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MISSION DESIGN CONSIDERATIONS FOR ROBOTIC LUNAR AND GATEWAY PAYLOAD RETURN

M.M. Wittal[1], J.D. Smith[2] and A.M. Cassell[3]
NASA
Kennedy Space Center
Ames Research Center
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ABSTRACT

A selection of lunar return trajectories is examined and assessed in terms of payload mass, vehicle mass, mission time, mission complexity, and total delta-V using a range of assumptions for the mission design based on historical precedence and near-future vehicle availability. Direct surface return trajectories using a single burn solution are compared with a range of Near-Rectilinear Halo Orbit return and Ballistic Return Trajectories. This study weighs anticipated mission needs, requirements and constraints with the aim of assessing the feasibility of commercial lunar cargo and/or sample return options utilizing NASA's Gateway and Deep Space Logistics project.

1. INTRODUCTION

Sustaining long-term presence at the Moon will likely require innovative approaches for frequent and affordable payload return as part of an overall effort to develop and maintain deep space supply chains. While the Orion vehicle provides a Lunar return capable asset, its infrequent mission cadence (once every 12 months), limited payload downmass (∼100 kg), and operational constraints suggest that alternative return logistics should be considered. One option is to examine the robotic ISS commercial cargo return model and its applicability to future Gateway operations for large downmass (>1000 kg) deliveries. A second option is to study on-demand small spacecraft that could return small amounts of payload (<100 kg) to complement the downmass capability the Orion vehicle provides. Small, robotic spacecraft as well as large-scale designs should be considered in order to fully understand how various mission scenarios and system capabilities most efficiently enhance sustainable operations. This paper describes an assessment of return trajectories, timing, and key operational considerations towards efficient and innovative Gateway utilization.

1.1. *Assumptions*

This study utilizes existing and projected technologies available for use such as the existing operational model for the Gateway Logistics Service (Dragon XL spacecraft from SpaceX), the SpaceX Starship, the constraints imposed by the Large External Orbital Robotic Interfaces (LORI), which will be used for the Gateway and Logistics Elements, and similar technologies as a foundation to conduct the study. Furthermore, the architecture of previous Lunar sample return missions such as Apollo [1], Luna [2] and Chang'e 5 [3], as well as other robotic sample return missions such as Stardust [4], Genesis [5], Hayabusa [6] and OSIRIS-REx [7] all provide a foundation for determining key design parameters and constraining spacecraft performance.

The Gateway Destination Orbit Model [8] is used as a baseline for Near-Rectilinear Halo Orbit (NRHO) arrival and departure for the duration of the study when utilizing Gateway as a rendezvous. This orbit is an important part of the Deep Space Logistics program and a fundamental consideration for mission design when including the SpaceX Dragon XL spacecraft in the mission concept. The gravitational model used includes the Earth, Moon, Sun, Venus, Jupiter, and Saturn for completeness, and assumes various cross-sectional areas and solar radiation pressures as is appropriate for each vehicle.

Below is a brief summary of the various mission concepts, the assumptions associated with each architecture, and the methodology used to derive the complexity metric as described in Table 1, and numbers used in Table 3 for the various parameters that factor into the final cost value. In addition, a range of expected dollar costs are described that will eventually play a role in determining the estimated cost-per-kilogram in §4.

1.1.1. *Lunar Direct - CLPS*

This mission architecture begins from the lunar surface and terminates at the surface of the Earth. The vehicle mass is no larger than the maximum CLPS payload, and is assumed to be launching from the surface of the moon at the equator when the Moon-Earth-Sun angle is at 180^o. Payload returned to Earth is on the order of 10 kg or less.

1.1.2. *Lunar Direct - Standalone*

This mission architecture begins from the lunar surface and terminates at the surface of the Earth. The vehicle mass is constrained only by the delivery capabilities of commercially available launch vehicles, and that both the landing and return element are being purpose-built. It is assumed to be launching from the surface of the moon at the equator when the Moon-Earth-Sun angle is at 180^o. Payload returned to Earth is on the order of 50 kg or less.

1.1.3. *Lunar Direct - Starship*

This mission architecture begins from the lunar surface and terminates at the surface of the Earth. Because it is

[1] Scientist, Swamp Works & Deep Space Logistics, NASA Kennedy Space Center, FL, 32899 USA
[2] Element Architect, Deep Space Logistics, NASA Kennedy Space Center, FL, 32899 USA
[3] Deputy Chief, Entry Systems and Technology Division, NASA Ames Research Center, Mountain View, CA 94035 USA

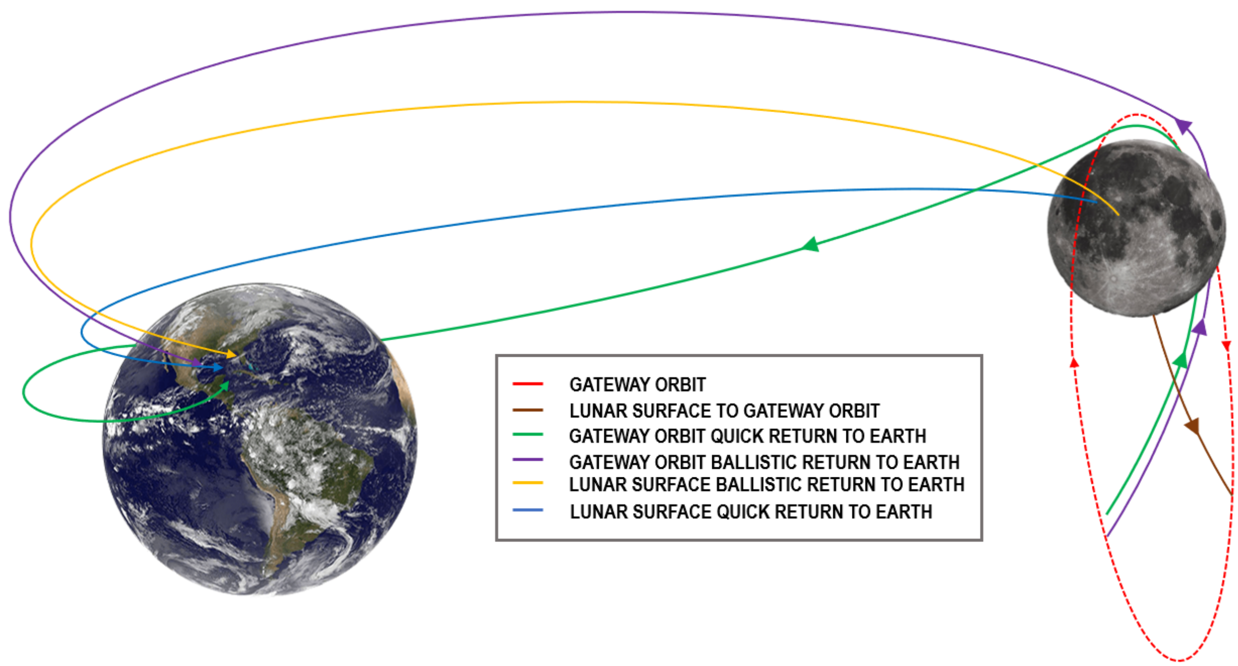

FIG. 1.— A variety of possible return trajectories are illustrated here. Departure locations could be from the lunar south pole, lunar equatorial regions, or the NRHO either from Gateway or departure from a larger spacecraft for a freeflyer on a return trajectory to Earth. These orbits are for illustration purposes only and are not to scale.

assumed to be utilizing a fully reusable vehicle, vehicle mass is not considered as the customer does not need to design anything more than a storage module, which is approximated as 100 kg in mass for a 1t payload. It is assumed to be launching from the surface of the moon at the equator when the Moon-Earth-Sun angle is at 180^o.

1.1.4. *BRT - CLPS*

This mission architecture begins from the lunar surface and terminates at the surface of the Earth. The vehicle mass is constrained to the maximum CLPS payload. The vehicle launches into an unstable HALO orbit and uses small burns to insert itself into a BRT. Payload returned to Earth is on the order of 10 kg or less.

1.1.5. *BRT - Ridealong*

This mission architecture begins when the ridealong capsule is released from the logistics module on final Earth Approach using a spring deployment mechanism that provides a separation velocity of a few meters per second, and terminates at the surface of the Earth. The host vehicle can either destructively reenter or perform an Earth flyby into heliocentric disposal. Total mass of the vehicle and payload is constrained to the maximum capacity of a standardized Large External Orbital Robotics Interface (LORI) of 150 kg.

1.1.6. *BRT - Freeflyer*

This mission architecture begins when the capsule is released from the logistics module prior to host vehicle heliocentric disposal using a spring deployment mechanism that provides a separation velocity of a few meters per second, and terminates at the surface of the Earth. Total mass of the vehicle and payload is constrained to the maximum capacity of a standardized Large External Orbital Robotics Interface (LORI) of 150 kg.

1.1.7. *BRT - Starship*

This mission architecture begins on the lunar surface and terminates on the Earth's surface. Because it is assumed to be utilizing a fully reusable vehicle, vehicle mass is not considered as the customer does not need to design anything more than a storage module, which is approximated as 100 kg in mass for a 1t payload.

1.1.8. *Gateway Direct*

This mission architecture begins as an external payload to the Logistics Module while in orbit of gateway and terminates at the Earth's surface. Total mass of the vehicle and payload is constrained to the maximum capacity of a standardized Large External Orbital Robotics Interface (LORI) of 150 kg.

1.1.9. *Starship Direct*

This mission architecture begins at the surface of the moon as the primary element of the Human Landing System (HLS) and terminates on the Earth's Surface. Because it is assumed to be utilizing a fully reusable vehicle, vehicle mass is not considered as the customer does not need to design anything more than a storage module, which is approximated as 100 kg in mass for a 1t payload.

2. METHODOLOGY

As a baseline, the Luna sample return mission is used as a starting point for a direct, single-burn solution. This brute-force approach allows for an examination of minimum, simple mission concept and gives the reader an

	0	5	10	15	20
Comms	No Demand	Dependency on proven spacecraft	Low demand on unproven spacecraft	High Dependency on proven spacecraft	High demand on unproven spacecraft
Interfaces	Cargo Only	Reentry Only	Launch & reentry	Interaction with other spacecraft or large reentry vehicle	Many demanding interactions with other spacecraft
GN&C	No Maneuvers	Single maneuver/burn	Several coarse maneuvers	Some precise maneuvers	Many precise maneuvers
Vehicle	No Vehicle	Ridealong	Freeflyer	Independent spacecraft	Independent ascent vehicle and spacecraft
Risk	Low	Medium-Low	Medium	Medium-High	High

TABLE 1
Complexity is best understood as a combination of factors that penalize overall mission design when compared against other concepts. The concepts listed above may not be comprehensive, but help provide a first step at quantitatively weighing several available options.

understanding of transitional mission design cost, first in terms of a weighted cost function examining Delta-v, vehicle mass, payload mass, time, and complexity as illustrated in Table 3 and then in terms of approximated financial cost in §3.1. Following this, various architectures for cargo return are considered using the same parameters. The mass, departure time, and architecture is varied for each concept and examined in terms of delta-V and overall mission cost. They are also compared in terms of direct (fast) transfer from NRHO to Earth return trajectory, and Ballistic Return Transfer (BRT), which is essentially a reverse of the Ballistic Lunar Transfer (BLT) described by [9].

2.1. *Ballistic Return Trajectory*

Much like the Ballistic Lunar Transfer, the Ballistic Return Trajectory makes use of the Weak Stability Boundary (WSB) that exists beyond the orbit of the moon. At this point, the gravity from the Earth-Moon system is approximately equal to the gravity of the Sun, and thus the trajectory of the spacecraft can be greatly effected by very small amounts of thrust. This envelope is useful for inducing changes to the orbital elements of a trajectory very efficiently. However, because such small amounts of thrust can induce very large changes in reentry time and position, it is very sensitive to uncertainties in guidance and propulsion system performance and thus may impose high demands on Earth-based deep space communications systems. Many small (< 10 m/s) midcourse corrections are likely to be required. Advanced autonomous navigation schema may be used to overcome this issue, but such systems have yet to be tested within the WSB and thus introduce additional risk to mission designers. If this trajectory can be used and mastered in the years to come, and such autonomous algorithms developed and tested, then the BLT and BRT would be an ideal trajectory for efficient travel to and from Cislunar space.

In this study, the aforementioned Gateway NRHO baseline reference trajectory was used to simulate families of BRTs separated by one orbital period of the NRHO. These return trajectories have similar costs and times, and are significantly effected by the cross-sectional area of the spacecraft considering the volatility of the WSB. As was the case with BLT's as described in detail by [9], BRT's can be grouped into various families depending on direction relative to the Earth-Sun rotating frame. There also exist return trajectories that utilize a lunar flyby during final approach, which can also be used to fine-tune the approach and target specific desired landing sites.

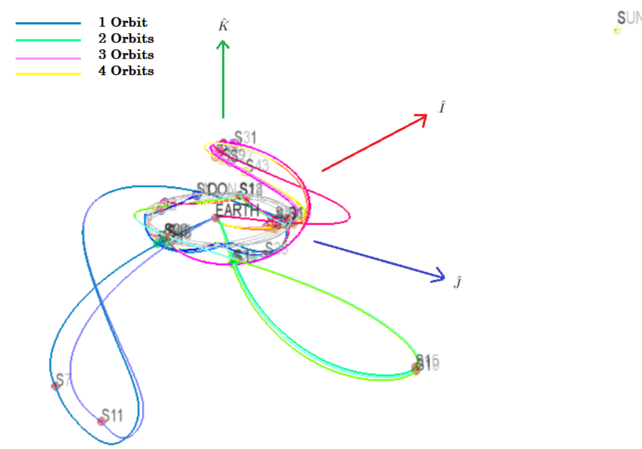

Fig. 2.— This figure illustrates the various families of BRT separated by one orbital period in the NRHO in the Sun-Earth rotating frame. The families are color coded in groups of Blue, Green, Red, and Yellow representing departure times. The red and yellow groups are both sun-facing trajectories, as the sun is the most dominant force during both departure phases, illustrating that one period of ~ 6.5 days may still result in a very similar ballistic arc.

2.2. *Scoring Complexity*

The numerical value ψ is used in this study to indicate complexity on a 0-100 scale. The components of complexity that are considered are displayed in Table 1. To determine the complexity of any given mission, 5 parameters are considered equally weighted for a maximum of 20 points each, with lower scores being more desirable and higher scores representing a penalty. The Comm category covers the expected demand on a communication system that must be provided by the payload delivery system. For example, fully autonomous systems or unguided concepts would have a very low demand on communications, while high-priority systems with complex interactions with other vehicles or vehicles on sensitive trajectories like the BRT would have a very high demand on communications.

The Interfaces category considers how many requirements will likely be imposed on the delivery system based on the natural and induced environments and its expected interactions with other spacecraft, which adds mission complexity as well as risk. Missions such as a unguided reentry capsule would score very low, while

Commercial Provider	Contract Award Date	Planned Landing Year	Landed Payload Mass (kg)	Contract Cost ($M)	Cost Per Landed Payload Kilogram ($\frac{\$k}{kg}$)
Intuitive Machines [10]	May 2019	2021	100*	77	770
Astrobotic Technology [10]	May 2019	2021	90	79.5	883
Masten Space Systems [11]	April 2020	2022	100*	79.5	759
Intuitive Machines [12]	April 2020	2022	90	47	522
Firefly [13]	Feb 2021	2023	94	93.3	993

TABLE 2
Estimated Cost Per Kilogram for Small-Class NASA Commercial Lunar Payload Services (CLPS) Missions to the Moon .
*estimated as the maximum payload mass announced on the CLPS RFP.

multi-stage missions that interact with Gateway would likely score much higher.

The GN&C category evaluates the number of burns and considers the precision required for those burns. For example, single-burn solutions from the surface or jettisoned sample cannisters from the logistics module during an Earth flyby would have a low score while BRT trajectories require a high level of precision to correctly execute small midcourse corrections and would thus be penalized.

The Vehicle category considers overall vehicle design complexity based on the expected degree of independence that will be required of the delivery vehicle. Systems that only require a heat shield or are just cargo containers would not be penalized, but fully independent spacecraft would have higher scores.

Finally, the Risk category examines overall Artemis mission risk based on a combination of factors including risk imposed on *other* vehicles and systems such as a lunar base, Gateway, and perhaps a Logistics Provider. This is distinct from the GN&C category as it considers the priority of the vehicles with which the concept is expected to interact. Gateway, for example, is a mission-critical asset while a nearby CLPS lander with a secondary science experiment or a disposed logistics module would not be deemed mission essential or mission critical and thus interactions with those systems, although potentially more complicated in terms of interfaces, would not be penalized in terms of overall mission risk.

2.3. *Cost Function and Scoring*

For each concept, a terminal cost function is given much in the same way as one would approach any optimization problem.

$$J = \frac{1}{2} p^T Q p \tag{1}$$

where J is the total cost, Q is the diagonal weight matrix, and p is the list of parameters defined to be:

$$p = \begin{bmatrix} dV \\ m_v \\ m_p \\ t \\ \psi \end{bmatrix} \tag{2}$$

Where dV is in km/s, the masses are in t, time is in days, and ϕ is unitless. The selection of weight matrix Q depends on the budget and tools at the disposal of the mission formulation team. For the purposes of this study, we propose a diagonal weight matrix defined as:

$$Q = \begin{bmatrix} 0.75 & 0 & 0 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0.0025 & 0 \\ 0 & 0 & 0 & 0 & 0.1 \end{bmatrix} \tag{3}$$

meaning that high payload masses are rewarded while high values for the other parameters are penalized. The results of using this cost function is shown in Table 3. The coefficients were chosen in order to scale the parameters roughly in proportion to one another. For example, average delta-V values are on the order of a few km/s or less, while the chosen method for grading efficiency is always on the order of 10s. Thus considering the relative importance and relative magnitude of these parameters, the coefficients of 0.75 and 0.1 were selected, respectively.

Total vehicle mass may be an issue when seeking a launch vehicle of significant size, but is less problematic when weighted and compared against the potential gains from the returned cargo. As described in §1, other factors also constrain overall vehicle mass, and it is thus considered far less of an issue and given the weight of 0.25. Finally, time can be an issue in terms of operation cost, which should be considered when calculating the dollar cost as described in §4.1, and can also impact mission complexity, which is considered in the cofficient Ψ. Of course, even after all of these components are considered separately it is more desirable to have cargo delivered quickly than to remain in transit for months at a time. Thus, time itself is still directly penalized, but scaled to match other values using a coefficient of 0.01.

3. ANALYSIS & DISCUSSION

The BRT offers a low-delta-V alternative to the traditional direct sample return mission, especially when the mission begins with a departure from NRHO. If a payload can be delivered to the Gateway, then the propulsive cost of returning that payload to an Earth Interface Point (EIP) can be as low as 20-30 m/s, with a mass limited only to the maximum capable payload when considering the disposal mass of the host spacecraft, such as the Dragon XL. This implies that so long as the Gateway remains in orbit, extremely low-cost sample return options exist as secondary payloads for the Deep Space Logistics program. Furthermore, even in the absence of a Logistics Module or even Gateway, notional sample return missions that can afford to wait several months can

Mission Concept	Total Delta-V (km/s)	Vehicle (t)	Payload (t)	Time (days)	Complexity	**Total Cost**
Lunar Direct - CLPS	2.525	1.5	0.01	3	45	**104**
Lunar Direct - Standalone	2.525	6.5	0.05	3	55	**159**
Lunar Direct - Starship	None	0.1	1	3	15	**31**
BRT - CLPS	2.3	1.5	0.01	180	70	**288**
BRT - Ridealong	0.15	0.05	0.1	180	50	**165**
BRT - Freeflyer	0.15	0.1	0.05	180	75	**322**
BRT - Starship	None	0.1	1	180	15	**71**
Gateway Direct	0.15	0.55	0.1	8	75	**281**
Starship Direct - South Pole	None	0.1	1	8	15	**45**

TABLE 3
A comparison between various nominal metrics for various mission concepts. This table seeks to quantify general features and may be expanded based on the needs of the provider.

afford to save several hundred meters per second of delta-V when utilizing a BRT.

3.1. *Estimating Cost Per Kilogram*

Estimating the cost per kilogram in terms of dollar amount is challenging, and evolving very rapidly. Launch costs can be estimated using publicly available user's guides from launch vehicle providers, and operational costs vary greatly depending on the size of the spacecraft and scope of the mission. Operational costs likewise vary depending on the demands placed on assets like the Deep Space Network or other space infrastructure.

However, as the Artemis program progresses, it is realistic to expect that the cost of accessing transportation to and from the moon will be reduced as a wider range of providers become capable of reliable logistics services to the Lunar surface or to Cislunar space. It is expected that advancements in technologies and a wider range of providers will spark competition within the market that will drive down cost. Those wishing to procure logistics services may find it far more affordable within the coming decade than it has been in the last 50 years.

As an example, the NASA CLPS contract provides important insight into cost estimation for competitive small-class missions on and around the Moon. The CLPS contract was established in 2020 and it follows NASA's emerging "fixed-price, commercial services approach" to procuring missions (similar to crew and cargo services contracts for the ISS) rather than using the traditional, and more expensive, "pay as you go" acquisition model. Table 2 shows the estimated cost per kilogram of landed payload mass for recently awarded CLPS missions that will deliver small science payloads ($\sim 100kg$ total payload mass) to the Lunar surface over the next few years. Commercial services contracts, like CLPS, allow NASA to take advantage of the most recent industry innovations, and use head-to-head competition, to drive down costs and get the best value for the government. A similar commercial services approach to sample return, from Gateway and the Moon, can also achieve best-value results for returned payload mass.

4. CONCLUSION

This work has examined a range of possible cargo delivery options from Lunar and Cislunar space to the Earth, considering the projected available technology and infrastructure available to mission designers for the foreseeable future. Using a range of assumptions described in detail in §1, the authors have developed a cost function that estimates the value of each concept relative to one another. The results of this effort can be seen in Table 3, suggesting a highly robust capability would be desireable from the perspective of logistics . The weight matrix used and described in Equation 3 was selected based on the needs and perspectives of NASA, and can be tuned to suit the needs of any organization considering returning cargo or samples from the moon. The final numerical examples and assumptions show that Starship or a similar, multi-purpose, super-heavy lift spacecraft has the potential to provide tremendous benefit to those that wish to requisition assets or samples from the lunar surface, but this may come at a high cost in terms of dollar amount unless ride sharing is considered. In the absense of a super-heavy lift capability such as Starship, CLPS lunar direct, Standalone Lunar Direct, and BRT Ridealong concepts remain viable options, with the biggest penalty for the former two concepts being overall payload while for the latter being the high burden placed in attitude control and communications systems.

However, the weight matrix used here was tuned to suit the perspective of NASA and it's logistics supply chain, but a private company may find value in a weight matrix tuned differently, or one designed to explore parameters not considered here. Future work intends to expand upon this concept and include additional factors as the Artemis program develops. Most importantly for the reader is the consideration of the *return* component of the deep space logistics supply chain which, until very recently, has not been practical.

The scope of this paper covers a rapidly evolving capability that is still in the mission formulation phase. As new providers are selected in support of NASA's Deep Space Logistics service, new CLPS missions are awarded, and new services procured in support of the Human Landing System, requirements will be refined and new problems will arise. Thus, these results are speculative and based on the current state-of-the-art within the Deep Space Logistics community. It is expected that this paper is the first in a series that will describe this evolving capability in an effort to engage the community both to illustrate the objectives and needs of NASA and to obtain feedback on the constraints and desires of potential stakeholders within the scientific community.

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