Options for Offloading a 90-Ton Common Habitat from its Lander on the Surface of Mars

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The Common Habitat is a large, long-duration habitat being explored as part of a conceptual study (not an active NASA program) that uses an SLS core stage liquid oxygen (LOX) tank as its primary structure. Measuring 8.4 meters in diameter and 15.6 meters in length, it is manufactured as a habitat and launched as such into space. It is intended for use on the Moon as part of a permanently occupied outpost, on Mars as part of an outpost that will be occupied for hundreds of days at a time, and in deep space as part of the Deep Space Exploration Vehicle where it will support crewed missions up to 1200 days in duration. A study of internal orientation and crew size resulted in a Common Habitat configuration sized for a crew of eight with a three-deck horizontal orientation. There are obvious challenges associated with the delivery of such a large habitat, which may mass as much as 90-tons when initially deployed. The Mars destination in particular imposes extreme challenges due to Martian gravity. This paper identifies initial options for the offloading of a 90-ton Common Habitat from a lander spacecraft on the surface of Mars. On Mars, the Common Habitat is part of a surface outpost where a Habitation Zone includes the Common Habitat docked to a two-chamber airlock node, up to two logistics modules, and up to two pressurized rovers. It is connected by underground conduit to a radiator farm and communications tower assembly. These elements and other surface infrastructure, including robotic systems for surface preparation, are landed prior to the Common Habitat. In the baseline Common Habitat Architecture, the Common Habitat is delivered on the third heavy cargo flight. The Habitation Zone configuration dictates that the Common Habitat needs to be offloaded from the lander. All of the docked elements need direct access to the surface and the Common Habitat must actually be placed in a trench to lower its docking ports to be level with those of the mated elements. Additionally, the habitat must be emplaced in a horizontal configuration, while for any conceivable Earth launch system it must be launched in a vertical configuration.

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It is true that the Common Habitat must be offloaded from its lander on both the Moon and Mars and a common offloading system must therefore work in both destinations. Mars, however, is considered the driving case for offloading in most, but not all, aspects. A four-day internal study in 2021 recommended that a modified Starship be used to land the Common Habitat on Mars and considered multiple approaches to offload the Common Habitat from the payload section and lower it to the surface. The topic was presented at a public hackathon organized by the Johnson Space Center's Emerge Employee Resource Group. One team took on the challenge and proposed a concept in some ways similar to the previously considered jib crane. Despite the excellent innovation in the team's work, a number of study refinements are necessary to truly establish feasibility. These and other future work needed to mature the concept are discussed in this work.

I. Introduction

The Common Habitat is the conceptual central element of a human spaceflight architecture signified by a long-duration habitat designed to be equally suitable for human use in different gravity environments: 0g, 1/6g, 3/8g, 1g, and artificial gravity. [1] The Common Habitat is not part of the current NASA reference architectures for exploration of the Moon and Mars. It is instead an ongoing study of potential options that – should viability be demonstrated – could potentially be applied to human exploration programs. It shares a similar design approach to Skylab [2] in that it uses the Space Launch System (SLS) Core Stage Liquid Oxygen (LOX) tank as the primary structure and pressure vessel. The Common Habitat is 8.4 meters in diameter and 15.6 meters long. Current analysis is in work to generate a bottoms-up mass estimate. The current control mass allocation for the habitat is 90 tons. Based on the results of a trade study, the Common Habitat features a crew of eight and has a horizontal orientation and is divided into a lower deck, mid deck, and upper deck. [3]

The hope is that Common Habitat studies will identify systems, architectures, and elements with potential to significantly advance NASA human space exploration if merged with NASA plans. An entire architecture has been created around the Common Habitat, enabling human exploration of much of the inner solar system. Extensive commonality is applied to other elements in the architecture, which are used to constitute Moon and Mars surface bases [4] and a Deep Space Exploration Vehicle (DSEV). [5] Earth orbiting propellant depots are also used to enable the architecture.

Due to the size and particularly due to the 90-ton control mass there are valid questions as to whether the Common Habitat can be landed on the Moon or Mars. With its greater gravity, Mars is generally considered to be the driving concern. Some have suggested that the Common Habitat might be viable as an in-space habitat, but it is impractical to place something this large on another surface. Preliminary analysis suggests that it should be possible to utilize the Common Habitat on both the Moon and Mars, but the need for a more detailed answer is the motivation for this study. The habitat mass drastically exceeds any Constellation-era or Artemis requirements. Nothing like the Common Habitat has been considered in previous Mars architecture studies and there has been limited surface habitat development in any prior exploration studies.

More than one hundred lunar lander concepts have been studied since Apollo [6] and neither they, nor the handful in development for Artemis have as requirements to offload a payload the size and mass of the Common Habitat. Even the largest of these, the SpaceX Starship, has stopped short of advertising such a capability. While SpaceX has publicly promised for years that it will be able to land 100 tons on the Moon or Mars with Starship, [7] there is no public material discussing how large a monolithic payload it can unload at either destination.

The only public mention of offloading capability is an artist concept in the Starship Users Guide [7] showing a lunar lander Starship in the process of unloading pressurized rovers from what appears to be four cargo bays, two of which presumably carried rovers. (It is unclear what purpose the other two bays serve in the image.) Pressurized rovers are expected to mass less than ten tons each, so this image provides no indication of capability to offload anything as large as a Common Habitat.

This paper will conduct a survey of select lander options and offloading approaches, reaching a preliminary recommendation on a concept to pursue in support of the Common Habitat architecture and will estimate the resources needed for such an effort.

II. Surface Base Camp Overview

The Moon and Mars base camps in the Common Habitat architecture are identical, with infrastructure deployed across four basic zones. [4] The Habitation Zone, shown in Figure 1, is the primary site for human activity, consisting of the Common Habitat, which is docked to a Two Chamber Airlock Node [8], up to two Logistics Modules [9], and up to two Pressurized Rovers. A radiator farm and communications tower assembly are visible a short distance from these elements, connected to the Common Habitat by buried conduit, and unpressurized rovers and robotic assistants are parked nearby when not in use.

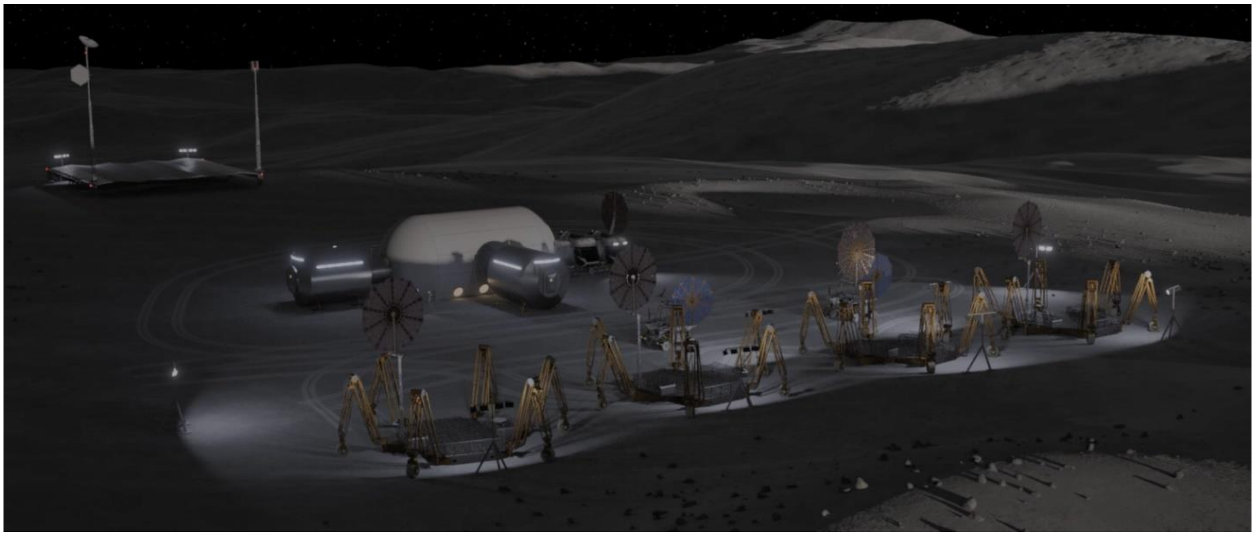

Fig. 1 Habitation Zone

The other zones include the Landing Zone, a dedicated region for repeated landings and launches; the Resource Production Zone, a region currently active for in-situ resource utilization activities; and the Power Zone, the site of a buried nuclear fission reactor that provides power for the entire base camp. [4]

Multiple cargo landers are used to pre-deploy the base camp, the third and last of which delivers the Common Habitat. The landing of interest for this paper is that one and how the Common Habitat is removed from that lander. Any needed pre-delivery of infrastructure needed to transport the Common Habitat from the landing site to the Habitation Zone and position the habitat will have already occurred. The only payload co-manifested with the Common Habitat is the equipment needed to remove it from the lander. As will be discussed later in this paper, the habitat does need to be removed from the lander – it cannot remain permanently integrated.

III. Moon versus Mars Offloading as the Architectural Driver

Because the Common Habitat is used on both the Moon and Mars it was important to determine which environment drives the design of an offloading system. Unsurprisingly, Mars is a more severe driver than the Moon in several, but not all, areas of importance. Consequently, an offloading system designed to exclusively lunar requirements may not be extensible to Mars. Similarly, an offloading system designed to Mars requirements may not be fully extensible to the Moon.

The obvious initial difference is that of gravity. Mars has a gravity of 3/8g versus the lunar gravity of 1/6g. Thus, the Common Habitat weighs more on Mars than on the Moon, driving a more powerful lifting system. Mars is also prone to dust storms, which could occur during offloading. This will result in dust potentially reaching higher points above the ground on Mars than on the Moon. Additionally, due to the distance from Earth, the communications delay on Mars is significantly greater than that on the Moon. This will impact ground control of offloading systems. (The crew is not present during offloading operations, thus the operation is conducted by Mission Control.)

The Moon is a primary driver in two areas. The Moon experiences significantly more extreme temperature swings than Mars. Thus, the thermal control system must accommodate a wider range of temperatures and cannot bias toward cold or hot temperatures as could be done on Mars. Additionally, the lunar south pole region experiences extremely long periods of darkness, while Mars has a nearly 24-hour lighting cycle.

Neither environment can totally drive the design of the offloading system. Mars is the driver for gravity, dust, and communications delay. The Moon is the driver for thermal and lighting. Thus, an offloading system is needed that can support a 90-ton habitat in Mars gravity, endure a dust storm, operate under ~20-minute one-way communications delays, operate in lunar cold and heat, and operate in darkness or illuminated with low sun angles.

IV. Internal NASA Four-Day Study Results

A. Study Overview

A brief, internal study was conducted to determine if there are any feasible options for offloading a 90-ton habitat. As this was a volunteer effort, it was limited to short Friday discussions during the month of February 2021, with very limited assessment between meetings. The study considered lander delivery, lander offloading, surface transportation, and emplacement at base camp.

Participation included NASA personnel from Johnson Space Center, Langley Research Center, Marshall Space Flight Center, Kennedy Space Center, and the Jet Propulsion Laboratory. Most of the participants are engineers supporting various Artemis teams. Conclusions reached in the study reflect general impressions and engineering expertise of the participants and do not reflect any official NASA positions. More detailed engineering assessments may potentially revise some of these conclusions and actual political and budgetary constraints may shift over time and diverge from participant perceptions that may have influenced conclusions.

Due to Human Landing System (HLS) competition sensitivity in progress at the time of the study, the team was very limited in its access to data. As a feasibility study not part of the current Agency objectives, this study could not be allowed to in any way influence any lander procurement efforts. Thus, there was no communication whatsoever with potential HLS providers. HLS data was only used if it could be located on a public website, such as public websites of the providers, general public CAD user communities, news articles, publicly available NASA papers, or Wikipedia. This clearly limited the available data and is a known limitation of the study.

B. Study Drivers

The study was driven by the following:

1. Surface power has already been delivered to the Moon/Mars surface and is operational prior to Common Habitat landing.
2. Moon, Mars, and Microgravity Common Habitats are developed in parallel, not in series.
3. The Lunar base camp's Common Habitat will land in the lunar south pole region and be transported to the Habitation Zone. [4]
4. The Mars base camp does not have a designated location on Mars and could be at any location, from polar to equatorial.
5. All Common Habitat landing, offloading, surface transport, and emplacement (including site preparation) will be accomplished with no crew presence or involvement. The only human interaction is Mission Control on Earth.
6. The Common Habitat is docked to an airlock, pressurized rovers, and logistics modules. Pressurized crew transfer is used between these elements. [4] [8] [10]

C. Lander Selection

Three landers were considered for lunar landing and three for Mars landing. The lunar landers considered were cargo variants of the HLS landers: the National Team Integrated Lander Vehicle (ILV), the Dynetics Autonomous Logistics Platform for All-Moon Cargo Access (ALPACA), and the SpaceX Starship. The Mars landers considered were the NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD) reference concept, the NASA Mid Lift over Drag (Mid L/D) reference concept, and the SpaceX Starship.

Published data for the ILV indicated capacity to deliver 14 tons to the lunar surface. [11] The team was unable to find any public data on ALPACA cargo capacity. In the absence of such data, the team considered ALPACA to have equivalent performance to the ILV. Starship, as previously mentioned, has an advertised capacity to deliver 100 tons to the lunar surface. [7] The HIAD Mars reference design has studied variants with a range of payload performance of up to 27 tons. [12] The Mid L/D Mars reference design includes variants with payload performance up to 22 tons. [13] The SpaceX Starship advertises the same 100-ton payload capacity to Mars that it promises to provide to the Moon. [7]

Most of these landers do not have the performance to land a 90-ton habitat, but that does not immediately exclude them from consideration. The Joinable Undercarriage to Maximize Payload (JUMP) study notes that launch vehicles have increased performance for decades by bolting multiple first stage boosters together. [14] In the same way, multiple landers can be bolted together to increase the resulting payload delivery capacity. It was not deemed practical to bolt seven landers together to land a 90-ton habitat, however, so for purposes of this study the smaller landers were assessed in the context of a reduced mass Common Habitat. The idea was the habitat could potentially be offloaded down to a mass of 30 tons and the remaining 60 tons could be delivered via subsequent outfitting flights. Thus, three to four of the ILV or ALPACA landers should be able to land a 30-ton Common Habitat on the Moon. Alternately, scaled up versions of the HIAD and Mid L/D might be able to land a 30-ton Common Habitat on Mars.

Several variants of the ALPACA lander were considered for lunar landing, notionally illustrated in Figures 2, 3, and 4. (The ALPACA CAD model used in this paper is a model released by Dynetics to the general public for home 3D printing. [15]) Two versions of a two-APLACA solution, two versions of a four-ALPACA solution, and a three-lander solution based on the Sky Crane were considered.

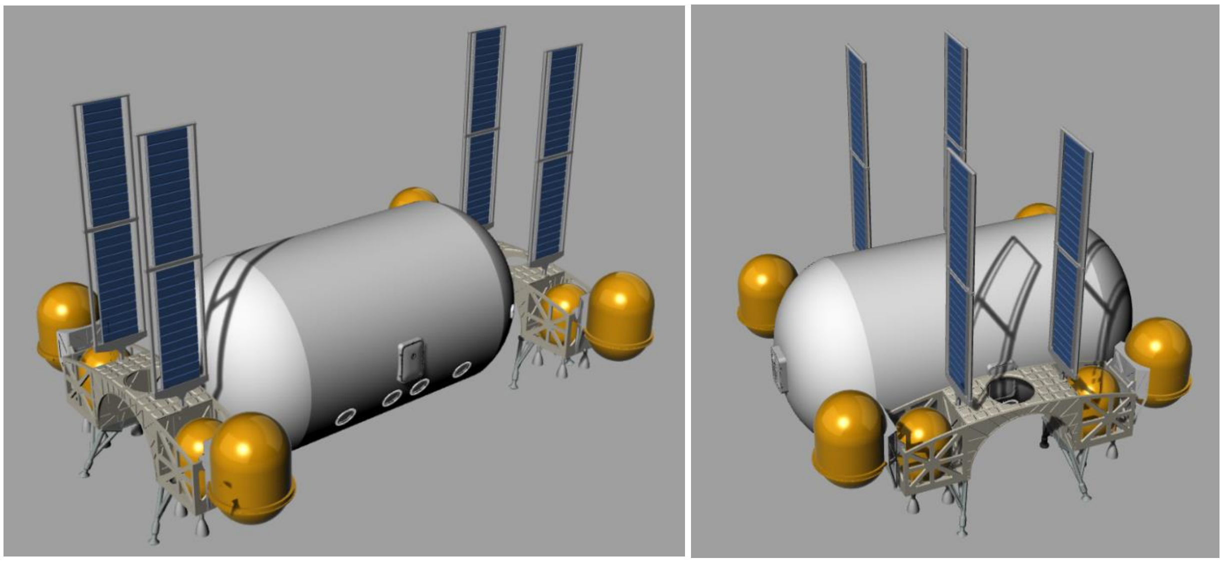

Fig. 2 Two-ALPACA Concepts, Option 1 (Left), Option 2 (Right)

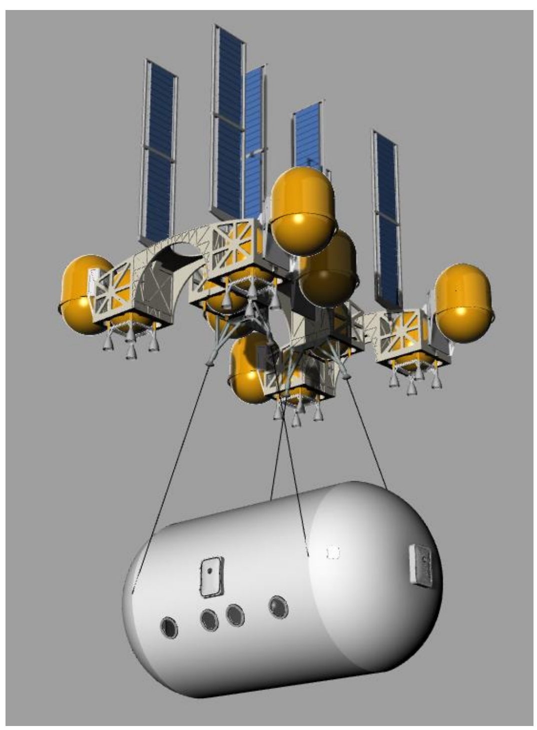

Fig. 3 Three-ALPACA Sky Crane Concept

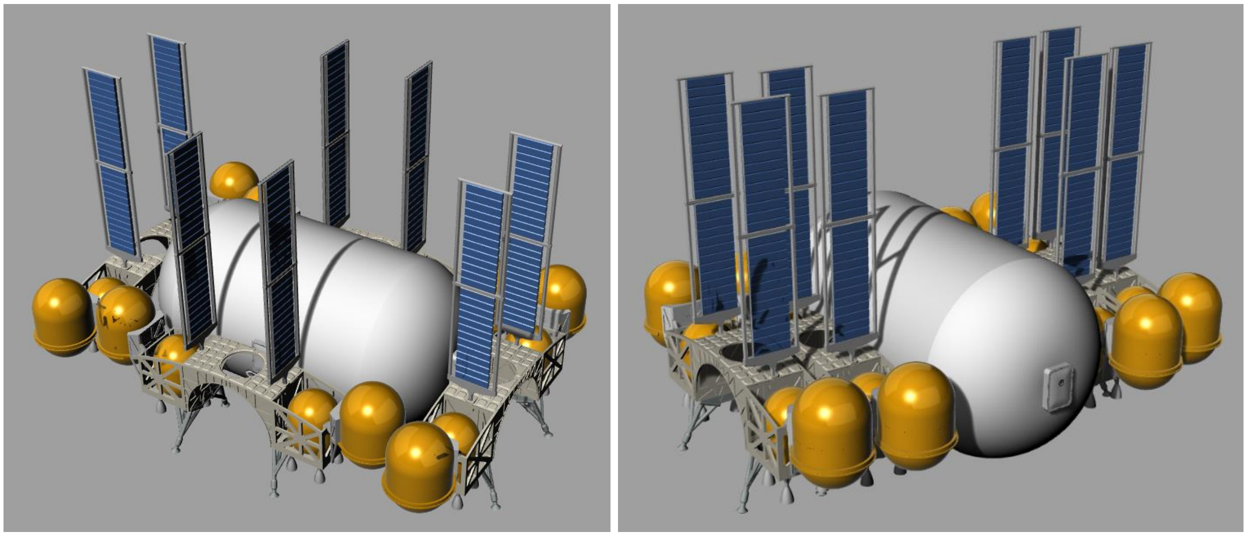

Fig. 4 ALPACA Lander Variants Option 1 (Left), Option 2 (Right)

Three and four-lander variants of the ILV lander were also considered for lunar landing, shown in Figure 5. (The ILV CAD model was purchased at personal expense by the lead author from the cgtrader website. [16])

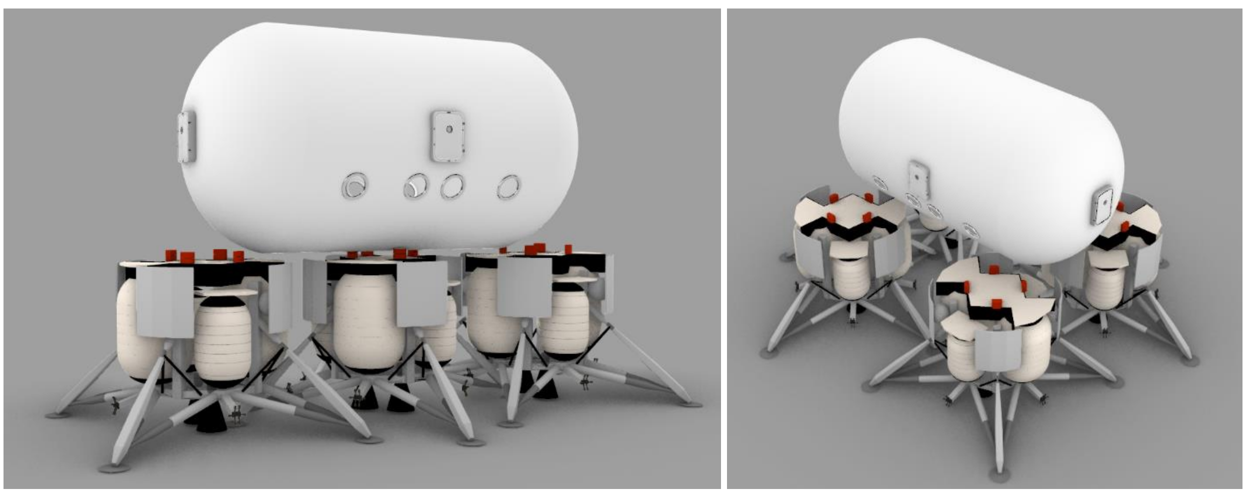

Fig. 5 ILV Lander Variants

The baseline Starship was found to be too short to accommodate the Common Habitat, as shown in the left image in Figure 6. (The Starship CAD was created based on data provided in the Starship Users Guide. [7]) When the Common Habitat CAD model was placed in the payload section of a model of Starship it protruded out of the top of the vehicle. It was necessary to stretch the barrel section of the payload fairing by 7.68 meters to enclose the Common Habitat, as shown in the right image in Figure 6. A nominal Starship configuration where the Common Habitat is housed in the Starship through landing was considered for both Moon and Mars landings, as was a variant where the Starship is modified to carry engines that support a Sky Crane-derived landing, as shown in Figure 7.

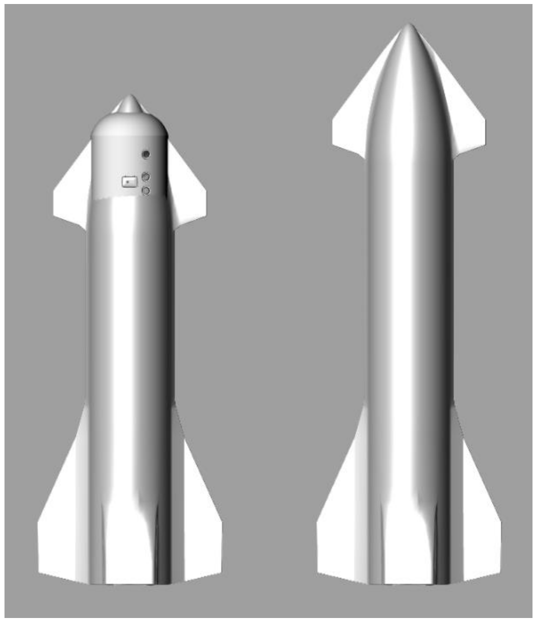

Fig. 6 Baseline Starship and Starship with Long Fairing

Fig. 7 Sky Crane Starship Concept

The HIAD lander was considered with the Common Habitat replacing what had been the Mars Ascent Vehicle in the original CAD package for Mars landing, as shown in Figure 8.

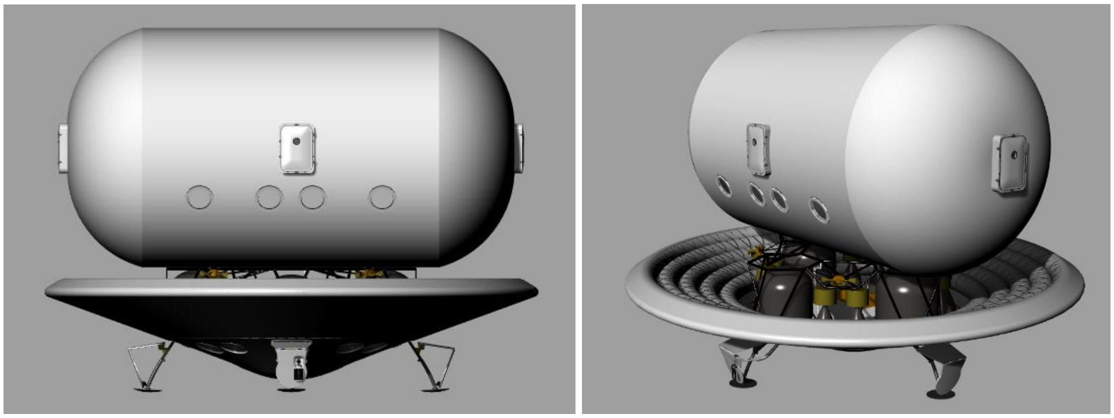

Fig. 8 HIAD Lander

Similar to the challenges with Starship, the Common Habitat did not fit inside the baseline Mid L/D, as shown in Figure 9. There are internal structures in the Mid L/D, not visible in Figure 9, that restrict how low the Common Habitat can rest in the lander, on top of the fact that the habitat exceeds the Mid L/D dimensions even if it could be fully buried in the model. However, scaling the Mid L/D up by a factor of 1.4 times grew the payload bay sufficiently that the Common Habitat could be placed inside for a Mars landing, as shown in Figure 10. A Sky Crane variant of the Mid L/D was also considered for Mars, shown in Figure 11.

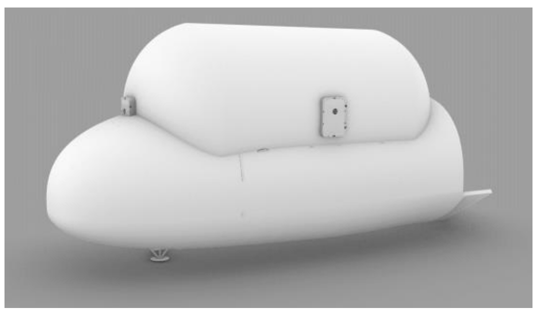

Fig. 9 Baseline Mid L/D Lander with Common Habitat

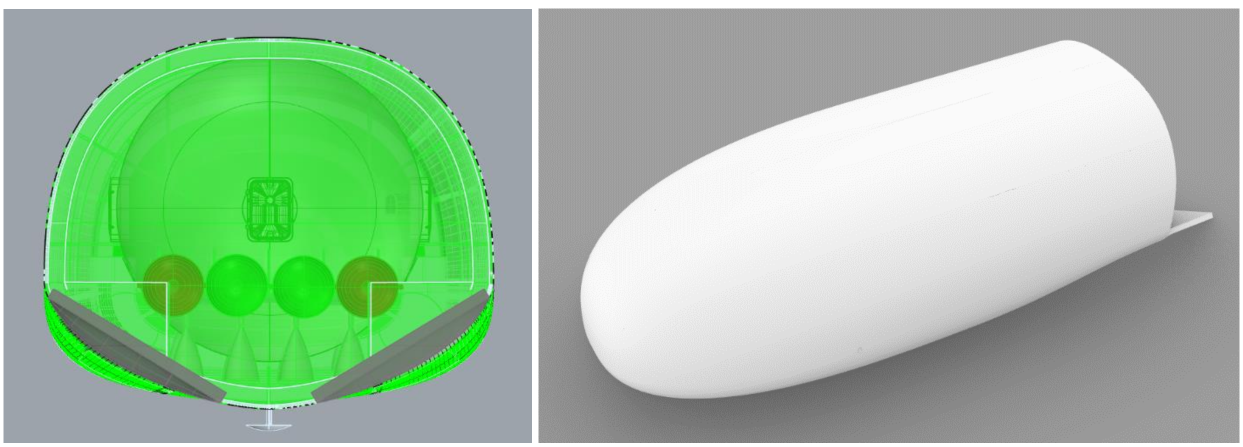

Fig. 10 Mid L/D Lander Scaled 1.4x

Fig. 11 Sky Crane Mid L/D

The team quickly assessed these concepts based on their engineering expertise. No actual engineering analyses were conducted due to lack of time or resources. Eight lander configurations were deemed potentially feasible for lunar landing:

- Two Dynetics ALPACA Cargo HLS Landers, Option 1
- Two Dynetics ALPACA Cargo HLS Landers, Option 2
- Four Dynetics ALPACA Cargo HLS Landers, Option 1
- Four Dynetics ALPACA Cargo HLS Landers, Option 2
- Dynetics ALPACA Cargo HLS Sky Crane Lunar Lander
- Three Blue Federation ILV Cargo HLS Landers
- Four Blue Federation ILV Cargo HLS Landers
- SpaceX Starship Cargo HLS Lander with Long Fairing

The Starship Sky Crane was the only lunar option rejected. It was felt that the complexity of transitioning the Common Habitat from vertical to horizontal while in hover would likely burn more propellant mass than the mass of landing gear saved by using a Sky Crane approach.

For Mars, only two lander concepts were deemed potentially feasible:

- Mid L/D Mars Lander (scaled up 1.4x)
- SpaceX Starship Mars Lander with Long Fairing

The HIAD lander was considered too small as the inflatable aeroshell is not large enough to protect the Common Habitat during Mars entry heating. A scaled-up version of the HIAD was not considered because the team's impression was that the HIAD team was experiencing increasing challenges as the diameter of the inflatable aeroshell increased. Additionally, the HIAD team had expressed concerns with fitting the HIAD into an 8.4-meter shroud and a larger HIAD would undoubtedly have adverse launch vehicle impacts. Therefore, increasing the diameter beyond what the HIAD team was developing diverged too far into a hypothetical concept.

Despite deeming the 1.4x Mid L/D lander potentially feasible there were significant concerns surrounding the lander. It is likely that the mass of the lander plus Common Habitat will exceed the lift capacity of either SLS or Starship/Super Heavy, driving a complex in-space assembly. The Mid L/D is also larger than either the SLS or Starship payload fairings, driving a custom launch vehicle integration with possible aerodynamic penalties negatively impacting launch vehicle performance.

The Mid L/D Sky Crane was deemed non-viable. In addition to the other Mid L/D issues, concern was raised that it might not be possible to position the descent engines in any way that would not plume the Common Habitat as it was being lowered, potentially damaging it.

It should also be noted that only the Starship lander delivers a 90-ton Common Habitat. All of the other lander concepts were based on a removal of 60 tons of outfitting for future logistics flights and land a ~30-ton or ~50-ton Common Habitat.

D. Offloading Approaches Considered

Each of the possible lander concepts impose considerations for offloading the Common Habitat. This, of course, triggers the question of why offload the Common Habitat at all? Could it not simply be left integrated with the lander? This was considered for each of the lander concepts.

In general, leaving the habitat integrated with the lander was deemed non-feasible. In the case of the Starship and ILV landers, this would leave the docking ports relatively high above the surface, creating problems with logistics module delivery, pressurized rover arrival/departure, and airlock operations. Starship also fully encloses the Common Habitat and lands with the habitat in a vertical orientation, making it unusable until offloaded. The ALPACA landers would place the Common Habitat closer to the surface, but the docking ports are still too high for the other elements to dock with it. More importantly, the Common Habitat docking ports would be blocked by the ALPACA structure. The Mid L/D lander also fully encloses the Common Habitat, so unless it is offloaded all of its docking ports are also blocked by structure.

Figures 12 and 13 illustrate the problematic nature of leaving the Common Habitat integrated with the lander, showing examples with the ILV, Mid L/D, and Starship landers. Figures 2 and 4 can also be referenced to envision the impossibilities of leaving the Common Habitat integrated with the ALPACA lander. As previously noted, the HIAD lander cannot protect the Common Habitat during atmospheric entry but even if it were a viable lander, leaving the Common Habitat permanently integrated with the lander would invoke similar problems as the ILV and Starship. All concepts that involve the Common Habitat remaining integrated with the lander were deemed a nonstarter, regardless of the lander under consideration.

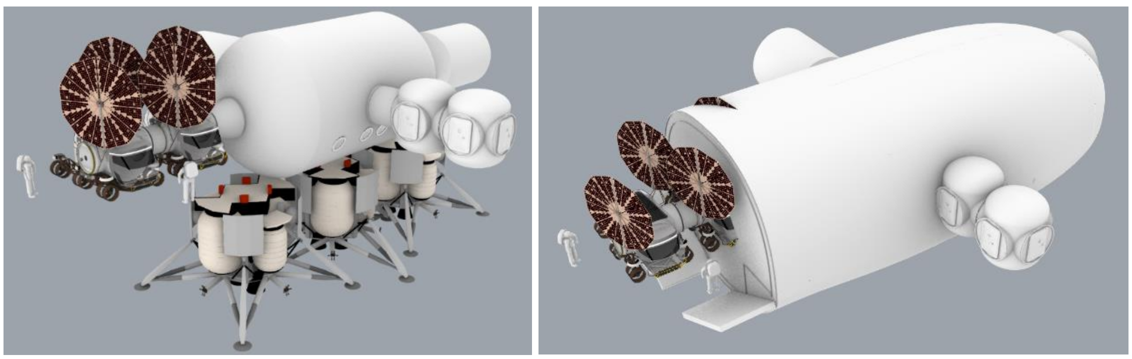

Fig. 12 Common Habitat Permanently Integrated with ILV (Left) and Mid L/D (Right)

Fig. 13 Common Habitat Permanently Integrated with Starship

The ALPACA Sky Crane carries an inherent offloading approach. Despite considering this a potentially viable approach, some concerns were noted. Like the other sky cranes, there was concern raised that the plume would impinge on the Common Habitat. Additionally, the crane deploy is a time critical maneuver (propellant is being burned) and unanticipated delay could cause loss of payload. Further, it needs multiple launches to integrate the lander system in space.

It should be noted that even if resting directly on the surface, the Common Habitat would still be too high. The habitat needs to not only be offloaded, but also placed in a trench roughly 1.58 meters deep in order to get its docking ports low enough for the airlock, logistics modules, and rovers to dock with them.

Offloading from the ALPACA and ILV landers can be performed by teams of All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robots. [17] Figure 14 shows a half-scale prototype ATHLETE robot being used in desert field trials during the Constellation program offloading a habitat mockup from the deck of a lander mockup The ATHLETE has a feature where it can split into two three-limbed halves, each of which can grasp the payload from opposite sides and lift the payload from the top of a lander. The ATHLETE platform is scalable, but carry capacities eventually reach a cross-over point where carry mass approaches ATHLETE vehicle mass. Ideally, rather than design one massive vehicle that can lift a heavy payload, it might be more practical to develop a vehicle with an optimized payload to vehicle mass tradeoff and use multiple such vehicles collaborating to lift the load. Recent versions of ATHLETE have included the design of high-capacity limbs that would have greater capacity to lift heavy loads. [18] Depending on Common Habitat mass, teams of multiple ATHLETEs could be used to accomplish the same feat. A 30-ton Common Habitat would need two ATHLETEs on the Moon.

Fig. 14 ATHLETE Half-Scale Prototype Offloading Mockup Habitat from Altair Mockup

However, the lander configuration is such that additional structure would be needed to reach around or over the landers to connect the ATHLETEs to the habitat structure. These structures would have to be delivered separately and would have large lever arms. The more ALPACA or ILV landers involved, the less advisable such an approach becomes. Figure 15 illustrates the use of two ATHLETEs to remove a Common Habitat from an ILV lander.

Access to the Common Habitat inside the Mid L/D lander is even more complicated. The shell of the Mid L/D would need to be disassembled around the habitat before ATHLETES could get to the habitat. This would add mass, further reducing the mass of the Common Habitat that could be landed.

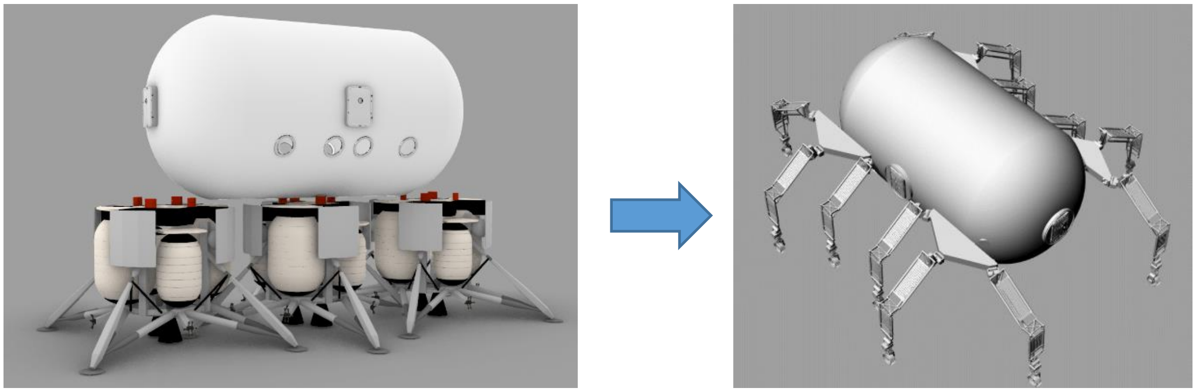

Fig. 15 Offloading of 30-ton Common Habitat by two ATHLETEs

The Lightweight Surface Manipulation System (LSMS) crane [19], shown in Figure 16, was also considered for each of the offloading tasks proposed for ATHLETE. In general, the LSMS was considered a viable option to offload the Common Habitat from any of the lander concepts, though forward work would be needed to determine structural supports and load paths.

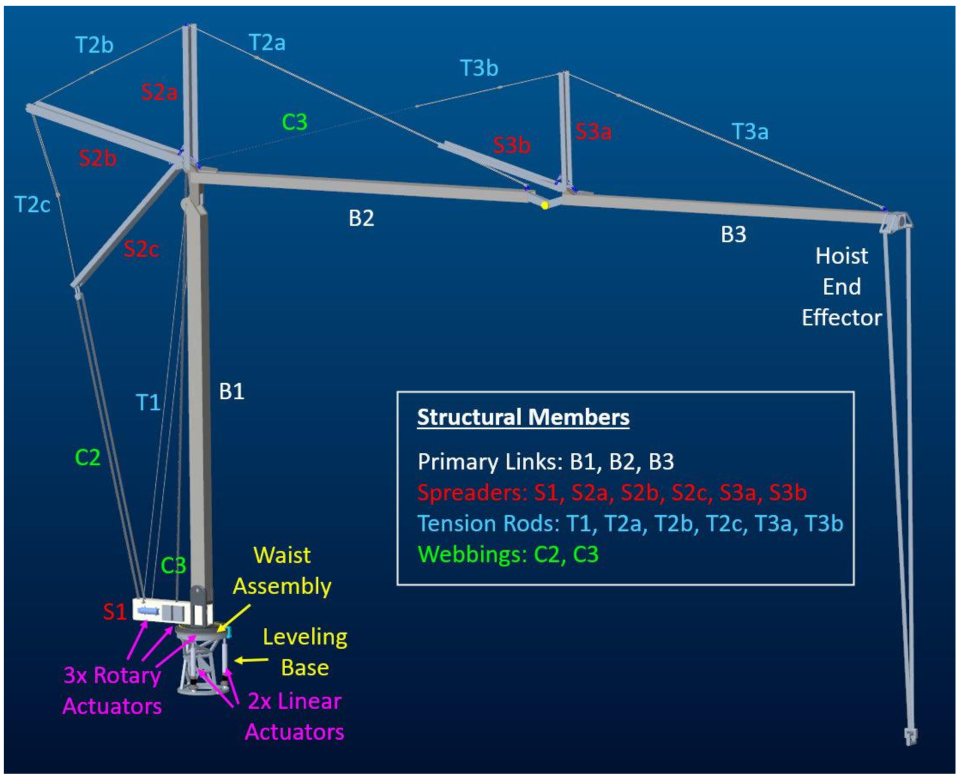

Fig. 16 LSMS Primary Components and Naming Convention.

Several additional concepts were considered specifically for the Starship. The first concept, shown in Figure 17, is a shear crane, or shear-leg crane. This concept used a shear-leg crane to first lift the Common Habitat from a support cradle on the Starship, then translate it outward before lowering it to a waiting surface transportation element. The concept did not identify how the habitat is transitioned from a vertical configuration to horizontal, but it is not inconceivable that a variation on this concept could do so.

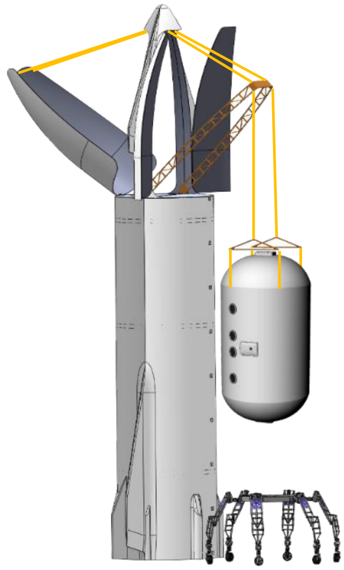

Fig. 17 Shear Crane Offloading Concept

The second Starship-specific concept involved a deployable system of two jib cranes. Shown in Figure 18, this delivery system attempts to combine both the lowering of the Common Habitat and the rotation to a horizontal configuration. Unlike the shear crane, this offloading uses a customized Starship payload fairing that is also an integral component of the offloading system. In the first step, the nosecone of the Starship is lifted off of the rest of the fuselage. Starship door panels open, exposing the entire assembly. Both jib cranes deploy, and the nosecone is rotated downward by the first jib crane. The nose cone is lowered to the surface where a robotic (potentially an ATHLETE equipped with a digging implement) asset fills the nosecone with regolith, creating a counterweight. At that point, the second jib crane begins to translate the Common Habitat out from its perch inside the Starship. It next rotates the Common Habitat from vertical to horizontal in a process analogous to that used during the shuttle program at Kennedy Space Center to rotate the shuttle orbital from horizontal to vertical, shown in Figure 19. Once rotated to horizontal, the Common Habitat is lowered the rest of the way to the surface.

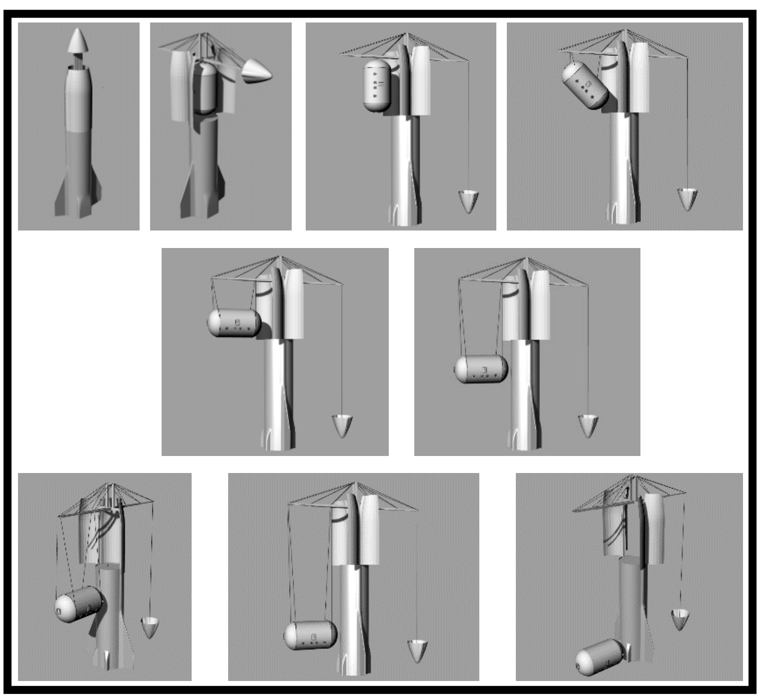

Fig. 18 Jib Cranes with Counterweight Offloading Concept

Fig. 19 Space Shuttle Orbiter Being Rotated to Vertical in the Vehicle Assembly Building

It is worth noting that the translation from vertical launch packaging to horizontal surface utilization is a necessary operation for the Common Habitat. The only launch vehicles capable of lifting the Common Habitat into space are the SLS and the Starship. Both by definition carry the habitat in a vertical orientation. A habitability and usability study determined that for purposes of living and working in the habitat, the best orientation for the specific mission of the Common Habitat is a horizontal orientation. [3] Because the Common Habitat architecture has prioritized crew living and working, it is necessary to rotate the habitat from vertical to horizontal after landing.

Based on this extremely rapid trade study, the decision was made to baseline the Starship for Earth launch and Moon or Mars surface landing of all surface elements. While the offloading approaches appear promising, it was recognized that more work was needed.

V. JSC Hackathon Concept

As an initial step to expand the analysis of offloading the Common Habitat from Starship, the annual Johnson Space Center Hackathon was utilized to gain external input. Organized by JSC's Emerge Employee Resource Group, the Hackathon is a variant on the traditional idea of a hackathon that is not limited to just software challenges. The 2021 Hackathon (held in February 2022) was open to both center employees and the public. One of the challenges made available for teams to choose from was the offloading of a 90-ton Common Habitat from a Starship lander. The challenge instructed the team to create a crane system that massed no greater than 10 tons that could lower the Common Habitat while also preventing tipping of the Starship during the offloading process, with Mars gravity used as the driving case.

One team selected this challenge to investigate. [20] They identified as key technical areas: lowering the habitat from the upper section of Starship (~ 33.5 m high), preventing tip over of Starship during displacement/descent of the habitat, controlling the rate of descent of the habitat, and developing supporting structures (struts, articulating joints, etc.) that are extremely strong and deploy from the interior volume of Starship.

Initially, they explored several rail and pendulum concepts, shown in Figure 20. However, both systems had inherent technical and mass challenges the team felt would limit their viability and the concepts were not developed further. The team used several rounds of brainstorming via white board before determining a possible solution, with some of the final whiteboard sketch work shown in Figure 21.

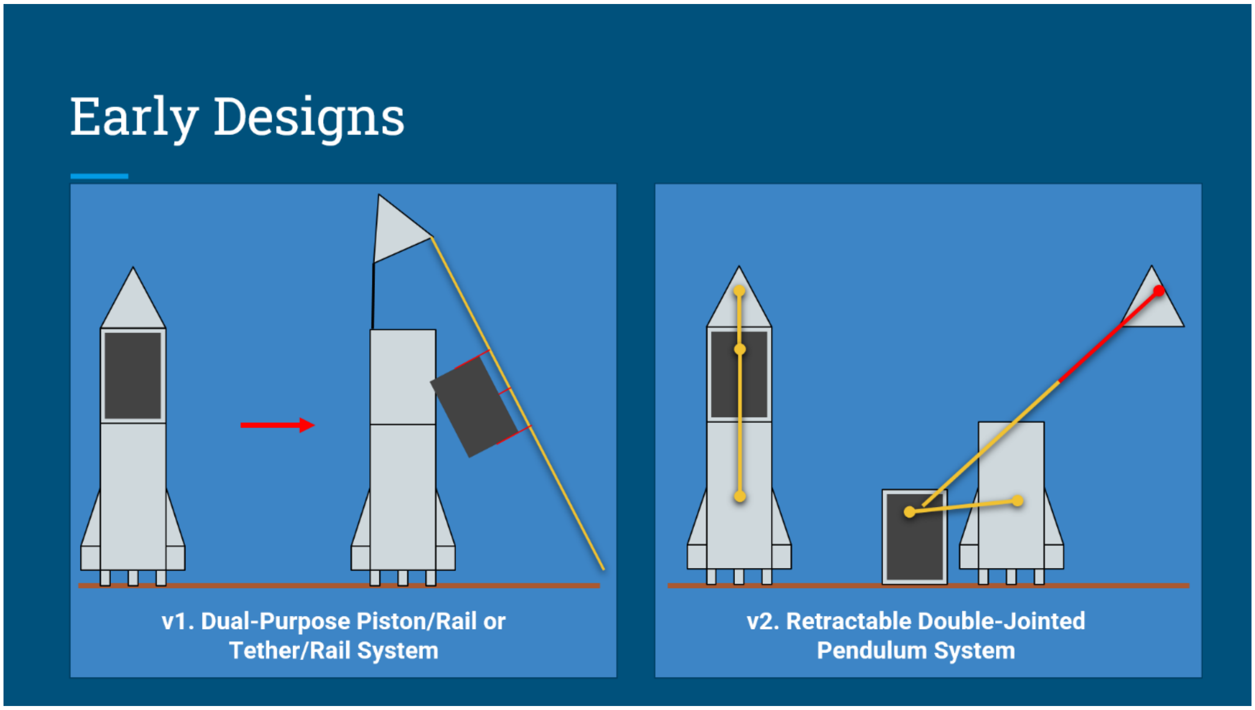

Fig. 20 Hackathon Team Initial Concepts

Fig. 21 Hackathon Team Whiteboard Sketches

The team eventually settled on a system loosely similar, but not identical, to the Jib Crane concept. Calling their final design the Dual Boom, Self-Stabilizing Crane, they performed a number of mathematical calculations to estimate the necessary size. They used the General Beam Bending Equation and General Beam Buckling equation, deriving from those the necessary equations to estimate beam deflection and critical load limits. Shown in Figure 22, based on these calculations they estimated the beam mass as just over 5 tons, well within the 10-ton limit. However, this mass does not include motors, cabling, attach fixtures, access doors, structural reinforcements to Starship, or other components. It does appear promising upon initial inspection.

Crane Data		
	Beam Hab	Beam Cap
Youngs' Modulus [Gpa]	2E+11	2E+11
Beam Length [m]	8.7	9
Beam Height [m]	0.45	0.45
Beam Width [m]	0.2	0.2
% of Original Width and Height	15	15
Material Density [kg/m^3]	8050	8050
Gravity [m/s^2]	3.721	3.721
Mass of Habitat [kg]	90000	90000
Distributed Load [Pa]	6.47454	6.6978
Beam End Deformation [m]	0.271897195	0.300987753
Beam Mass [t]	1.749124125	1.80943875

Yellow = changeable variables

Support Beam Data	
Youngs' Modulus [Gpa]	2E+11
Beam Length [m]	12.76
Beam Height [m]	0.2
Beam Width [m]	0.1
% of Original Width and Height	15
Number of Support Beams	3
Material Density [kg/m^3]	8050
Supported Force of 1 Beam Before Buckling [N]	202058.504
Mass of 1 Supprt Beam [t]	0.5700849
Total Supported Force Before Buckling [N]	606175.512
Total Mass of Support Beams [t[	1.7102547

Total Mass of Beams [t]
5.268817575

Fig. 22 Hackathon Team Mass Estimation Summary

Like the jib crane concept, they also used the nosecone as a counterweight to prevent the Starship from tipping. The automated, eight-step offloading process recommended by the team is shown in Figure 23. The graphic might lead to pre-conceptions of a smooth, prepared surface, but the team recognized this will not be the case and indicated that there should be additional considerations made for landing on an uneven surface.

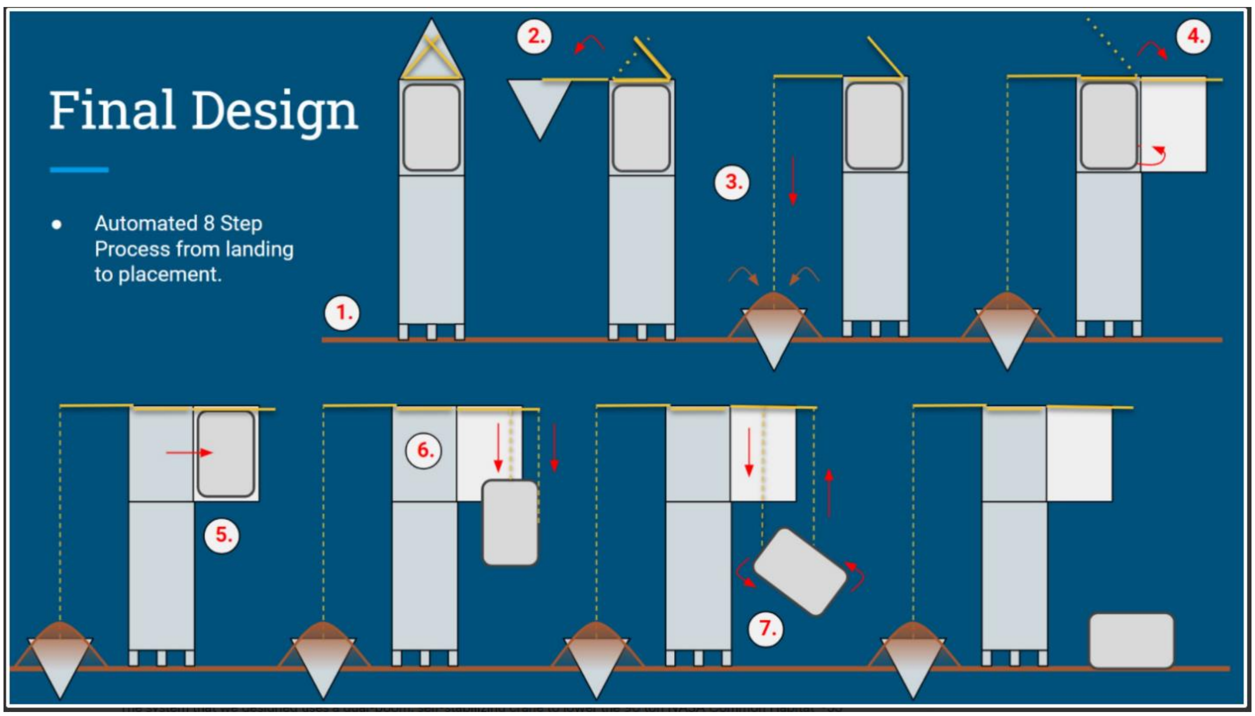

Fig. 23 JSC Hackathon Offloading Concept

The team also suggested several areas of investigation for future design work. Their initial sketches did not feature any crane masts. They recommended that a central mast could help to improve the crane's performance, transferring some of the load to that mast in tension. With respect to the previously noted terrain issues, they suggested adding deployable airbags or bladders to be placed on the Common Habitat exterior to cushion it when lowered by the crane onto the surface. These recommendations are notionally illustrated in Figure 24.

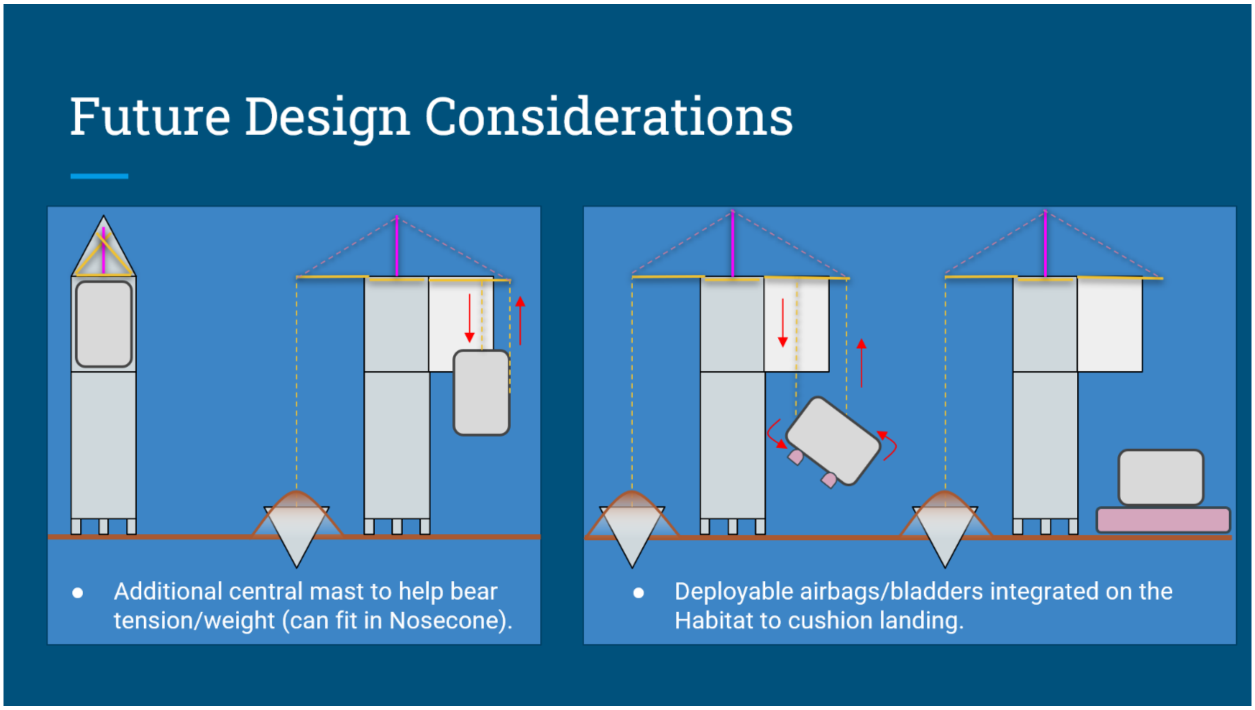

Fig. 24 Hackathon Team Future Design Considerations

The team was judged by a panel of eleven engineers against other hackathon teams and was awarded "Best of Topic: Martian Mission Planning", winner "JSC Sponsored Challenge," and "JSC Hackathon 2021 Best Overall."

VI. Conclusions and Forward Work

The conceptual exercises conducted have advanced the offloading concept nearly as far as it can be developed without funded support and specialized structural engineering expertise. The work to date is sufficient to conclude that there is likely at least one credible path to offloading a Common Habitat from its lander on both the Moon and Mars.

A baseline approach is identified for future work. It utilizes the Starship to land a 90-ton Common Habitat, which it then offloads by means of a deployable crane system that also deploys and uses the nosecone, loaded with regolith by a pre-deployed robotic asset (such as ATHLETE), as a counterweight to prevent tipping. It rotates the habitat from a vertical to horizontal orientation as part of the process of lowering it to the surface. As forward work, at minimum, a structures and mechanisms design and analysis cycle is needed to more accurately size the mass, dimensions, and deployment of this offloading system.

The Hackathon concept and the Jib Crane concept represent a similar, high-level approach, but both leave significant forward work. The nosecone is suspected to be capable of holding the needed regolith, but it is possible that the nosecone may utilize some degree of reinforcement to contain the tons of regolith used for c.g. control. The mass of such reinforcement would count against the 10-ton mass limit for the offloading system. Additionally, the nosecone integration with the fuselage would need to be designed to support the expected aerodynamic loads during Mars entry.

The crane deployment mechanisms are also largely handwaved. The Hackathon and Jib Crane concepts notionally illustrate different approaches to deploy the crane systems. Both need higher fidelity design and analysis before they can be effectively sized and traded against each other or merged into a single concept. (It is also possible, but not a given, that the cranes in either of these approaches could be a derivative of the LSMS crane.)

The crane itself needs additional analysis to properly size it for the tasks of rotating the Common Habitat from vertical to horizontal and lowering it to the surface. Both concepts utilize multiple winch systems to accomplish the vertical to horizontal transition by lowering the two longitudinal ends of the Common Habitat at different rates. While the horizontal to vertical transition has been accomplished repeatedly in the Vehicle Assembly Building during the shuttle program, this implementation will need to be performed in a lower mass system without direct human intervention and over time delayed communications.

Additional work is needed to define how the offloading system will hand off the Common Habitat to the surface transportation element that will transport it to the base camp Habitation Zone. [4] An unresolved, related question is whether the habitat will need some form of cradle to allow it to be placed on the surface or if the handoff can be accomplished in a manner that keeps the habitat suspended at all times until it reaches its Habitation Zone destination.

The surface transportation element itself is presently undefined. In order to address the handoff question, the functional needs of the surface transportation element will need to be defined. At least one conceptual alternative for this element will need to be developed at a sufficient level to enable an analysis.

In addition to the baseline offloading concept, at least one and ideally two alternatives should also be carried in a detailed engineering analysis to complete an informed trade. Pending sufficient resources, a physics-enabled simulation of these concepts can be used to aid in both the analysis and provide a more accurate data source for visualization, as opposed to a simple illustrative animation.

Funding proposals are currently in work, looking to Agency innovation calls as an opportunity to secure the needed structural engineering specialists to complete this analysis.

References

[1] R. Howard, "Opportunities and Challenges of a Common Habitat for Transit and Surface Operations," in *2019 IEEE Aerospace*, Big Sky, MT, 2019.

[2] B. Griffin, D. Smitherman, K. Kennedy, L. Toups, T. Gill and A. S. Howe, "Skylab II: A Deep Space Habitat From a Space Launch System Propellant Tank," in *AIAA Space 2012 Conference & Exhibition*, Pasadena, California, 2012.

[3] R. Howard, "Down-Selection of Four Common Habitat Variants," in *2022 IEEE Aerospace*, Big Sky, MT, 2022.

[4] R. Howard, "A Common Habitat Base camp for Moon and Mars Surface Operations," in *AIAA ASCEND 2021*, Las Vegas, NV + Virtual, 2021.

[5] R. Howard, "A Common Habitat Deep Space Exploration Vehicle for Transit and Orbital Operations," in *AIAA ASCEND 2021*, Las Vegas, NV + Virtual, 2021.

[6] J. Connolly, Ed., After LM - NASA Lunar Lander Concepts Beyond Apollo, NASA.

[7] SpaceX, "SpaceX Starship," [Online]. Available: https://www.spacex.com/media/starship_users_guide_v1.pdf. [Accessed 5 June 2022].

[8] R. Howard, "A Two-Chamber Multi-Functional Airlock for a Common Habitat Architecture," in *2021 AIAA ASCEND*, Las Vegas, NV + Virtual, 2021.

[9] R. Howard, "Stowage Assessment of the Common Habitat Baseline Variants," in *2020 AIAA ASCEND*, Virtual Confernece, 2020.

[10] R. Howard, "A Multi-Gravity Docking and Utilities Transfer System for a Common Habitat Architecture," in *2021 AIAA ASCEND*, Las Vegas, NV + Virtual, 2021.

[11] B. Origin, "HLS National Team," [Online]. Available: https://www.blueorigin.com/blue-moon/hls-national-team/. [Accessed 5 June 2022].

[12] T. Polsgrove, J. Chapman, S. Sutherlin, B. Taylor, L. Fabisinski, T. Collins, A. D. Cianciolo, J. Samareh, E. Robertson, B. Studak, S. Vitalpur, A. Lee and G. Rakow, "Human Mars Lander Design for NASA’s Evolvable Mars Campaign," in *IEEE Aerospace Conference*, Big Sky, MT, 2016.

[13] D. Calderon, J. A. Garcia, H. Newton, J. Amar and Z. Wiens, "Human Mars Entry, Descent, and Landing Architecture Study: Phase 3 Summary," in *AIAA SciTech Forum*, Orlando, FL, 2020.

[14] R. Howard, "A Joinable Undercarriage to Maximize Payload (JUMP) Lunar Lander for Cargo Delivery to the Lunar Surface," in *AIAA Propulsion and Energy Forum 2019*, Indianapolis, IN, 2019.

[15] "3D Print Your Own Dynetics' Human Landing System," Dynetics, 12 June 2020. [Online]. Available: https://www.dynetics.com/newsroom/features/2020/3d-print-your-own-dynetics-human-landing-system. [Accessed 25 January 2021].

[16] Brickmack, "National Team Integrated Lander Vehicle 3D model," cgtrader, 17 May 2020. [Online]. Available: https://www.cgtrader.com/3d-models/space/spaceship/national-team-integrated-lander-vehicle. [Accessed 26 January 2021].

[17] B. Wilcox, "ATHLETE: A Limbed Vehicle for Solar System Exploration," in *2012 IEEE Aerospace Conference*, Big Sky, Montana, 2012.

[18] A. S. Howe, H. Nayar, A. Erwin and G. Wang, "ATHLETE Offloader Limb as a High-capacity Crane," in *2021 AIAA ASCEND*, Las Vegas, Nevada + Virtual, 2021.

[19] T. Jones, "A Protoflight Lightweight Surface Manipulation System to Enable High-Load, Long-Reach Lunar Surface Operations," in *AIAA 2021 ASCEND*, Las Vegas, NV + Virtual, 2021.

[20] T. Sommer, C. Euker, J. Kivijarv, J. Stahmer and J. Yao, "Team Rocket," Devpost, 2022. [Online]. Available: https://devpost.com/software/jsc-design-challenge-lowering-the-hab. [Accessed 5 June 2022].