Docking System

While NASA has amassed decades of experience with docking systems in microgravity these systems do not entirely translate to surface applications. Alignment of elements imposes unique challenges for docking in a gravity environment. In microgravity, relatively low thrust reaction control rockets can precisely align elements with no environmental disturbances. However, on the surface, docking systems must contend with uneven terrain. Additionally, systems used to align elements such as wheels, motors, and cranes are often not capable of the same levels of precision as RCS thrusters.

Translation paths also require adjustment for gravity applications. In microgravity, crew can float in any orientation through a docking hatch. This allows the hatch to be sized for the smallest cross-sectional area. In gravity, crew members cannot float. Depending on the scenario they may need to crawl, crouch, or walk upright. Additionally, there is often a tunnel between two hatches and depending on the distance from one hatch to the other, the crew may need to be able to stand upright when inside a docking tunnel.

Dust tolerance is a third concern, that while not unique to surface applications has not been a significant concern for historic microgravity missions. In Earth and lunar orbits and cislunar space there is very little potential for dust to reach and interact with docking seals. Consequently, none of the previously mentioned docking or berthing systems were designed with dust tolerance as a driving requirement. However, docking systems on both the Moon and Mars may be exposed to significant quantities of dust, which could compromise the ability of a docking seal to maintain a pressurized connection.

One of the first NASA concepts for a surface docking system was developed during the Constellation Program by the Small Pressurized Rover (SPR) team. While only advanced to the level of a low fidelity, structural prototype, shown in Fig. 7, and was never intended to be pressurized, the Active-Active Mating Adapter (AAMA) introduced several innovations that are not present in prior microgravity docking systems. The AAMA is essentially a Pressurized Mating Adapter that has an active docking system on each end.

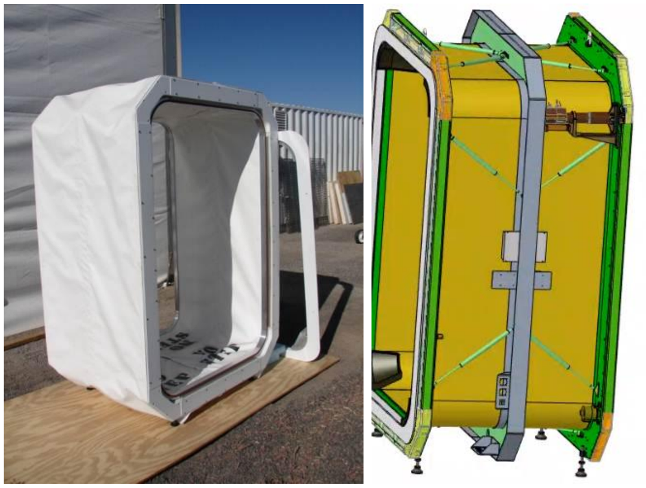

Fig. 7 Active-Active Mating Adapter Prototype at Desert Field Test and CAD Image of Mechanisms

The docking system largely departed from the petals and latches prevalent in historic docking systems and was based on the suit port concept, extending its use from the original idea to dock surface spacesuits to the rover. Essentially, the docking system is analogous to a giant suit port, allowing rover-to-rover or rover-to-habitat docking. It does include structural guide cones on the spacecraft side (roughly analogous to the petals) that helped guide the docking vehicle into the AAMA. The cones visible in the CAD model in Fig. 7 are attached to the (not visible) docking spacecraft, not the AAMA. They are visible on the Small Pressurized Rover (SPR) in Fig. 8.,

Fig. 8 Small Pressurized Rover with Docking Guide Cones on Docking Hatch

Another innovation was to make all spacecraft passive docking elements. Typically, one spacecraft is equipped with an active docking system and the other a passive system. A few exceptions, such as the APAS, are androgynous allowing either spacecraft to function as either active or passive. However, the passive system is always lighter than an active or androgynous system, thus the mass of each element is reduced by making them all passive. The AAMA is based on each spacecraft being equipped only with a passive system in the form of the previously mentioned guide cones and a large flange comparable to a spacesuit's suitport interface plate (SIP). This is difficult to see in Fig. 8 but can be seen in Fig. 9 as the gray metal surrounding the hatch door. The AAMA itself is equipped with a larger version of the Marmon mechanism used in the SPR's suit ports. This mechanism clamps around the flange, creating a structural seal. In a flight version, an inflatable seal activates within this mechanism, forming a pressurized connection. The all-passive approach improves docking system reliability for crewed elements. In the event of a non-repairable failure in the active docking system, replacing the adapter is easier than replacing the larger, more complex crewed element.

Fig. 9 Enlarged View of SPR Docking Hatch Illustrating Flange.

The AAMA offered the Constellation lunar architecture operational flexibility in that it allows the SPRs to dock to each other or the habitat in either of two orientations. The rovers could dock facing either the same or opposite direction as shown in Fig. 10. This level of flexibility may be necessary due to terrain constraints, internal cabin activities, or mission objectives. It would not have been possible if the rover side hatches were non-androgynous.

Fig. 10 Flexibility in Docking Orientation

The AAMA was tested during NASA's Desert Research and Technology Studies (DRATS) field expeditions to the Arizona desert in 2009 and 2010. The AAMA was used to dock the SPR to the Pressurized Excursion Module (PEM), a "microhab" habitat mockup, and to a second SPR. Fig. 11 shows SPR Cabin 1A docked to SPR Cabin 1B during a crew rescue simulation in the 2009 DRATS field test. Fig. 12 shows the SPR Cabin 1B preparing to dock with the PEM, with Fig. 13 showing an internal view looking from inside the SPR through the AAMA and into the PEM after docking was completed.

Fig. 13 also illustrates a lesson learned from the DRATS testing – namely that the tunnel height is insufficient. The astronaut in Fig. 13 is forced to bend over at an awkward angle while inside the tunnel because its height is only 60 inches. Previous testing had identified a recommended hatch size of roughly 40 inches in width and 60 inches in height (exact dimensions 39" x 63"), as sufficient for a crew member in a pressurized surface spacesuit to translate across. However, these dimensions were only intended to apply to the hatch opening, not to a connecting tunnel. And even for the opening, the test results stipulated the lower lip of the hatch was to be raised 16 inches above the floor.

[11] These dimensions can only be sustained for a very short distance – roughly the distance a suited crew member can step sideways – before the vertical height needs to return to a sufficient clearance to accommodate suited stature. This insufficient height is an annoyance for unencumbered shirtsleeve operations but can become more challenging when carrying items as shown in Fig. 14 and would likely force the astronaut to assume a crawling posture if wearing a spacesuit.

Fig. 11 LER Cabin 1A Docked to Cabin 1B via AAMA

Fig. 12 SPR Cabin 1B on Final Approach to Dock with PEM

Fig. 13 View from the SPR Hatch Through the AAMA to the PEM Interior

Fig. 14 Crew Member Preparing to Transport Stowage Through the AAMA from LER to PEM

Despite the limitations in tunnel height, test crews were able to demonstrate surface docking with the SPR and AAMA. Test results in 2010 did indicate a need for improved side window visibility, camera views, and overall situational awareness, but all three out of three docking and undocking attempts were successful and met the test criteria of attachment or detachment in ≤5 minutes. [12] This was a significant improvement over the 2009 tests, where only 7 out of 15 attempts were successful. [13] However, all of the reasons for the disparity in results were not clear. The 2010 crews did receive more docking training than the 2009 crews. [12] Also, the 2009 crews tested over a wider diversity of terrain types and did note difficulty docking in loose gravel due to difficulty making fine maneuvers in the gravel. [13]

IV.Multi-gravity accommodation and docked elements in Common Habitat architecture

The Common Habitat architecture is based on commonality across multiple gravity regimes including 0g, 1/6g, 3/8g, and 1g. As such, it needs a docking system that can operate in all of these environments. This includes near-identical surface base camps on the Moon and Mars, which will be described more fully in a separate paper. It also includes a deep space vehicle designated the Deep Space Exploration Vehicle (DSEV), which is also described in a separate paper. All three of these habitable space vehicles would also be represented on Earth with trainers and analogues. There are five elements that frequently dock or undock to form shirtsleeve connections across these vehicles.

As previously introduced, the Common Habitat [1] is a large, horizontally oriented habitat that serves as the primary living and working volume in this architecture. It features four docking ports on its mid deck, clocked at 90-

degree angles to each other (two axial and two radial). In both the surface base camp and the DSEV, the Common Habitat is docked to the Airlock, Logistics Modules, and Pressurized Rovers.

Described in a separate paper, [14] the airlock is an external module that is roughly analogous to the ISS Quest Airlock and the ISS Nodes in that it serves dual functions of facilitating extravehicular activity (EVA) and also serves as a temporary node. The airlock is primarily docked to the Common Habitat, but as dictated by mission needs can also be docked to Logistics Modules and Pressurized Rovers. When used as part of the DSEV, it serves as the primary docking port for docking with Orion, Gateway, or other visiting vehicles.

Roughly comparable in dimensions to a Multi-Purpose Logistics Module (MPLM), the Logistics Module (LM) is a horizontally oriented cylindrical pressure vessel that severs as the primary bulk stowage location for the surface base camps and DSEV. While it does not have its own mobility system it can be relocated within the base camp or DSEV and may be docked to the Common Habitat, Airlock, Pressurized Rover, another Logistics Module, Orion, or Gateway.

The Pressurized Rover (PR) is derived heavily from the NASA Reference Vehicles used for pressurized rovers dating back to the Constellation Program. This is a small cabin spacecraft intended to support a crew of two for missions several days in duration, with missions up to 30 days currently being proposed. It is equipped with two suitports on the aft bulkhead to facilitate EVA activity. There are two versions of the PR – a surface PR that is equipped with a wheeled mobility chassis and a microgravity PR that is equipped with a propulsion module. The PR docks to the Common Habitat, Airlock, Logistics Modules, other PRs, the Pressurized Crew Transfer Module, Orion, and Gateway.

The Pressurized Crew Transfer Module (PCTM) is a pressurized cabin derived from the Pressurized Rover. Notionally, it is a PR cabin without wheels and with a suitport bulkhead on both the forward and aft sections. Details of the PCTM integration with a lander spacecraft are beyond the scope of this paper and will be covered in a future paper. For purposes of this paper, Moon and Mars lander spacecraft are assumed to be vehicles with a crew module positioned such that a direct docking from PR to lander cabin is not possible. The PCTM articulates between the lander and the PR and as such it docks to those two vehicles.

V.MGAAMA Concept

A common docking and berthing system is used for all of these elements in all gravity environments. The system that enables this approach is the Multi-Gravity Active-Active Mating Adapter (MGAAMA). Like the AAMA approach used by the Constellation SPR prototypes, the system places passive systems on all elements and uses an active-active adapter between each element. An advantage of this architecture is that the complex mechanisms hosted on the mating adapter instead of the spacecraft, which simplifies maintenance strategies.

It is worth noting that docking vs. berthing is a function of both vehicle and operational drivers, such that the same space vehicle might dock in one scenario but be berthed in another. As such, the word docking is used in this paper generically and encompasses both technical meanings of docking and berthing.

The MGAAMA includes a softgoods tunnel, Marmon mechanism, hatches and bulkheads on each end, a center bulkhead, utilities conduit, and an internal skeletal structure that can accommodate angular offsets of up to 15 degrees in roll, pitch, and yaw axes between docked elements. This enables docking with substantial angular misalignment, particularly with docking of mobile assets across significant terrain slope variations.

Fig. 15 shows an early concept model of the center bulkhead and the skeletal structure and Marmon mechanism on one side of the system. Not shown is a bulkhead with hatch that is attached to the Marmon mechanism. The opposite side of the center bulkhead mirrors this arrangement. The internal skeletal structure is a Stewart platform and uses electric linear actuators (sized for the worst case load to manipulate MGAAMA mass in 3/8 gravity and maintain cabin pressure at 14.7 psia) to adjust the x,y,z translation and roll, pitch, and yaw of the Marmon mechanism and its attached bulkhead with hatch. Because this is replicated on the opposite side of the center bulkhead, the MGAAMA is essentially a double Stewart platform, shown in Fig. 16, both with and without the soft goods pressure vessel visible.

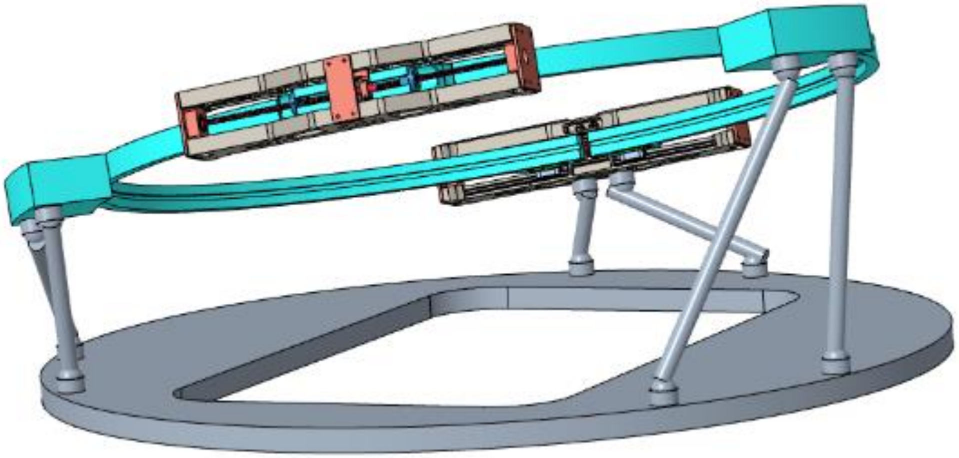

Fig. 15 MGAAMA Stewart Platform

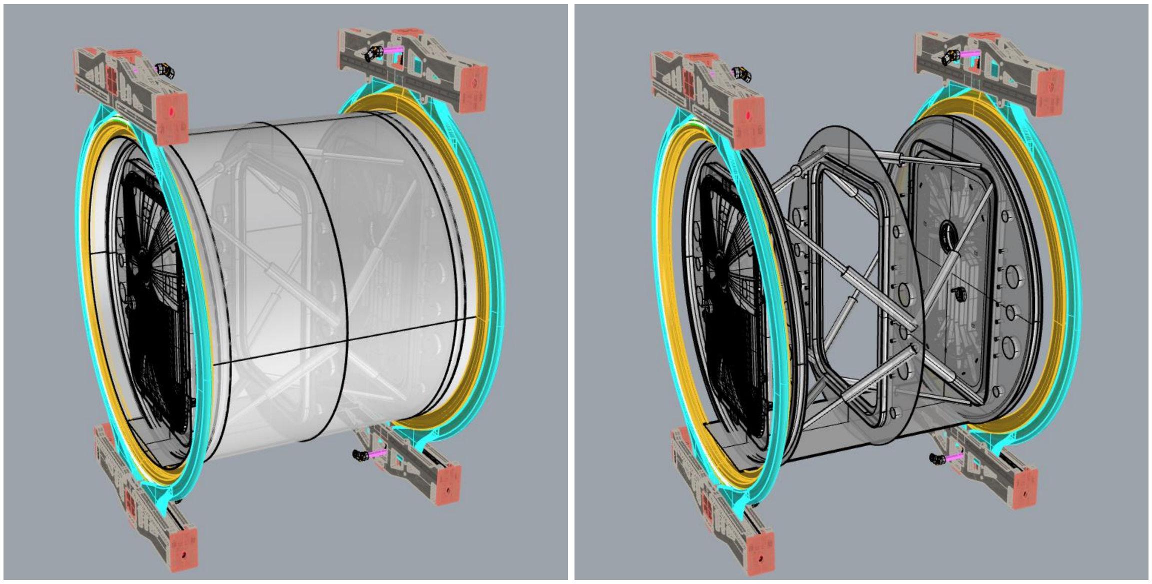

Fig. 16 MGAAMA Double Stewart Platform

As previously mentioned, the spacecraft side is passive with no mechanisms, only a Docking Interface Ring (DIR), the cylindrical ring that surrounds the hatch and utility connections. The DIR is the portion of the docking system that is directly adapted from the spacesuit SIP. Figures 17 and 18 show the location of the DIR on a Logistics Module. The DIR is captured by the MGAAMA's Marmon mechanism, which forms the structural connection and uses an inflatable seal to establish a pressurized connection.

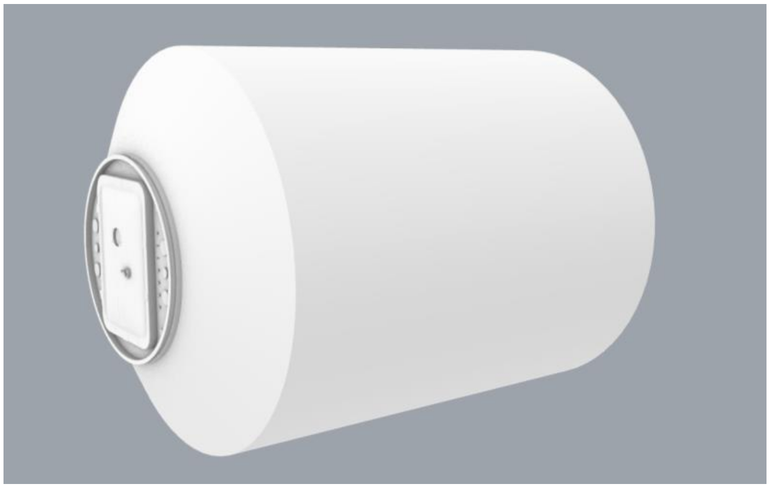

Fig. 17 Logistics Module with MGAAMA Passive Docking System

Fig. 18 Close-Up View of the Docking Interface Ring

The MGAAMA can be positioned by surface or orbital manipulators. Attach points on the exterior are structurally connected to the center bulkhead and can be grappled by the LSMS, ATHLETE, or robotic arms.

A unique feature of this docking system is that it is intended as a family of docking systems. This enables the Common Habitat architecture to use specific implementations to dock with other vehicles including landers, space stations, capsules, or other vehicles regardless of what docking systems the other spacecraft are equipped with. For instance, the DSEV can switch out different versions of this same docking system to dock with a Soyuz, the International Space Station, and Gateway over the course of the same mission, with no modification required to those other vehicles.

VI.MGAAMA Utilities Transfer

The International Space Station required numerous EVAs during its assembly to establish utility connections between modules. [15] This reliance on EVA precluded the possibility of spacecraft assembly without hours of crew involvement for each element berthing. Such an approach would be impractical in the Common Habitat architecture as element docking and undocking must be a routine operation when crew are not present and must not require EVA activity even when the crew are present. However, the nature of the surface base camps and DSEV require that gases, fluids, power, and data be exchanged between docked elements. Consequently, utilities transfer ports, as shown in Fig. 19, allow for automated utility connections within the MGAAMA. For each utility connection, there is always at least an A loop and a B loop to allow for redundancy. This also enables the MGAAMA to support two docking orientations for any given spacecraft.

High pressure gas transfer is used to refill oxygen and nitrogen tanks associated with the habitat, airlock, logistics modules, pressurized rovers, and other visiting vehicles. The high-pressure system is notionally based on blind mate connectors for half-inch, 10,000 psi gas transfer lines. Four high-pressure lines are included – two each for oxygen and nitrogen.

Low pressure gas transfer is used to circulate cabin air throughout the docked spacecraft complex. This system is notionally based on blind mate connectors for six-inch conduit operating at ambient pressure of the docked stack, which could vary from as low as 8.2 psi to as high as 22 psi. (The 22 psi operating pressure would likely be associated with dual rovers or a rover and airlock at elevated pressure for hyperbaric chamber operations.) Four low-pressure lines are included – two each for cabin air supply and cabin air return.

Water transfer is used to circulate water between docked open and closed loop systems. This includes potable water, gray water (including condensate), and urine water. Two half-inch blind mate connectors provide for potable water transfer at ambient temperature. Systems requiring hot or cold water must heat or chill the incoming water to the needed temperature. Two three-inch blind mate connectors transfer gray water and two three-inch blind mate connectors transfer urine.

Thermal fluid can be transferred across the docking system to allow docked elements to share the Common Habitat's thermal control system, in particular providing access to the external heat rejection system attached to the Common Habitat in both base camp and DSEV configurations. Two half-inch blind mate connectors allow for thermal control fluid transfer.

The high-power transfer system is designed to allow electricity for high-power propulsion systems or utilization payloads to be powered across any docking connection. Each high-power conduit bundles five insulated 1.33-inch cables in a plus-shaped configuration, forming a 4-inch diameter conduit. There are two four-inch blind mate connectors for high-power transfer.

The low-power transfer system delivers electricity for use by primary system operations. Two half-inch blind mate connectors enable the low-power electrical transfer.

The data system is a high-speed optical network for voice, video, and data communication across docked elements. Four half-inch blind mate connectors are used for high-speed data transfer.

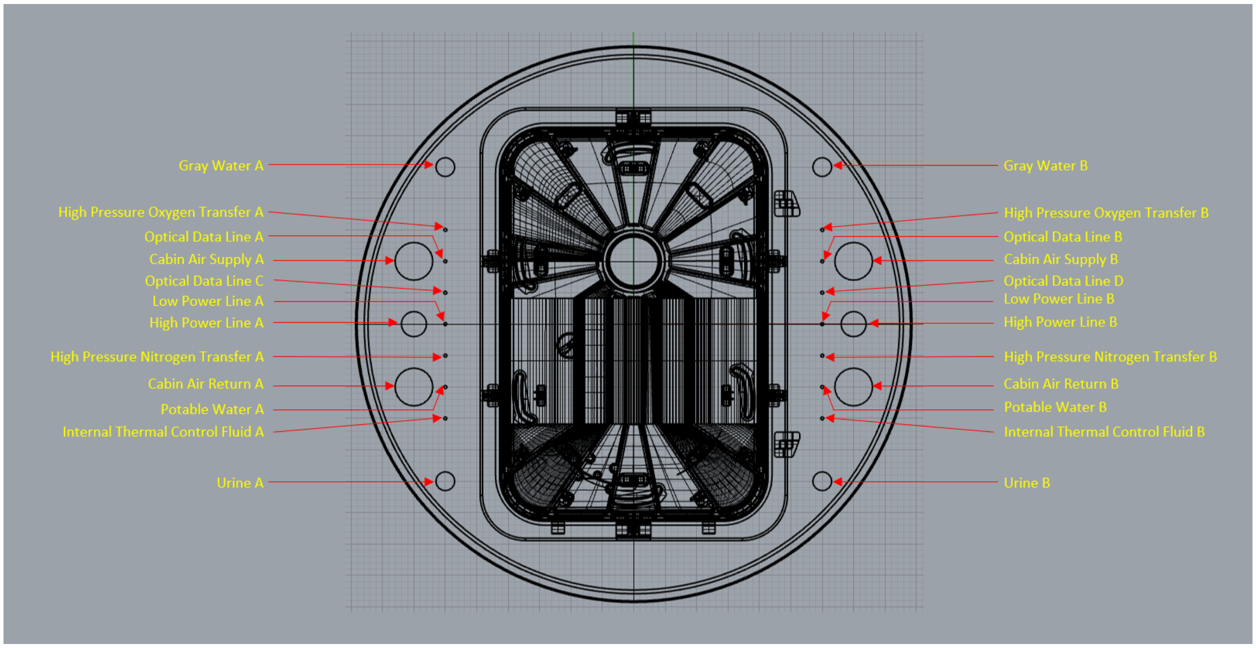

Fig. 19 MGAAMA Utilities Transfer Ports

The MGAAMA includes routing systems to control the flow of utilities across the docking interface. This includes both active routing – where the flow can be enabled or disabled – and passive routing – where utilities transfer is permanently blocked. As will be described later in this paper, the MGAAMA is a family of different types of docking systems that enables docking between elements otherwise incapable of docking. Passive routing is applied in cases where an element that nominally transfers a particular utility is docked to a spacecraft that never transfers that utility. For instance, the Common Habitat nominally can exchange water with the Airlock when the two are docked. Active routing is applied to the potable, gray, and urine water connections. Water transfer can be commanded on or off as needed. However, with a different type of docking adapter in the MGAAMA family, the Common Habitat can also dock to Orion. Orion cannot exchange water and therefore that MGAAMA carries passive routing for water. That MGAAMA will not accept water from the Common Habitat because it cannot be carried across Orion's NASA Docking System interface.

There is no propellant transfer across docking ports. This is an intentional decision to separate propellant transfer from crewed pressure vessel interiors. Many propellants are either cryogenic or toxic and as such do not mix well with habitable interiors.

For the Moon and Mars base camps, propellant transfer only exists in limited circumstances. ISRU propellant production sites transfer propellant to lander spacecraft for refueling. This includes transfer from propellant production equipment to propellant transfer vehicle to lander. None of these transfers require the use of a crew docking port.

In the case of the DSEV, the cryogenic and nuclear electric main propulsion systems are refueled by means of an orbital depot that again does not utilize a crew docking port for transfer. The reaction control system (RCS) is currently forward work, but presumably shares propellant with the cryogenic main propulsion system. Thruster locations have not been determined but are presumed to not be on the Common Habitat itself. Depending on thruster location, they will either have RCS propellant tanks that will be refueled by the in-space Pressurized Rovers or they will be directly connected by propellant lines to the main propulsion system. In either case the crew docking ports will not be used.

The in-space Pressurized Rovers will refuel by docking or berthing their service modules to the DSEV propulsion system.

VII.Hatches and Thermal/Dust Covers

The MGAAMAs can spend significant periods of time with at least one of its two ports undocked, which means that without some form of protection the interior can be exposed to the local environment. In LEO, temperatures on the International Space Station exterior can reach as high as 121 C. [16] The coldest temperature in space is that of Cosmic Microwave Background Radiation, -270.42 C. [17] On the Moon, temperatures can vary from 127 C in sunlight down to as low as -248.15 C in a permanently shadowed crater. [18] The temperature swing on Mars is significantly milder, ranging from 20 C to -125 C. [19] These temperature ranges are such that MGAAMA systems and crew must be protected from exposure to them.

In general, the deep space environment can be considered dust-free. However, an exception exists for missions that might operate in the vicinity of asteroids, whether Near Earth Asteroids (NEAs) or main belt asteroids. Dust on the surface of an asteroid could be liberated by thruster firing, astronaut EVA, or physical contact with spacecraft or other deployed elements. This dust could potentially be placed on trajectories that intersect with docking systems. This asteroid dust concern primarily impacts the in-space variant of the pressurized rover, which will fly to and land on such asteroids, exposing it and its docking adapters to the dust environment. The surfaces of the Moon and Mars are both dusty environments. Mars shares similar dust concerns with the lunar surface, but because Mars has a thin atmosphere, dust can remain airborne longer than lunar dust and the wind can circulate the dust in different directions. Mars is also subject to periodic dust storms that are not present on the Moon.

Consequently, thermal and dust protection should be applied to protect the MGAAMA interior. The umbilical connectors would also be exposed and should similarly be protected, though they may or may not be protected by the same system as the interior. Three options exist for protecting the MGAAMA interior: hatch, thermal/dust cover, or hatch with thermal/dust cover.

A thermal/dust cover is the lowest mass solution. With the proper seals, the hatch can prevent the intrusion of dust into the MGAAMA interior and can also insulate the MGAAMA interior against the external thermal environment. A thermal/dust cover may or may not also provide protection for utility connectors. Thermal protection may be achieved though some form of insulation (e.g. multi-layer insulation, spray-on foam insulation, or thermal tiles). Dust protection may be achieved through dust-repelling coatings, smooth surfaces, air hoses/blowers, or electrostatic techniques. [20]

A hatch also protects the MGAAMA interior against dust. Assuming the hatch is equipped with insulation it also provides thermal protection. Additionally, a hatch would enable the MGAAMA to maintain its own internal atmosphere instead of requiring pressurization from docked vehicles (and depressurization prior to undocking). This would enable faster docking and undocking, which may be valuable in certain emergency scenarios. It should be noted that the outer surface of the hatch becomes part of the spacecraft interior once docking has been achieved. So, it remains critical to protect the hatch exterior surface in some way.

The baseline approach for the MGAAMA is to use both a hatch and a thermal/dust cover on each end. The thermal/dust cover is hinged to the exterior and can rotate out of the way just prior to docking, ensuring clearance for adjacent docked elements, approach/departure corridors, and appendages or other mechanisms. The hatch must open into the MGAAMA to avoid physical interference with the docked element. Thus, the hatch needs some means of articulation. Additionally, the inner surface of the thermal/dust cover must be protected from dust when elements are docked. An example of a sufficient protection system might be a flexible dust cover that closes upon itself as it deploys out of the way of a docking connection.

From a mechanical design perspective, the simplest approach for hatch articulation is a removable hatch. The crew member unlatches the hatch and physically lifts it from the hatch opening, carrying it to a designated stowing area where it is placed until needed again. The Apollo Command Module docking hatch (used only in microgravity) was removable, while the side hatch (used in both microgravity and on Earth) was hinged. [21] [22] Removable hatches would be undesirable for the larger MGAAMA variants due to the presence of gravity and should be avoided if possible. Though they would weigh only 3/8 of their Earth weight, manipulating 40” by 60” hatches in the small confines of an MGAAMA would be challenging at best for the crew. There is not enough room inside the 4x6 or smaller MGAAMAs to mount hatches on rails. Thus, the hatches must either be removable or hinged. If hinged, there is not enough room to articulate vertically, thus the hinge must be to one side, similar to the hinged hatches in the Apollo and the current NASA reference Pressurized Rover. This does drive a minimum tunnel length of roughly 2.5 meters for MGAAMAs with 40-inch wide hatches. This approximate length will enable hinged hatches to fully open without impacting the center bulkhead. 40x60, 40x40, and CBM hatches are hinged, while IDSS and SSVP-G4000 hatches (both used only in microgravity) are removable.

VIII.MGAAMA Docking System Family

The basic MGAAMA architecture is implemented across a family of differently sized MGAAMAs to accommodate the variety of different hatch sizes and docking systems used across human spaceflight. Despite attempts for common docking systems dating back to APAS, both vehicle and environmental constraints have led and continue to lead to variations in docking systems.

The 6x6 MGAAMA is the primary docking system for habitable elements in the Common Habitat architecture. It links the Common Habitat with the Logistics Modules and Airlock. It features a 40-inch wide by 60-inch tall hatch opening, surrounded by a 2.25-meter diameter Marmon mechanism. All of the previously discussed utilities are transferred across the 6x6 MGAAMA.

The 4x4 MGAAMA is a docking system where both ends are 40-inch by 40-inch hatches and 1.63-meter diameter Marmon mechanisms. This MGAAMA is primarily intended to dock two PRs together or one PR to a PCTM. All of the previously discussed utilities with the exception of high-power transfer are transferred across the 4x4 MGAAMA.

The 4x6 MGAAMA enables spacecraft with 40x40 hatches to dock with spacecraft with 40x60 hatches. One end features a 40-inch by 40-inch hatch while the other features a 40-inch wide by 60-inch tall hatch. All of the previously discussed utilities with the exception of high-power transfer are transferred across the 4x6 MGAAMA.

The Ix4 MGAAMA is only used in microgravity and it supports docking with spacecraft designed to the International Docking System Standard (IDSS). One end contains a NASA Docking System while the other end features an identical 40-inch by 40-inch hatch and Marmon mechanism configuration found on the 4x4 MGAAMA. Utilities transferred across the Ix4 MGAAMA are Low Power Line A, Low Power Line B, Optical Data Line A, Optical Data Line B, Optical Data Line C, and Optical Data Line D. These utilities are combined within the MGAAMA to match the IDSS Power and Data Transfer Umbilical. [23]. The Ix4 MGAAMA can be returned to Earth to add water transfer should IDSS at some point incorporate water transfer capabilities.

The Ix6 MGAAMA is similarly only used in microgravity. It supports docking with spacecraft designed to the International Docking System Standard (IDSS). One end contains a NASA Docking System while the other end features an identical 40-inch wide by 60-inch tall hatch and Marmon mechanism configuration found on the 6x6 MGAAMA. Utilities transferred across the Ix6 MGAAMA are Low Power Line A, Low Power Line B, Optical Data Line A, Optical Data Line B, Optical Data Line C, and Optical Data Line D. These utilities are combined within the MGAAMA to match the IDSS Power and Data Transfer Umbilical. [23]. The Ix6 MGAAMA can be returned to Earth to add water transfer should IDSS at some point incorporate water transfer capabilities.

The 6x5 CBM MGAAMA denotes one where the hatch on one side is a 40x60 hatch but the other is a CBM active port. This variant is used in microgravity only and would only be launched if needed to support the berthing of a CBM-equipped spacecraft to the DSEV but is not manifested in the baseline Common Habitat architecture. Utilities transferred across the 6x5 CBM MGAAMA are Low Power Line A, Low Power Line B, Optical Data Line A, Optical Data Line B, Optical Data Line C, and Optical Data Line D. These utilities are combined within the MGAAMA to terminate in CBM utility jumpers.

The 6xDC MGAAMA denotes one where the hatch on one side is a 40x60 hatch but the other is a Russian SSVP-G4000 passive port. Its only use is in microgravity and would only be launched if needed to support a Soyuz docking to the DSEV but no such mission is manifested in the baseline Common Habitat architecture.- Utilities transferred across the 6xDC MGAAMA have not currently been identified but would be constrained based on what utilities can be transferred across the SSVP-G4000.

IX.Conclusions / recommendations

The MGAAMA helps advance commonality while reducing risk and EVA overhead. Particularly in surface architectures, the MGAAMA may enable pressurized crew transfer immediately after landing, even for deconditioned crew. For EVA transfer involving ladders or translation over unprepared terrain it may be preferable for the crew to adapt to surface gravity before exiting the lander, requiring a wait of several days. Such a wait may not be needed if all transfers are in the more controlled environment of spacecraft interiors.

The MGAAMA further enables functional redundancy and replacement of docking systems. In the event of a failure in the active docking system, the failed MGAAMA can simply be replaced by another unit and the docking can continue. If the MGAAMA cannot be repaired, it is a much lower burden to fly a replacement MGAAMA than to replace an entire spacecraft.

Acquisition for long-term human spaceflight docking systems is also simplified by the MGAAMA concept. Regardless of surface or microgravity destination, the same basic architecture can be applied. This also enables docking compatibility across dissimilar spacecraft. Whether legacy spacecraft or future vehicles that have yet to be conceived, the MGAAMA family of docking systems can mate elements with different hatch sizes or docking systems.

Forward work remains to develop the MGAAMA in multiple areas. Further design maturation is needed in areas of the Stewart platform actuators, pressure vessel soft goods, suit port mechanisms, and thermal and dust control. Additional habitability design work is needed in areas of tunnel lighting, mobility aids, and floor and ceiling surfaces – which must both be flexible and load bearing.

Structural analyses will be needed for the MGAAMA docking connections. Analyses will be needed to determine if the MGAAMA can be cantilevered off a docking port on a surface element. Examples of driving cases include a 6x6 MGAAMA cantilevered off the Common Habitat and a 4x4 or 4x6 MGAAMA cantilevered off a Pressurized Rover while driving. If either the docking system or the pressure vessel cannot support this load, additional structures will be needed to offload the forces acting on the docking interface. It will also be important to determine how compactly the 4x4 and possibly 4x6 MGAAMA can be retracted when not in use. Because the PRs will nominally traverse with a 4x4 MGAAMA it is helpful to enable this one to compact as tightly as possible when it is not supporting a docking event.

Analyses will also be needed to determine if the MGAAMA can support the mass of docked DSEV elements during cryogenic main propulsion system burns. The Logistics Modules are docked along the DSEV central axis, but the Pressurized Rovers are nominally docked to each other on Common Habitat port docking hatch and the Airlock is nominally docked to the Common Habitat starboard docking hatch. If they cannot support this load there will need to be additional structure to offload the docking system.

The point of departure sizing for the MGAAMA geometries requires additional assessment. At present, the Stewart platform actuators and center bulkhead constrain crew mobility and may interfere with floor placement. This can be alleviated through trades in MGAAMA diameter or length, or perhaps a combination of both. The trade may also lead to reconfiguration of the Stewart platform actuators. This trade study will need to be conducted in conjunction with human-in-the-loop testing for the different configurations of the MGAAMA. This includes nominal suited and unsuited crew transfer, suited and unsuited incapacitated crew transfer, and equipment/logistics transfer. This testing can begin in CAD alone and progress to Virtual Reality, but as the trade space narrows it will need to include load-bearing physical mockups and eventual incorporation into full mission analogues.

The 6x6 MGAAMA is large enough that it is worth asking the question whether it could serve an airlock function, for instance as a contingency single-person airlock. It is not clear if this would offer sufficient advantages to justify its use, however this does bear further analysis. It could alternately be used to allow two docked elements to nominally operate at different pressures, using the MGAAMA as a vestibule to step the pressure up or down when transitioning between modules. This also may have subtle complexities and bears further analysis.

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References

[1] Robert Howard. Opportunities and Challenges of a Common Habitat for Transit and Surface Operations. IEEE Aerospace 2019. Big Sky, Montana. March 2-9, 2019.

[2] Robert Howard. A Common Habitat base camp for Moon and Mars Surface Operations. AIAA ASCEND 2021. November 15-17, 2021.

[3] Robert Howard. A Common Habitat Deep Space Exploration Vehicle for Transit and Orbital Operations. AIAA ASCEND 2021. November 15-17, 2021.

[4] Robert Howard. An Introduction to the Concept of a Deep Space Science Vessel." IEEE Aerospace 2019. Big Sky, Montana. March 2-9, 2019.

[5] NASA Project Gemini Familiarization Manual. SEDR 300. McDonnell. July 1, 1966, changed August 22, 1966. Last Accessed May 7, 20201. https://www.ibiblio.org/apollo/Documents/GeminiManualVol2.pdf.

[6] John G. Cook, Valery Aksamentov, Thomas Hoffman, Wes Bruner. ISS Interface Mechanisms and their Heritage. AIAA Space 2011. January 1, 2011. Last Accessed May 8, 2021. https://ntrs.nasa.gov/citations/20110010964.

[7] Edward Ezell and Linda Ezell. An International Docking System. The Partnership: A History of the Apollo-Soyuz Test Project. NASA SP-4209. 1978. Last Accessed May 8, 2021. https://www.hq.nasa.gov/pao/History/SP-4209/ch6-5.htm.

[8] David Portree. Mir Hardware Heritage. NASA RP 1357. March 1995. Last Accessed May 8, 2021. https://history.nasa.gov/SP-4225/documentation/mhh/mirhh-preface.pdf.

[9] Erik Illi. Space Station Freedom Common Berthing Mechanism. NASA Technical Documents. May 1, 1992. Last Accessed May 8, 2021. https://core.ac.uk/reader/42812486.

[10] Justin McFatter, Karl Keiser, Timothy Rupp. NASA Docking System Block 1: NASA's New Direct Electric Docking System Supporting ISS and Future Human Space Exploration. Aerospace Mechanisms Symposium. May 16, 2018. Last Accessed May 8, 2021. https://ntrs.nasa.gov/citations/20180004167.

[11] Harry Litaker, Shelby Thompson, Ronald Archer, Karen Young, Sherry Thaxton, Sudhakar Rajulu, Robert Howard. Lunar Extravehicular (EVA) Hatch Size Evaluation. Internal Test Report. December 18, 2007.

[12] Harry Litaker, Robert Howard. Human Factors Assessment of a Dual Rover Field Study. Internal Test Report. January 2011.

[13] Harry Litaker, Shelby Thompson, Robert Howard, Rich Szabo, Carl Conlee, Evan Twyford. A Human Factors Assessment of the Lunar Electric Rover (LER) During a 14-Day Desert Trial. Internal Test Report. February 2010.

[14] Robert Howard. A Two-Chamber Multi-Functional Airlock Node for a Common Habitat Architecture. AIAA ASCEND 2021. November 15-17, 2021.

[15] David Anderson, Debra Meyer, Kashyap Shah. International Space Station EVA Operations –Phase 2 Hardware Lessons Learned. 31st International Conference On Environmental Systems. Orlando, Florida. July 9-12 2001. Last Accessed May 21, 2021. https://spacecraft.ssl.umd.edu/design_lib/ICES01-2202.ISS_EVA_lessons.pdf.

[16] Staying Cool on the ISS. NASA. March 20, 2001. Last Accessed May 22, 2021. https://science.nasa.gov/science-ews/science-at-nasa/2001/ast21mar_1/.

[17] Edward Wollack. Fluctuations in the Cosmic Microwave Background. Universe 101 Our Universe. August 20, 2014. Last Accessed May 22, 2021. https://wmap.gsfc.nasa.gov/universe/bb_cosmo_fluct.html.

[18] Tim Sharp. What is the Temperature on the Moon? Space.com. Last Accessed May 22, 2021. https://www.space.com/18175-moon-temperature.html.

[19] Tim Sharp. What is the Temperature on Mars? Space.com. Last Accessed May 22, 2021. https://www.space.com/16907-what-is-the-temperature-of-mars.html.

[20] C.I. Calle, J.L. McFall, C.R. Buhler, S.J. Snyder, E.E. Arens, A. Chen, M.L. Ritz, J.S. Clements, C.R. Fortier, and S. Trigwel. Dust Particle Removal by Electrostatic and Dielectrophoretic Forces with Applications to NASA Exploration Missions. ESA Annual Meeting on Electrostatics 2008. Last Accessed May 22, 2021. http://www.electrostatics.org/images/ESA_2008_O1.pdf.

[21] Ken Glover (editor). Docking. Apollo Lunar Surface Journal. June 5, 2018. Last Accessed May 22, 2021. https://www.hq.nasa.gov/alsj/CSM11_Docking_Subsystem_pp87-92.pdf.

[22] L.J. Walkover, R.J. Hart, E.W. Zosky. The Apollo Command Module Side Access Hatch System. JPL Technical Memorandum 33-425. January 15, 1970. Last Accessed May 22, 2021. http://www.ninfinger.org/models/vault2012/Apollo%20CM%20Hatch%20Design.pdf.

[23] International Docking System Standard (IDSS) Interface Definition Document (IDD). Revision E. October 2016. International Space Station (ISS) Multilateral Control Board (MCB). Last Accessed May 16, 2021. https://www.internationaldockingstandard.com/download/IDSS_IDD_Revision_E_TAGGED.pdf.