Developing an Integrated Logistics Infrastructure for Lunar Surface Habitats

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The Artemis program is building up to a return to human lunar exploration, with the goal of extended and eventually permanent human lunar surface habitation. While this effort builds on almost 25 years of permanent human habitation at the International Space Station, logistics resupply will be uniquely different on the lunar surface, due to both substantial gravity and the greater challenge of logistics transport. While ISS resupply is accomplished with 6-8 dedicated cargo missions per year for a cumulative annual cargo mass of approximately twenty metric tons, there is an open question of the optimum number and size of resupply missions for a lunar surface base. Logistics for human habitats will remain primarily focused on the use of pressurized modules to protect the resupply items from vacuum and temperature extremes, as well as to simplify the process of bringing the logistics into the habitat for use.

This paper focuses on technologies for establishing a robust logistics infrastructure for upcoming surface habitats and bases. Following a review of potential lander vehicles with their associated payload mass and volume limits, it identifies a set of candidate scales for incoming logistics elements, from full habitat modules to dedicated ISS-type logistics modules to small multi-unit logistics elements capable of being manipulated by EVA astronauts or robotic systems. Developmental testing includes the use of underwater simulation of human and robotic logistics tasks ballasted to replicate lunar gravity conditions.

Nomenclature

CAD	Computer-Aided Design
CLPS	Commercial Lunar Payload Services
CTB	Cargo Transfer Bag
CTBe	Cargo Transfer Bag equivalent
EVA	Extravehicular Activity
HLS	Human Landing System
ISS	International Space Station
LPLM	Lunar Pressurized Logistics Module
LTV	Lunar Terrain Vehicle
NBRF	Neutral Buoyancy Research Facility
PLSS	Portable Life Support System
SEV	Space Exploration Vehicle
SPLC	Suitport Logistics Carrier/Small Pressurized Logistics Carrier
SSL	Space Systems Laboratory
TLX	[NASA] Task Load Index
UMd	University of Maryland

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I. Introduction

There is an old saying in warfare that "amateurs study tactics and strategy, but professionals study logistics". Over the decades of International Space Station operations, logistics have been central to the continued success of the program. In each of the recent years, International Space Station (ISS) has received, on average, seven cargo missions via Dragon, Cygnus, and Progress vehicles. Over the lifetime of the station to date, seven different vehicles have transported logistics to ISS (including the space shuttle and both versions of Dragon), and additional vehicles such as Dream Chaser are scheduled to begin transport flights in the next year. A sizable fraction of crew time is allocated to logistics, from unloading packaged cargo from transports and stowing it in the ISS habitable volume, moving stowage items around to clear infrequently used volumes such as the U.S. airlock module, and collecting trash and down-payload items for reloading into the cargo vehicles before departure. Estimates from ISS data would indicate that logistics handling could require up to 35 crew hours per cargo vehicle and another 11 crew hours per month for general logistics "housekeeping".[1] Clearly, any space habitat such as ISS has to place a high priority on logistics resupply operations.

Now, the United States and other foreign partners are actively developing systems for a human return to the Moon, including the potential for extended human stays on the lunar surface before the end of this decade. Logistics will play at least as large a role in lunar human spaceflight as it does for ISS; indeed, given the greater wear on equipment in the lunar environment and the likelihood of much more frequent extravehicular activity (EVA) associated with lunar surface exploration, the demand for logistics resupply may be markedly increased over that for ISS.

This realization is further complicated by the fact that logistics operations on ISS are greatly simplified by the microgravity environment. The largest logistics packages may be moved with the touch of a finger, and stowed with simple bungee cords or nets to an empty section of wall or corner of a module. On the lunar surface, logistics packages will have to be supported against gravity, and stowage solutions will be organized and retrievable much more formally than the "large piles of cargo transfer bags" system used to date.

This paper summarizes results to date in an ongoing effort at the University of Maryland (UMd) Space Systems Laboratory (SSL) to investigate the operational implications of lunar logistics, and to develop concepts and technologies which will minimize the impact of resupply on the overall timeline of lunar surface habitat crews.

II. Logistics Overview

While the gravitational environments are an important difference, more than two decades of experience with International Space Station provide a wealth of data for estimating lunar surface habitat logistics requirements. Table 1 presents the design characteristics of cargo vehicles currently resupplying ISS, or due to begin cargo operations this year. Of particular note is that all four vehicles, spanning more than a 2:1 range in payload sizes, have been designed for a very narrow range of maximum pressurized payload densities around 290 kg/m^3.

Spacecraft	Pressurized Volume (m^3)	Pressurized Payload (kg)	Payload Density (kg/m^3)
Progress MS[2]	7.6	2230	293
Dragon 2[3]	8.6	2507	292
Cygnus[3]	12.9	3754	291
Dream Chaser[3]	17.7	5000	282

Table 1. Design pressurized payload mass and volume design limits for ISS logistics cargo vehicles

Table 1 is only the first step in deriving ISS cargo requirements, in that it does not provide information on what the actual payload utilization is nor how often crew resupply flights take place. While there is more than two decades of information on ISS operations, it was decided to focus this study on the years 2020-2023, as this is the most recent set of data available, and it represents the era of full seven-person crews on station due to the start of commercial crew rotations with the Dragon spacecraft. Figure 1 shows the flight dates for all cargo missions to ISS between the start of 2020 and March 31, 2023, along with the mass of pressurized cargo transported on each mission.

Table 2 takes pressurized cargo mass data from Figure 1 and reflects the actual cargo mass carried as opposed to the design limits of Table 1. It is apparent that Progress and Dragon carry significantly less cargo per flight on average than their design limits; this is due to the unpressurized cargo transported by Dragon and supplies of water, oxygen, and propellants which reduce available payload mass for Progress. Cygnus, which has no substantial capacity for either fluids or unpressurized cargo, comes closest to being mass-limited on internal (pressurized) cargo.
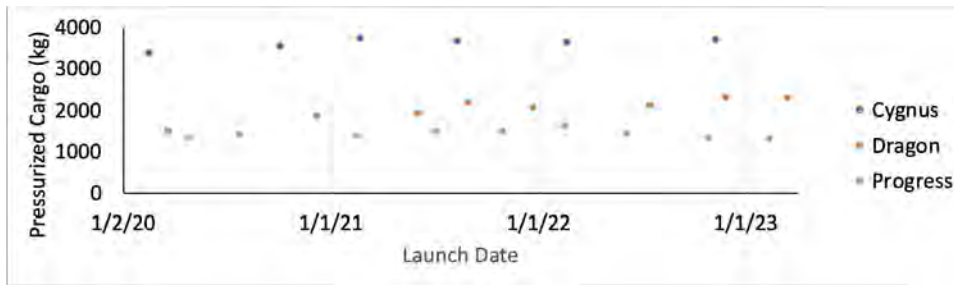
Figure 1. Cargo launch cadence 1/1/20-3/31/23 (data[2,4])

Spacecraft	Avg. Pressurized Cargo (kg)	Avg. Days between flts	Cargo/crew-day (kg)
Progress MS	1432	129	1.59
Dragon 2	2128	138	2.20
Cygnus	3629	184	2.83
Totals		51	6.61

Table 2. Average pressurized payload mass and flight frequency for ISS logistics cargo vehicles (data[2,4])

From this table, we see that on average since the start of 2020, a resupply vehicle has arrived at ISS every 51 days, or 7 times per year on average, and carries pressurized cargo that represents 6.61 kg of consumables per crew member per day, or 2420 kg/person/year. Since this period entirely corresponds to seven-person crews on ISS, this means the total pressurized cargo to ISS averages 16,900 kg per year.

However, pressurized cargo is not the only category of logistics resupply for ISS or for a lunar base. As noted earlier, some of the logistics cargo for ISS consists of stored gases or items intended for exterior installation, and therefore transported external to the pressure vessel. These categories will also be required for a lunar surface habitat. However, over 90% of the total logistics mass to ISS is in the form of pressurized cargo, so that category will be the focus of this series of studies.

A question arises as to the best strategy for logistics resupply of a lunar habitat. While the optimum answer depends on crew size and total logistics resupply mass, for the purposes of this study it was assumed that the lunar crew size is four astronauts in "expeditions" of six months echoing the standard ISS crew assignments. Based on the ISS data, earlier missions to a lunar base on an "occasionally crewed" basis would require 740 kg of resupply for a four-person crew for a 28-day sortie corresponding to one full lunar day/night cycle. It is likely that this amount of material could be delivered with the crew , or split between the human landing system (HLS) and a commercial lunar payload services (CLPS) lander.

A standard year corresponds to 13 lunar cycles, or 9620 kg/year for a crew of four. While the exact site of a long-term lunar base is still undecided, it is likely that a favorable launch window for a logistics mission would occur on 28-day intervals. Sending cargo to the lunar base every two months (56 days) would correspond almost exactly to the average resupply rate for ISS, and would ensure that high-priority cargo would be available with minimal delay. This would require a CLPS lander with a payload delivery capacity of approximately 1500 kg, which is larger than any yet announced, but substantially smaller (and hopefully less expensive) than an HLS-based delivery.

The delivery of 1500 kg at the "universal" cargo density of 290 kg/m³ would correspond to a lunar pressurized logistics module (LPLM) of 5.17 m³ if perfectly filled. As shown by comparing Tables 1 and 2, Cygnus operates at a volumetric packing factor of 97%, but it is probably unreasonable to expect all lunar logistics missions to attain that level of packing precision. To accommodate alternative cargo and provide some growth capacity, adopting a 90% packing factor would require an LPLM pressurized volume of 5.75 m³. Using the mass estimating relation for a pressurized vessel[5]

$$m_{structure} = 91.03 \left(V_{pressurized} \right)^{0.83}$$

the structural mass of the LPLM is estimated at 385 kg, producing an initial mass estimate for the LPLM fully loaded of 1885 kg.

However, delivery of logistics cargo to the habitat is only the first step in resupply. As shown in Table 3, logistics cargo is generally organized in modular packaging for delivery to the habitat. Once connected and opened, the crew

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is tasked with removing launch restraints, transporting the packages into the habitat, and stowing them with some strategy for finding and retrieving hardware on need. To that end, NASA has developed a standard set of logistics packages, known as cargo transfer bags (CTBs). These come in four sizes, labeled "half", "single", "double", and "triple"-sized CTBs, along with large packages labeled M01-M03 bags. Table 2 relates the volume and mass limits of each type of logistics package, along with the relative frequency of use on ISS resupply missions. The flexible design of the packaging allows empty bags to be collapsed for minimum stowage volume; some development been done examining ways that empty CTB packaging material can be reused as a program of "logistics to living".[6]

Bag size	Volume (m^3)	Max Load (kg)	Avg Load (kg)	Avg Density (kg/m^3)	ISS Utilization
Half CTB	0.0247	13.6	5.13	207	15%
Single CTB	0.0529	27.2	10.26	194	75%
Double CTB	0.107	54.4	20.5	191	2%
Triple CTB	0.160	81.6	30.8	193	3%
M01	0.391	136	61.6	157	3%
M02	0.243	90.8	41.0	169	2%
M03	0.638	227	103	161	–

Table 3. Mass and volume limits of commonly used logistics packaging[7]

This table tells us that the previous estimate for LPLM volume, and therefore mass, is inaccurate as the packing density will, on average, be less than the overall mass density of the commercial resupply spacecraft itself. Using the average payload density of 194 kg/m^3 for a single CTB, the two-month resupply LPLM would be 8.5 m^3 in volume with a mass estimate of 540 kg, rather than 385 kg. The logistics landing system would now have to have a payload of slightly over two metric tons. Table 4 presents the LPLM design data for resupply rates between 1 lunar cycle (28 days) and 13 (1 year).

Resupply Rate (months)	Cargo mass (kg)	CTBe	Volume (m^3)	Container mass (kg)	Total LPLM mass (kg)
1	741	72	4.24	302	1040
2	1482	144	8.49	537	2020
3	2222	217	12.7	752	2970
4	2963	289	17.0	955	3920
6	4445	433	25.5	1340	5780
9	6667	650	38.2	1870	8540
13	9630	939	55.2	2540	12,200

Table 4. LPLM design characteristics based on resupply rate

While this table shows a minor economy of scale to larger, more infrequent resupply, the larger LPLM designs are comparable in mass as well as volume to an actual habitat module. Resupply on a biannual or annual basis to a fully occupied four-person lunar base would require an HLS-class lander for the logistics module, along with specialized surface infrastructure for transporting the LPLM from the lander to the base habitat and berthing it to a pressurized connection for unloading. On the other hand, shorter resupply rates would entail more surface operations for berthing and unberthing LPLMs, along with great likelihood of a resupply failure due to a higher number of flights. To balance the scale of logistics operations with the expense and complexity of larger LPLMs, it would seem reasonable to proceed with an initial baseline of a two-month resupply rate. This LPLM design is approximately two metric tons, which should be feasible for the larger range of planned CLPS landers, and the 56-day lunar resupply rate is very similar to the 51-day average shown by recent ISS operations, as documented above.

Adopting a two-month lunar surface resupply cycle, the 1500 kg of landed cargo would correspond to 144 single CTBs, known as "CTB equivalents" (CTBe). If the distribution mirrored that of cargo to ISS,[7] two month's supplies for a four-person lunar base would be packaged in

- 18 half CTBs

- 90 single CTBs

- 2 double CTBs

- 4 triple CTBs

- 4 M01 bags

- 2 M02 bags

Based on the crew time allocations cited earlier,[1] this would represent a time commitment of 14.6 crew hours/resupply mission and 11.7 crew hours/month for logistics "housekeeping", or a total of 237 crew hours/year for resupply. There would be additional crew time requirements for filling the LPLM with trash and other discarded material for contained disposal on the lunar surface.

III.   Pressurized Module Passthrough Study

While the overarching goal of this study is to examine the differences between microgravity and lunar logistics, the general topic is too broad for one set of studies or one report. Microgravity greatly simplifies the process of proximity operations and docking/berthing for cargo vehicles arriving at ISS. On the lunar surface, the LPLM would have to be removed from the lander, transported to the habitat site, docked to a pressurized mating port, and physically supported while the crew removes the cargo and stows it in the habitat. The same infrastructure would then be used to remove the LPLM, probably filled with discarded materials, and deposit it in some designated disposal area. While parallel activity has been underway at the University of Maryland to perform preliminary analysis of such a surface logistics system,[8] that work focuses on vehicle design and operations, and is one step removed from the scope of this paper.

Instead, the research covered here was focused on how the crew deals with the differences between manipulating logistics elements in microgravity and at more noticeable gravity levels, such as on the Moon and Mars. This will include evaluation of human factors relating to handling of CTBs in a laboratory environment on Earth, and in simulation of lunar gravity via ballasted underwater testing.

Once the LPLM is berthed to the habitat, the next step is to unload the logistics elements. As detailed above, a notional manifest would have 120 cargo elements ranging in lunar weight from 8-220 N (2-50 lbs) on the Moon, which must be unloaded from the LPLM and stowed inside the habitat pressurized volume. This is the procedure followed by all of the logistics missions to ISS, albeit considerably aided by the microgravity conditions.

One of the critical elements of this logistics transfer process is the size of the hatch, which varies from vehicle to vehicle. Figure 2 shows an astronaut moving a cargo transfer bag from an HTV resupply vehicle into ISS; this vehicle had a full-size hatch compliant with the common berthing mechanism (CBM) standard of 1.25m square. The Cygnus vehicle also is berthed via a CBM, but has a hatch size limited to 94cm square. Resupply vehicles which dock, such as the Dragon 2 cargo vehicle, use the NASA IDS interface which has cylindrical transfer volume only 80 cm in diameter, which severely limits the size of cargo containers to be transferred. All of these interfaces are designed originally for microgravity. NASA's preference for human transfer hatches in gravitational fields is a "walkthrough" hatch 1.5m high by 1m wide, allowing the crew to step or walk through with minor adaptation to prevent hitting their head on the way. This hatch size is not compatible with the CBM sealing diameter of 1.27m, and will drive the size of the overall docking interface for the LPLM if adopted.[9]

In terms of human spacecraft resupply, the issues under investigation for lunar systems is the accommodation of gravity loads on the transfer items, along with the effect of hatch size and shape on cargo offloading. Cargo elements on ISS can be offloaded either by floating them through the hatch, or by a single crew "carrying" the item through the hatch and directly into the habitat. The analogous situation for lunar systems would be the ability for a single crew to transport a cargo element through the hatch from the LPLM into the habitat; the feasiblity of this would be strongly influenced by the size and vertical location of the pressurized passageway as defined by the hatches.

An experimental investigation was conducted with three different concepts for transporting CTBs between modules in a gravity field. In the closest analogy to the microgravity case, a 1m wide by 1.5m tall passageway was created, and test subjects stepped through carrying a CTB ballasted to appropriate lunar weight (Figure 3). Two alternative test configurations used a Cygnus-sized hatch (0.97m square), approximately one meter above the floor. With this hatch configuration, it was not deemed credible that a single crew would crawl back and forth through the hatch carrying a CTB, so these cases used one crew on each side to hand the CTB through the restricted opening. In one case, the CTB was manually handed through the opening (Figure 4). Since some of the larger test cases strained the test subjects even with lunar-appropriate weights, the team also designed a mechanical conveyance to help support the cargo elements between modules (Figure 5). The distance across the interface vestibule was held at 0.5m in all cases.

Figure 2. Maneuvering cargo item from HTV into ISS

Figure 3. Testing CTB transfer with walkthrough hatch

A number of concepts were considered for the mechanical assistance system to move cargo through the docking hatches. Primary consideration was given to the fact that these hatches are safety critical, and must be able to be closed quickly in case of a pressure leak, fire, or other contingency. To that end, the team finally arrived at a "monorail" design with a low-friction cart to which the cargo element could be easily attached and detached. The system itself was designed to be simply assembled through the hatches and quickly removed in case of an emergency.

Figure 4. Testing CTB transfer with direct handoff through Cygnus hatch

Figure 5. Testing CTB transfer using rail transport system through Cygnus hatch

Testing was performed with a set of single and double sized CTB analogues. Two test conditions were set for each size: one ballasted to the lunar equivalent of the average ISS payload for that unit as listed in Table 3 ("light"), and the other ballasted to the lunar equivalent of the maximum CTB designed payload ("heavy"). For the initial tests, six subjects participated in moving the CTBs through the various interfaces, including moving the elements three meters from initial stowage to the simulated docking fixture and another three meters on the other side to the deposition site. Walking through the large transit port was a single-person task; the other two cases with the Cygnus-sized port were two-person tasks. Test subjects were timed in the performance of the task, and gave NASA Task Load Index (TLX) evaluation scores after each test configuration.

The average completion times across the six test subjects is shown in Figure 6. The metric chosen here was crew time: a two-person task counted twice a single-person task for the same total completion time. As the results show, the walkthrough with the large transit hatch was the favored system, largely because the efficiency of not requiring two crew to perform the operation. The lowest performance was the smaller hatch size with the support rail system. While it removed the need for the crew to lift the logistics element though the vestibule to the person on the other side, each person had to lift the CTB and manually connect it to the rail slider supports. This was awkward, particularly with the larger and heavier items, and required significantly longer than simply handing the elements through the simulated hatches.

The test subject evaluations of the techniques are illustrated by the NASA TLX results, shown in Figure 7 for the CTBs loaded to average ISS masses, and in Figure 8 for full rated loads, all adjusted to lunar weights. The general trends were consistent across all three test cases and the two different mass configurations. The test subjects rated
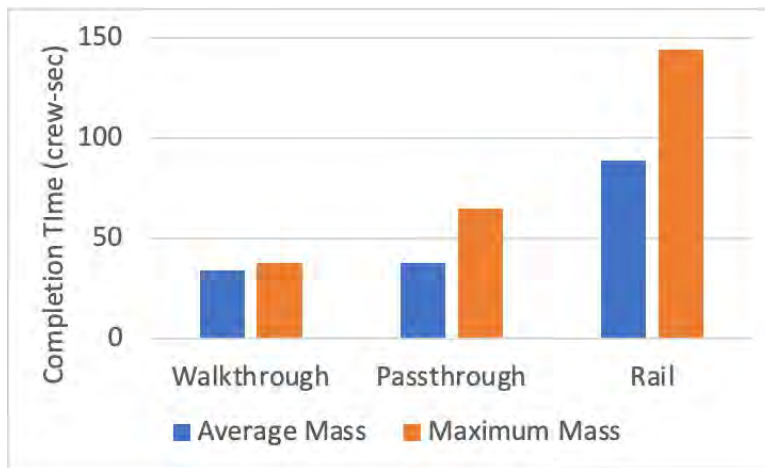
Figure 6. Average times for CTB transfer through three modes tested

their performance as near-optimum in all test cases. Other than that, the major difference across all cases was that the other five factors (physical workload, mental workload, temporal demand, overall effort, and frustration level) were uniformly higher for the maximum CTB load case as compared to the average load levels.
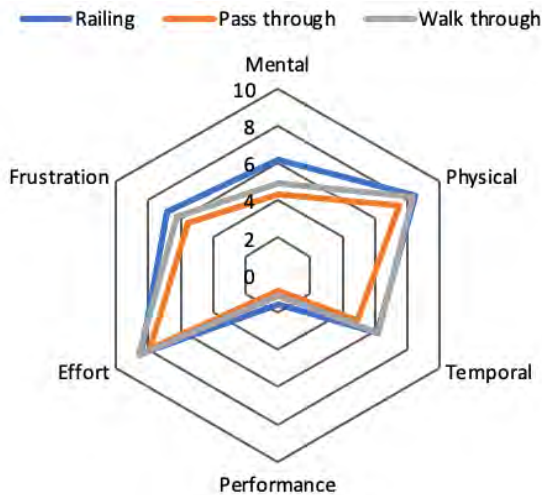

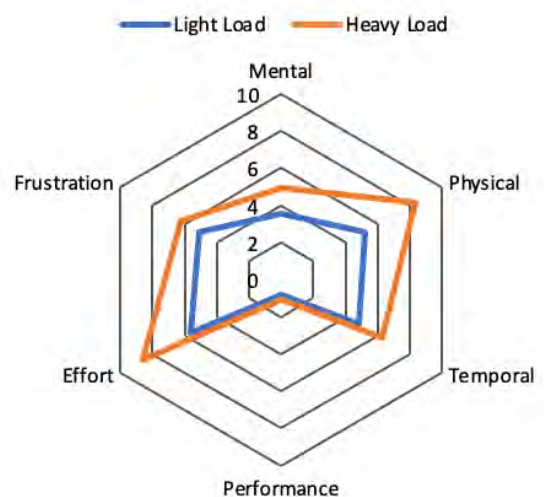**Figure 7. Average NASA TLX ratings of test modes using average mass CTBs**

Figure 8. Average NASA TLX ratings of test modes using maximum mass CTBs

The results to date, while highly consistent, still have some significant shortcomings, chief among which was the fact that the tests were performed in Earth gravity, with the CTBs weighted to lunar-appropriate levels. To address this, the tests were modified and repeated in the UMd Neutral Buoyancy Research Facility. Test subjects were ballasted to lunar weight using body segment parameter techniques, with ballast weights appropriately distributed on the front and back of the torso, upper thighs, and lower legs.[10] Subjects wore a full-face mask to allow bilateral voice communications, and were remotely supplied with air via 30-ft umbilicals to eliminate the mass and inertia disruption of a backpack-mounted air tank. Small emergency breathing units were worn in case of a problem with the primary air source (Figure 9). Six CTBs were used for these tests: two larger units representing double CTBs and four smaller as single CTBs. One of the large CTBs was ballasted to the lunar weight of a maximally loaded double CTB for locker stowage (inertial mass 85 kg; lunar weight 140N/31lb), the other was at the weight limit for a strap-restrained double CTB (inertial mass 61 kg; lunar weight 100N/22lbs). Two of the small CTBs were ballasted for an inertial mass of 35 kg (lunar weight 58N/13lbs), one was at 48 kg (lunar weight 78N/18lb) and one at 28 kg (lunar weight 46N/10lb).

Standard rack units were used to form a section of the LPLM and the portal for access to the larger habitat. For simplicity, the habitat was not modeled other than providing another rack with shelves for stowing the CTBs after removal from the LPLM. As shown in Figure 10, the racks forming the LPLM had shelves for storing CTBs. Two

different racks were interchanged for the portal to the simulated habitat: one had two 1m x 1m portals representing a typical passageway such as that on Cygnus, and the other had a vertical 1.5m x 1m "walk-through" portal as per the NASA standard for hatches in a gravity field.[9]

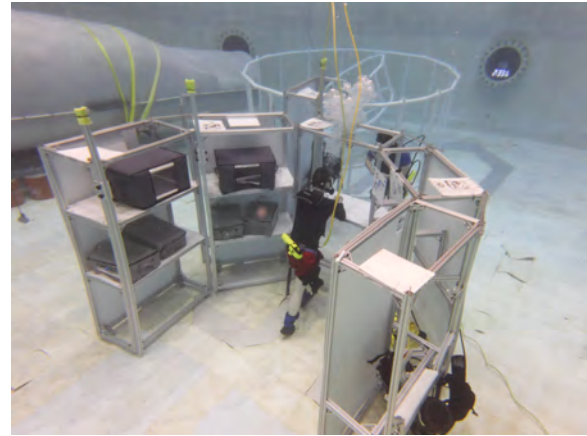**Figure 9. Underwater test subject ballasted to lunar gravity with racks containing CTBs**

Figure 10. Set-up of tracks to form segment of LPLM with replacable portal rack to "habitat"

The tests consisted of moving the six CTBs from shelves in the LPLM side to shelves on the habitat side, followed by moving them back into the LPLM. Each direction was timed in the aggregate for completing the transfer of all six CTBs. Five transfer cases were tested:

- Subject A passes CTB to Subject B through small upper portal (Figure 11)

- Subject A passes CTB to Subject B through small lower portal (Figure 12)

- Subject A passes CTB to Subject B through large portal

- Subject carries CTB through large portal and stows on other side (Figure 13)

- Both subjects carry CTBs through large portal to other side (Figure 14)

Both test subjects alternated as Subject A and B. Each subject did the solo transfers independently.

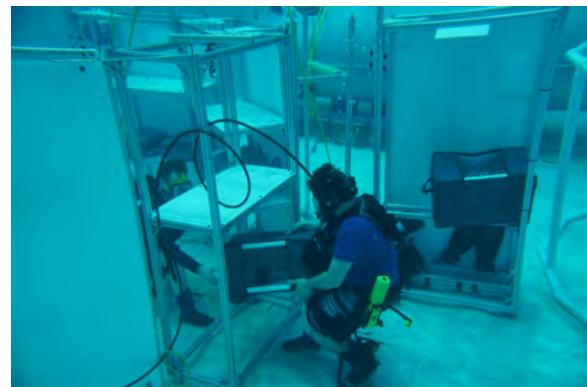**Figure 11. Passing large CTB through upper 1m x 1m portal**

Figure 12. Passing large CTB through lower 1m x 1m portal

The timing data from this test series is shown in Figure 15. All three cases where the CTBs are handed through the portal, and the crew each stay on their side throughout, are essentially indistinguishable in terms of completion time. The two cases where the crew walk back and forth through the larger portal carrying the CTBs are somewhat faster,

Figure 13. Carrying CTB through 1.5m x 1m portal (solo transfer)
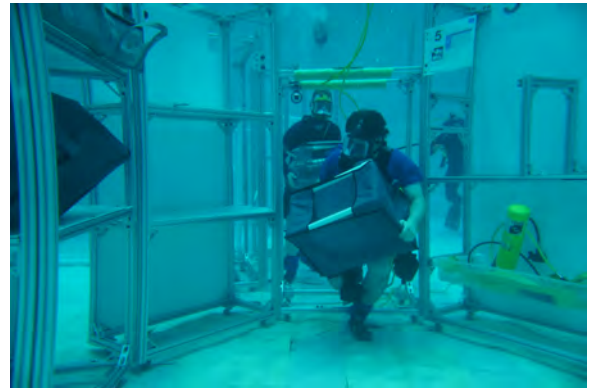

Figure 14. Both subjects carrying CTBs through 1.5m x 1m portal

with the solo loading or unloading slightly better than both crew working together. This was obvious from observing the tests, in that one subject would have to wait for the other to clear the portal before carrying their item through.

Despite the results, the crew preferred the smaller upper (chest-high) portal as it minimized vertical motion of the CTBs, and provided a convenient "shelf" to leave the CTB, thereby decoupling the timelines of the two test subjects. It should be noted that the subjects never translated through the smaller portals themselves, but only handed cargo through them. They did suggest that a collapsible/removable shelf in the middle of the larger portal would work as well.
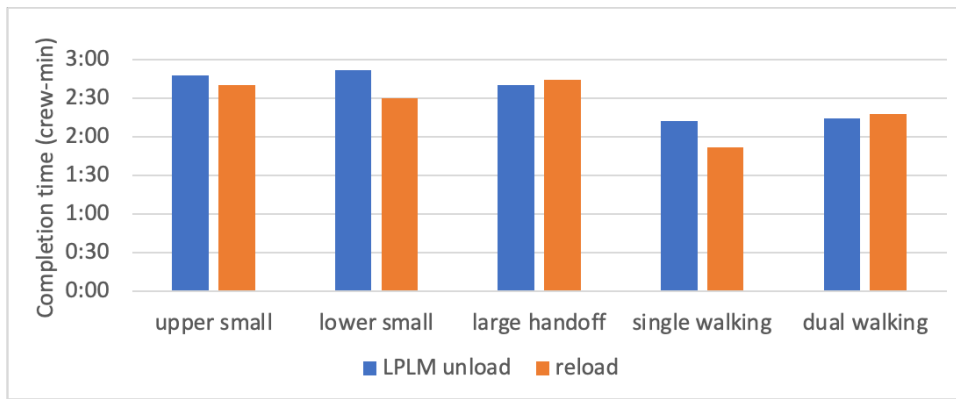

Figure 15. Completion times for transferring CTBs through portals at lunar gravity

An unexpected result is that both test subjects commented that the heavier large CTB was near their limit to comfortably manipulate single-handed, despite the fact that its actual weight was only about 30 lbs. Post-test analysis showed that the water enclosed by the fabric envelope produced an effective inertia of 100 kg, which is larger than the 82 kg maximum load of a double CTB when stowed in a locker, and almost twice the inertia of a maximally loaded CTB restrained by straps. The subjects commented on the sensed inertia, particularly when accelerating the large CTBs vertically. Although a simulated M01 bag had also been prepared for testing, this would have had an underwater inertia of 400 kg, compared to a maximum payload limit of 136 kg. The team is examining other options for simulating larger stowage bags, such as high-flow mesh fabric to minimize trapped water to more accurately model the desired inertia for future tests.

While further testing is needed to allow quantification of learning effects, utilization of a larger number of test subjects, and extended operations to quantify fatigue, these tests to date indicate that manual manipulation, transport, and stowage of logistics elements up to double-sized CTBs is definitely feasible at lunar gravity levels. Focused testing is indicated to examine the issue of weight limits beyond the fully-loaded double CTB, including M01 bags and larger custom logistics elements. This testing should also be performed at Mars gravity, which might restrict the use of manual logistics operations even further due to weight limits.

IV. Suitport Logistics Module Study

While the preceding sections examined the requirements and sizing of a lunar pressurized logistics module, its manipulation and transport on the lunar surface, and crew involvement in unloading the contents into a lunar habitat, there are other requirements for lunar logistics that represent "edge cases" to the nominal approach examined to date. These alternative approaches also offer an opportunity to develop a specific lunar resupply architecture end-to-end including realistic ground-based simulation of the system in action.

One of the drawbacks of the logistics architecture developed to this point in this study are the "scars" on the habitat to accommodate the LPLM. The pressurized interface, particularly if it incorporates a walkthrough passageway for crew, represents a docking interface close to two meters in diameter, which is both a large sealing surface to keep clean and a substantial portion of the habitat hull requiring routine access and prohibiting installed equipment in the area. Smaller pressurized vehicles, such as the NASA concept of a Space Exploration Vehicle pressurized rover, would not be capable of interfacing to the LPLM, thus doubling the number of logistics operations for those supplies: removal from the LPLM and stowage in the habitat, then collation and installation into the SEV during turnaround between sorties.

One recurring concept for surface habitats is the use of suitports for routine extravehicular activity (EVA) access. Each suit would seal to an interface which envelopes the portable life support system (PLSS) on the back of the pressure suit, which would swing open inside the habitat to allow the crew to ingress and egress the suit. This concept allows external access without the need to pressurize and depressurize an airlock, and having the suit remain external to the habitat prevents the incursion of regolith or other undesirable contaminants from the surface.

NASA has incorporated suitports into the SEVs used in analogue field tests such as the Desert Research and Technology Studies (Desert RATS). One augmentation of the concept was to use the suitport as a place to dock a simulated mini-pressurized logistics module to resupply the SEV during extended field trials.[11] Early Artemis missions will not be populated continually, and small pressurized logistics carriers (SPLCs) could utilize suitport interfaces to provide pressurized cargo without needing an additional interface. The ability to manipulate these small carriers manually via EVA would also postpone the cost impact of developing an LPLM and the surface transport infrastructure required to use it. Recent NASA studies have looked into lunar surface scenarios with logistics resupply based entirely on SPLCs.[12]

In 2021, NASA requested proposals to study suitport logistics carriers (also SPLCs) as part of the RASC-AL student design competition. A University of Maryland team was selected as one of the finalists in this category, which focused on the development of a complete logistics resupply architecture based on the use of suitports, but which also encouraged experimemtal investigation and verification of concepts.

The Level 1 requirements for this study specified the use of a commercial lunar payload services (CLPS) lander, with a total landed payload of 1800 kg and a targeted logistics payload (including containers) of 1600 kg. The mission concept including unloading from the lander, installation on a surface transport system (Figure 16), transport to the habitat, and installation of the SPLCs in turn to suitports on the habitat (Figure 17). The transport system was required to provide power and thermal control to the SPLCs while waiting to be installed and unloaded. The SPLCs would then be reloaded with trash and dropped in a convenient surface disposal location after use, and the entire infrastructure would be reused for the next resupply mission.

Figure 16. Offloading of SPLC modules from lunar lander onto transport trailer[13]

Figure 17. Station transport trailer at habitat for installation and removal of SPLCs[13]

It should be noted that, entirely by coincidence, the logistics resupply mass specified in this program was approximately equivalent to the two-month LPLM design chosen in the beginning of this paper. The requirement to integrate it onto a suitport necessitates a larger number of smaller logistics modules; the salient question was how many and what size?

The use of suitports at least implies the ability to use EVA crew to install and remove the SPLCs. To this end, a set

of experiments were conducted to investigate the capabilities of lunar EVA crew to manually transport and manipulator large masses, using the UMd Neutral Buoyancy Research Facility.

The challenge for planetary surface simulations is to accurately duplicate both the inertia and appropriate weight of the hardware. The best way to accomplish this is to enclose the correct amount of water to represent the desired inertia, while adding ballast to produce the appropriate weight. Commercially available 27-gallon plastic bins with lids capture almost exactly 100 kg of water; additional lead is then added to produce an underwater weight of 16 kg. This proved to be a cheap, quick, and effective way to create test modules which each created the weight and inertia of a 100 kg package on the moon. EVA handrails were added as crew interfaces, and straps added to allow stacking the modules to create higher mass packages to test human manipulation. Test subjects were again ballasted according to body segment parameters to create a simulation of lunar dynamics that includes an appropriate apparent weight to all major body segments. Test subjects were also equipped with full face masks for bidirectional voice communications, and used 30-ft hoses to remote air supplies to remove the air tank from their body to minimize inertial deviation from lunar conditions.

The modular test hardware was used to investigate the ability of test subjects to manipulate masses of 100, 200, 300, and 400 kg inertia, corresponding to 157 N (35 lb), 314 N (70 lb), 470 N (106 lb), and 627 N (141 lb) apparent weight. The 100 kg case was easily accomplished with two collaborating subjects, and was feasible but challenging for a single subject. 200 kg (Figure 18) was robustly feasible if not easy; 300 kg was challenging, and 400 kg (Figure 19) was extremely difficult. (All tests beyond 100 kg inertia were only performed by pairs of test subjects.) Given the results, it was decided that 200 kg was the upper limit of inertial mass for an EVA-tended SPLC.

Figure 18. Two-subject installation of 200 kg inertial mass module (314 N/70 lb lunar weight) in mockup suitport under simulated lunar gravity

Figure 19. Two-subject manipulation of 400 kg inertial mass module (627 N/141 lb lunar weight) under simulated lunar gravity

Given a 200 kg design goal for a single SPLC, the team performed detailed design on the elements of the logistics system. The design of the pressurized SPLC is shown in Figure 20. The suitport interface is 0.53m wide by 0.73m tall, mirroring the size of the current EMU PLSS. The overall module is one meter tall and 0.75m in diameter. Its nominal packaging consists of two single CTBs of 25 kg or four half-sized CTBs of 12.5 kg each, surrounded by six new "quarter-sized" CTBs of 6.25 kg conceptualized to make best space of the available volume of this cylindrical shape. The ellipsoidal endcaps each contain four conformal water containers, each with ten liter capacity. Along with the estimated mass of the structure, each SPLC has a mass of 200 kg.

The nominal resupply mission would consist of seven "dry goods" CTBs and one specialized unit carrying compressed gases which keeps the pressure bottles external to the habitat while allowing the crew to make the physical connections. These eight units on each resupply mission are offloaded by a davit onto a SPLC logistics trailer (Figure 21), which incorporates power for thermal regulation of the logistics modules, some electrical power for items in the modules which require it, and sufficient power to allow the trailer wheels to be driven to offload the drawbar pull requirements of the tow vehicle, which was assumed to be a Lunar Terrain Vehicle (LTV) unpressurized rover or an SEV pressurized rover. SPLCs would remain on the trailer and thermally regulated until removed for installation on the suitport for cargo transfer. A 7 degree of freedom (DOF) dexterous manipulator was also added to the trailer to install the SPLCs into restraints for travel, and to mount them onto suitports without the requirement for EVA operations.

The final design of the SPLC led to one additional iteration on the underwater human factors assessment of the concept. A higher fidelity mockup of the SPLC was designed and fabricated (Figure 22), which incorporated a hatch and internal volume for CTBs. This was manually berthed to a suitport by two test subjects, who subsequently simulated IVA crew in opening and removing the internal CTBs (Figure 23), and replacing them before closing up the
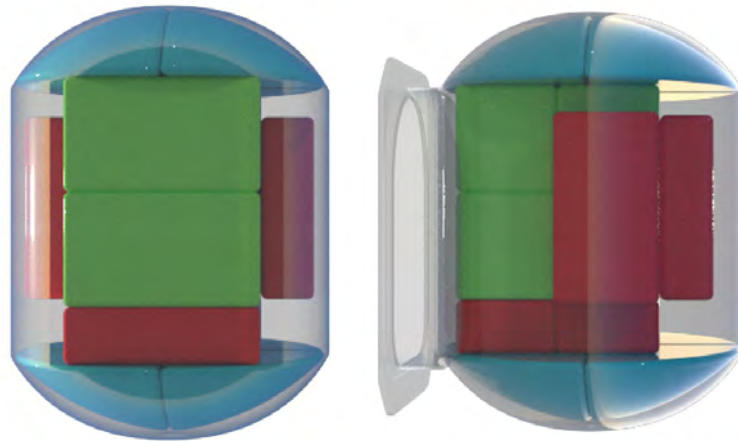
Figure 20. Front and side internal views of suitport logistics module. Green items are half CTBs, red are quarter CTBs, and blue are conformal water containers[13]
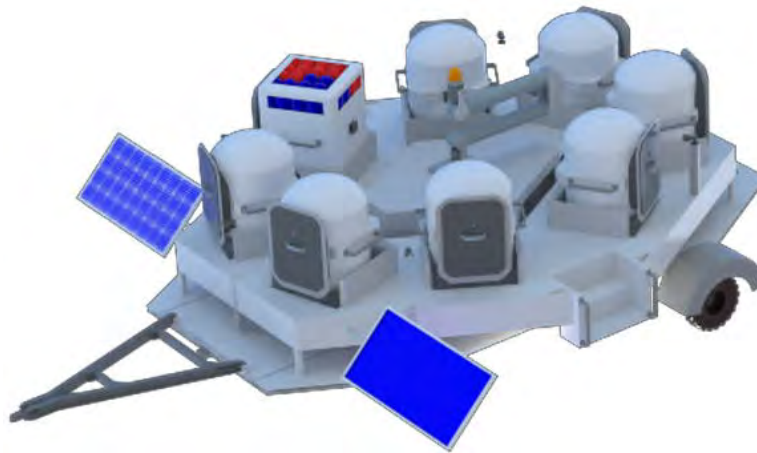

Figure 21. SPLC transport trailer supporting seven "dry goods" SPLCs and dedicated pressurized gases SPLC[13]

SPLC.

It was realized at an early point that while it was important to design the SPLCs to be manipulated by EVA crew upon need, it would be counterproductive to require an EVA every time an SPLC needs to be installed or removed, although recent NASA studies have adopted this as part of the baseline concept of operations.[12] This is doubly true if one also considers the work required to remove the SPLCs from the landing vehicle and installing them on the transport trailer in addition to rotating the SPLCs through a limited number of suitport interfaces on the habitat.

To verify the concept of a robotic manipulator for doing this task, an end-to-end laboratory experiment was conducted to verify robotic capability for SPLC external operations. A half-scale mockup of the SPLC trailer and a full set of modules was created from lightweight materials to stay within the payload limits of the available dexterous manipulator. An overhead bridge crane representing a payload davit lifted the SPLC mockups off of the simulated lander deck; the dexterous manipulator grappled each payload, the bridge crane released it, and the manipulator installed it onto the trailer. At a simulated suitport, the arm picked up an SPLC (Figure 24) and installed it, followed by a demonstration of removing the SPLC after it was emptied. This end-to-end simulation demonstrated a completely robotic performance of logistics resupply without the need for human physical intervention. With this sort of robotic infrastructure, the SPLC concept becomes much easier to integrate into lunar surface operations, as the modules can be manipulated from landing to habitat to disposal without adding to the EVA workload of the human crew.

V.   Conclusions

Logistics resupply for human habitats on the lunar (or, ultimately, Mars) surface will be challenging, with limited overlap to the wealth of experience in low Earth orbital microgravity logistics. This paper has presented a brief

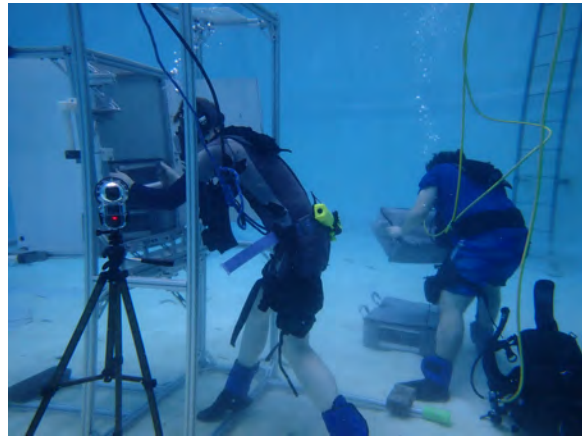**Figure 22. Transport of higher fidelity SPLC mockup under simulated lunar conditions**

Figure 23. removing CTBs from interior of SPLC under simulated lunar conditions

Figure 24. Robotic manipulator removing SPLC mockup from trailer mount prior to installation into suitport (half scale)[13]

summary of activity in the area of planetary logistics underway at the University of Maryland, leveraging extremely limited funding associated with student projects and competitions. Two different end-to-end logistics architectures have been examined, one based on ISS-type use of a lunar pressurized logistics module, and the second focusing on smaller suitport-based logistics modules to minimize impact on habitat design and exploit commonality between EVA and logistics interfaces. Many of the basic techniques and technologies for manipulating thousands of kilograms of annual cargo need to be conceptualized, investigated, evaluated, and implemented; this is a critical field that needs support far beyond the student project funding level.

Acknowledgments

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