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MOONPORT: A cost-effective transport solution for cislunar space

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Abstract

Over the past decade, commercial interest in transportation services to the Moon has increased significantly. Both governmental space agencies and commercial companies are investing in establishing a long-term human presence on and around the Moon, for both exploratory and commercial purposes, leading to a growing need for a reusable transportation system. This work suggests a commercially viable cislunar transportation system, specifically targeting cargo missions with a payload of up to 8 tons. The proposed transportation system is based on a refuelable space tug using a chemical-electric propulsion system. The solution, named Moon On-Orbit Nexus Providing Orbital Rendezvous and Transportation (MOONPORT), has been developed from an engineering, financial, and legal standpoint, and is supported by both mature technologies and modern market analysis. This transportation system will assist in cislunar activities by providing a low-cost alternative to a heavy launch vehicle or other tug solutions. Additionally, MOONPORT aims to provide a solid foundation for NewSpace startups aiming to fill the niche of cislunar transportation.

Keywords: *cislunar, chemical-electric propulsion, in-space refueling, space tug, space transportation solution*

1 Introduction

The rise in the NewSpace economy has led to an increased interest in the provision of cislunar transportation services and space applications. With this industry perspective in mind, the authors worked on this project during the 2021 Space Studies Program at the International Space University (ISU) with the aim of proposing a commercially viable cislunar transportation system based on a refuelable space tug.

In order to develop a competitive and technologically viable solution, previous space tug solutions were researched. Heavy payloads (in the order of megatons) can be delivered from Low Earth Orbit (LEO) to Low Lunar Orbit (LLO) by means of a refuelable tug based on nuclear thermal propulsion, as proposed by Reynolds et al. [1]. Although nuclear propulsion allows for an increased specific impulse (I_{sp}), legal implications arise as the nuclear propulsion system may be erroneously associated with nuclear weapons, the operation of which is prohibited in space according to the space treaties. Zhang et al. [2] proposed a reusable modular tug instead, powered by solar electric propulsion to reach both lunar and martian orbits. The downside of this solution is that the proposed nested-channel Hall Effect thrusters have not reached a mature technology level yet (Technology Readiness Level (TRL) < 7). Kinefuchi et al. [3] described a preliminary study using high power Hydrogen (H_2) electric propulsion based on Magneto-Plasma-Dynamics thrusters and Direct Current arcjets to bring a payload of 6.8 tons to LLO. However, H_2 is difficult to store as a propellant due to its low density, and the TRL of the propulsion system was not disclosed in the paper. Mammarella et al. [4] suggested the use of Hall-effect thrusters to reach LLO due to the reduced mass requirements. However, the slow transit time across the Van Allen belts can lead to premature degradation of the spacecraft. The same consideration applied to Richard et al. [5], where a solar-electric spacecraft was proposed. Based on the literature research, a chemical-electric propulsion system was selected for this work, as it balances the mass of the spacecraft, the time spent in the Van Allen belts, the launch cost, and the transportation time between LEO and LLO.

This paper covers a conceptual space transportation solution named Moon On-Orbit Nexus Providing Orbital Rendezvous and Transportation (MOONPORT), and dissects its feasibility, from a financial, engineering and legal perspective. Section 2 describes the business model, the Concept of Operations (ConOps), and the market research, and then proposes a business case for a commercially viable space transport solution. Section 3 discusses the selected propulsion system, the orbit transfers, and the spacecraft concept design. Section 4 examines the legal barriers to entry into the space transportation market, including topics such as insurance, end-of-life procedures, and liability.

2 Market Analysis and Opportunities

2.1 Identification of the Problem

Access to cislunar space is extremely limited. At the time of writing, the primary mode of entry into cislunar space is by way of a dedicated launch provider, and then traveling from the launch site to the desired orbit aboard the same vehicle. The number of launch providers capable of such a transfer is also somewhat limited. Currently, only a few rockets exist which can achieve translunar injection (TLI) for a significant payload mass. The development of cislunar space, with multiple separate companies, faces a large economic hurdle primarily due to the lack of ride-share opportunities on a rocket performing a TLI burn.

With programs such as Artemis scheduled to run their course over the next decade [1], cislunar space is becoming a central focus for the future of space development. However, due to these barriers to entry, it is challenging for cost-effective solutions to be developed to support cislunar activities. Creating an alternative transportation solution will enable economic savings for both governmental and commercial ventures, expanding the possibilities, and increasing the rate of development of cislunar space. In view of this, our mission is to provide commercially viable access to cislunar space, to enable the development of lunar infrastructure and the accompanying maturing economy. In particular, this project aims to meet the conditions set out in the NASA Commercial Lunar Payload Services (CLPS) contracts, which focus on regular large-scale cargo transportation within cislunar space [2].

2.2 Market Landscape

At the outset, the projected market for large-sized cargo requiring transportation to cislunar space was surveyed. Whilst there is an increasing interest in smaller missions, such as CubeSats and small rovers, a key finding was that a majority of payloads destined for lunar orbit or landing have masses between 2,000kg and 8,000kg. This includes logistics resupply services for the Lunar Gateway (a lunar space station within NASA's Artemis program) [3], transportation of modules to expand the station, as well as modules for vehicles and equipment landing on the lunar surface. The Lunar Gateway acts as a multi-purpose orbital outpost to provide support for sustainable, long-term crewed missions to the lunar surface. NASA budgeted €666M for the development of the Lunar Gateway in fiscal years 2019 and 2020, and there is expected to be at least another €2.3B over the next five years. In 2020, NASA and the European Space Agency (ESA) formalized an Artemis Gateway Partnership, in which ESA will contribute habitation and

[1] https://www.nasa.gov/specials/artemis/
[2] http://www.nasa.gov/content/commercial-lunar-payload-services-overview
[3] http://www.nasa.gov/gateway/overview

service modules [4]. Other international partners have also committed themselves in support of the Lunar Gateway, such as the Japan Aerospace Exploration Agency (JAXA) for logistics and experiments, and the Canadian Space Agency (CSA) for Canadarm3 [5]. One of the key elements of the Lunar Gateway includes the logistics capabilities for the delivery of critical cargo, experiments, and other supplies to the lunar station. These missions, called the Gateway Logistics Services (GLS), will be fulfilled by commercial companies, the first contract for which was awarded to SpaceX in 2020 [6]. SpaceX will deliver up to 5,000kg of cargo using its Dragon XL spacecraft, with the first two deliveries expected in 2024 and 2026. NASA published a solicitation in 2019 to procure fixed-price contracts valued at €6B in total, over a fifteen-year period [7]. Spread across 15 years, this indicates a potential market size of approximately €398M per year for lunar deliveries under the GLS program. This solicitation also discussed requirements for resupply spacecraft to deliver at least 4,400kg of pressurized and unpressurized cargo to and from the Lunar Gateway on each flight. This comprises part of the target market that MOONPORT aims to address.

Human Landing Systems (HLS) modules will also need delivery capabilities to lunar orbit and the lunar surface in the coming years. NASA has detailed that at least 1,595kg will be delivered from the Lunar Gateway to the lunar surface. Several commercial companies have unveiled lunar lander designs ranging from Blue Origin's 15 metric ton Blue Moon lander [8] to Lockheed Martin's 62 metric ton lander [9]. The market opportunity for the transportation of landers of this scale to the Moon is beyond the scope of this project, and consequently the focus will be restricted to only include payloads of up to 8,000kg.

[4] http://www.nasa.gov/press-release/nasa-european-space-agency-formalize-artemis-gateway-partnership
[5] http://www.nasa.gov/gateway/international-partners
[6] http://www.nasa.gov/press-release/nasa-awards-artemis-contract-for-gateway-logistics-services
[7] https://spacenews.com/nasa-to-buy-rides-on-commercial-landers-by-years-end
[8] https://www.space.com/blue-origin-blue-moon-lander-explained.html
[9] https://spacenews.com/lockheed-martin-unveils-lunar-lander-concept/

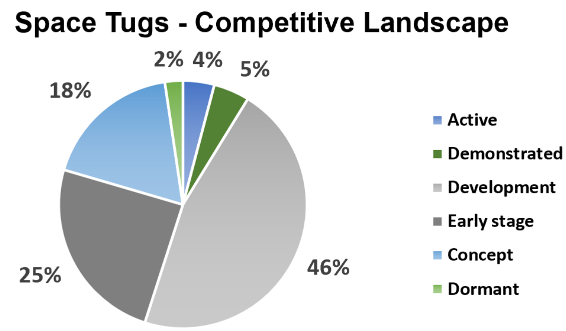

Fig. 1: Space Tugs: Competitive Landscape

2.3 *Space Tugs Competition*

The following section reviews the space tug competitive landscape. In total, 171 commercial companies are building a business which focuses on space transportation solutions. This excludes launchers and companies focused on propulsion technologies [10]. Most Earth to LEO transportation services focus on new concepts for transportation rather than launch vehicle development, while LEO to Moon transportation services include both services and transportation spacecraft design. While most of the projects are in development, there are several in the active stage. Twenty one companies in total are involved in tug development, however 6 of these are currently in the dormant state. Nineteen companies provide in-space logistics. In some cases the product differs from solo tug manufacturing, and instead, provides turnkey solutions for customer payload delivery to orbit.

Referring to Fig. 1, out of the selected projects, 18% are in the active stage, providing the services and technologies related to space transportation. Only 5% of projects have demonstrated the technology in space, while the majority are still in development or early stage.

MOONPORT stands in competition with multiple market solutions but can address specific market segments. Starting with direct space tug competition, most of these vehicles have not yet flown and are primarily advertising LEO services [11]. Considering the

[10] https://www.factoriesinspace.com/transport-services
[11] https://www.forbes.com/sites/frederickdaso/2020/01/07/epic-aerospace-a-y-combinator- space-startup-is-building-a-satellite-transportation-network/?sh=618ed5262090

Table 1: Design assumptions made in the development of the MOONPORT solution

MOONPORT - Assumptions		
Mission Element	**Design Assumption**	**Value**
Launch Costs	Launch cost to LEO	€2,314/kg
	Launch cost to LLO	€9,591/kg
Tug Design	Dry Mass	1,169.1kg
	Tug lifetime	3 years
	Cost - Cost of Operation	€1,000,000
	Cost - Assembly Cost	€10,000,000
	LEO to TLI Δv	3,208m/s
	TLI to LLO Δv	975m/s
	LLO to LEO Δv	4,100m/s
	I_{sp} - Chemical Engine	322s
	I_{sp} - Electrical Engine	3060s
Refueling Station Design	Number of refueling missions	3
	Cost - Cost of Operation	€1,000,000
	Cost - Assembly Cost	€10,000,000
	Dry Mass	200kg
	Propellant for own use - Electrical	50kg

mature launch market, it is foreseen that medium and heavy launchers could be considered competition to LLO. The current lowest bound for transferring a payload from LEO to Geostationary Orbit (GEO) is set by SpaceX's Falcon Heavy rocket, when fully expendable. Here, the price difference when transporting a payload of 20,000kg from LEO to GEO is approximately €2,314 versus €9,591 per kilogram [12]. Since the Δv for transfer from LEO to GEO is similar to the Δv for transfer from LEO to LLO, this price will be used as a reference for comparison with the MOONPORT solution. However, the services of MOONPORT differ from launch providers and therefore this €7,273 per kilogram difference should not be taken as a hard requirement, but rather as a benchmark figure.

2.3.1 Financial aspects

MOONPORT's value stems from its ability to service multiple customers across a number of separate missions. By using estimates based on the Δv required for transfers using chemical-electric propulsion and the latest prices available for delivery to both LEO and LLO, a solution capable of beating the current price by a significant margin was proposed. Modelling a viable solution required some assumptions, which can be found in Table 1. For more information on these values, see Section 3.

Based on these assumptions, a variety of metrics were generated for the MOONPORT solution. The calculated values can be found in Table 2. The most noteworthy value in this table is the cost from the ground to LLO, which sits at a value of €8,054/kg and is achieved by using the MOONPORT solution in conjunction with a SpaceX Falcon 9 launch vehicle. This is a significant improvement on the current price of approximately €9,591/kg. Note that MOONPORT also remains the optimal choice for payloads as small as 3,241kg, at which point the cost of direct launch approximately equals the cost of using MOONPORT.

2.4 Business Strategy

A variety of analytical methods were used to develop a working business strategy for MOONPORT. This section details the results.

2.4.1 ConOps

Fig. 2 visually describes the ConOps. To commence, a tug will launch into an appropriate parking orbit. This orbit is where the tug will wait between missions, and where it can easily be refuelled via a launch from Earth. When ready, the customer payload will then launch aboard a separate launch vehicle to LEO, at which point the tug will

[12] https://www.spacex.com/media/Capabilities&Services.pdf

Table 2: Calculated values as part of the MOONPORT solution

MOONPORT - Calculated Values		
Mission Element	**Design Element**	**Value**
Tug Design	Propellant storage capacity - Chemical	17,019kg
	Propellant storage capacity - Electrical	480kg
	Minimum viable payload	3,204kg
	Maximum viable payload	8,000kg
	Tug Launch Cost	€61,710,246.53
	Wet mass without payload	**18,668kg**
Refueling Station Design	Propellant for refueling tug - Chemical	51,057kg
	Propellant for refueling tug - Electrical	1,440kg
	Refueling station Launch Cost	€122,057,347
	Wet mass	**52,747kg**
Cost of using MOONPORT from ground to LLO		**€8,169**
Total mission cost		€562,172,013
Maximum Mission Profit		**€194,883,987**

rendezvous using its electric engines. Due to the payload having a lower mass than the tug, it is more economical if the payload performs the final docking manoeuvres. The tug will then use its chemical engines to conduct a TLI burn, before the electric engines slow down at the Moon into LLO and the payload is deployed into its desired orbit. Finally, the electric engines are then used to return the tug back to its parking orbit, where it can be refuelled ahead of the next mission. There are a number of options for safe disposal of the tug once it reaches the end of its operational life. These will be mentioned in Section 4.

2.4.2 Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis

Some launch vehicles already have the capability for payload transfer to cislunar space, and there have also been numerous attempts at designing a space transportation solution (for more information on competition, see Section 2.3). In this section, the distinction between MOONPORT and other solutions is highlighted using a SWOT analysis.

- **Strengths**
  MOONPORT has a variety of advantages over competitors. Firstly, MOONPORT offers a low-cost alternative to the use of a launch vehicle. This is primarily due to its re-usability across multiple missions. Secondly, MOONPORT allows for payloads to rapidly traverse the Van Allen radiation belt, preventing excessive degradation of the payload's systems before use, due to radiation exposure. Finally, by removing the need for a transfer stage to be launched on the same rocket as the payload, the client has an overall lower mass required to launch to LEO. This allows for the use of a variety of other launchers that would otherwise be unable to carry a payload destined for cislunar space, thus increasing the client's flexibility in choice of launch provider.

- **Weaknesses**
  MOONPORT has a higher complexity compared to the use of a launch vehicle or a tug with just one type of engine. This will increase the risks of component and manoeuvre failures, which will require the development of mitigation strategies. In addition to this, no multi-use tug has been employed in space at the time of writing, and therefore there are some major hurdles that need to be overcome before operations begin. Thus, a number of missions will need to be planned to demonstrate key features of the final solution, such as rendezvous and docking, refueling, and cislunar navigation.

- **Opportunities**
  MOONPORT would be developed at the ideal time to capture the growing cislunar market. The Artemis program has a number of missions that will require the use of a transport solution in the mass

category in which MOONPORT is situated, and NASA is awarding CLPS contracts to encourage the development of solutions.

- **Threats**
  The primary risk is that MOONPORT may not be financially viable, either at first launch or at another point during operations. There are a variety of possible causes for this, such as launch providers lowering costs faster than MOONPORT, the cislunar market not developing according to the forecasts, or other unforeseen changes that cause either development and operating costs to spike or competing prices to shrink. In all cases, once not financially viable, MOONPORT would no longer be a working solution. The solution could also never reach fruition if research and development does not run smoothly and cheaply. Many features of MOONPORT are complex and underdeveloped, and resources will therefore need to be committed to encourage our customers to use what may be seen as unproven technology.

2.5 Strategic Roadmap

There are a number of steps which need to be taken, regarding both technological and financial development. Fig. 3 shows one possible route for MOONPORT to be realised, with Year 1 representing the first year that MOONPORT receives funding. Note that all dates are to be used as a rough guide only.

3 Conceptual Spacecraft Design

The key drivers for the engineering design of MOONPORT were re-usability, rapid transfer and low development cost. To reach the envisioned cost-effectiveness, proven technologies and Commercial Off-the-Shelf (COTS) components were selected. Furthermore, to achieve an acceptable mission timeline, a combination of chemical and electric propulsion was chosen to reduce the time spent through the Van Allen belts and to reduce the total launch cost. This section presents the engineering solution for a concept design. The implications of a slow transfer maneuver across the Van Allen belts are discussed further in Section 3.7.

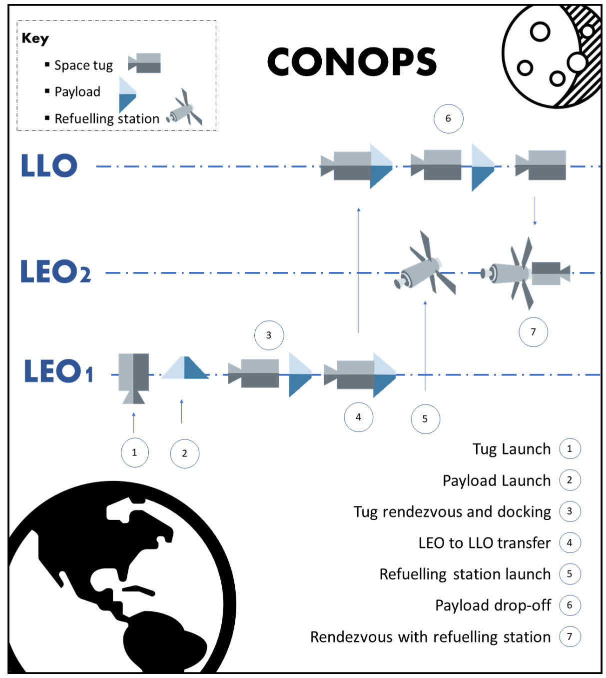

Fig. 2: Concept of Operations (ConOps)

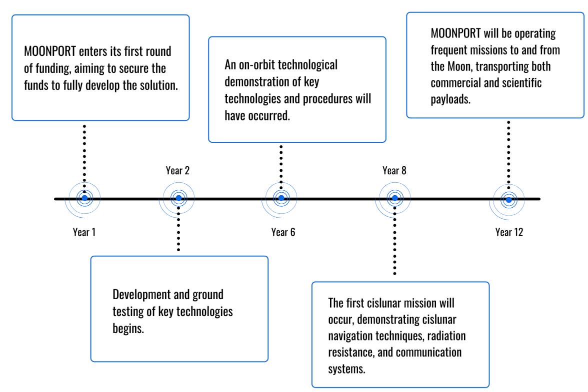

Fig. 3: Strategic roadmap

3.1 System Requirements

The European Cooperation for Space Standardization (ECSS) were followed to define the system requirements. In addition, a third-party launcher was selected based on the mission budget presented in the previous section. In this conceptual design both the tug and the payload are

launched from French Guyana because the latitude of 5.16° coincides with the inclination of the Moon's orbit, thus no propellant-expensive plane change needs to be performed. The high level functional requirements are reported in Table 3, where *M* is a must-have (shall) requirement and *NH* is a nice-to-have (should) requirement.
An overview of the system architecture in its phases between LEO and lunar orbit is shown in Fig. 4. The deployment of both the tug and the customer payload is done in LEO, followed by a rendezvous and docking of the two assets. A refueling station in LEO would allow for refueling of the tug. Separation of the payload from the tug is done in LLO, where the payload becomes fully operative.

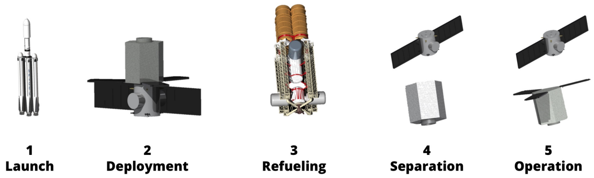

Fig. 4: Conceptual transportation system

3.2 Orbital Transfer

To further reduce the cost and propellant consumption compared to a traditional orbital transfer, a temporary ballistic capture (or weak capture) is often exploited. This concept is defined on the framework of an n-body problem and it exploits the dynamics of the solar system more efficiently [6]. Transfer costs can be saved by using such low-energy transfers, where the Δv required for ballistic capture is reduced [7]. As the capture is temporary, a final maneuver is performed to achieve a stable orbit. Although Weak Stability Boundary (WSB) trajectories do not yield significant improvements for transfers from LEO to upper Earth orbits, from GEO onwards, the use of WSBs can deliver up to a 30% reduction in Δv and over a 60% increase in payload capacity [1]. A low-energy orbital transfer was selected, as WSB transfer to the Moon can be launched without a time or date constraint within the Ariane 5 dual-launch window. Moreover, several final orbit injection options are available after ballistic capture. Successful missions based on gravitational capture include Hiten (JAXA), SMART-1 (ESA), GRAIL (NASA), and BepiColombo (ESA). To improve the performance of low-energy transfers without increasing the transfer time using a low-thrust engine (i.e. electric), a hybrid propulsion transfer based on chemical and electrical thrusters is suggested by Mingotti et al. [7].

The solution proposed for MOONPORT firstly considers a Hohmann transfer from LEO to High Earth Orbit (HEO) to cross the Van Allen belts as quickly as possible, followed by a WSB transfer to LLO with a duration of 90 to 120 days (WSB data taken from [7]). The critical point of this concept is the slow crossing time through the Van Allen belts when the tug re-enters LEO from LLO. Radiation mitigation strategies are suggested in Section 3.7.

The orbital transfers proposed for MOONPORT are as follows:

1. LEO_1 parking orbit (compare Fig. 2): 167 km [7], inclination 5.16°, circular orbit. Rendezvous and docking of tug and payload occur here.
2. LEO_1 to HEO transfer orbit: Highly elliptical with 260 km perigee and 60,000 km apogee. Additional minor plane change at apogee from 5.16° to 5.145° (Moon inclination). The change of plane requires a budget of Δv = 3,143 m/s + 65 m/s. After the change in plane, the orbit is not circularized but the electrical propulsion system is initiated to reach LLO.
3. HEO to LLO via WSB: This phase uses an electrical propulsion system. A final Δv = 975 m/s is required for capture and circularization burns.
4. LLO drop-off orbit: 50 km, circular orbit [7].
5. LLO to LEO_2 (compare Fig. 2): A Δv = 4,100 m/s was estimated for the electrical propulsion system to reach LEO. Continuous thrust is required to reach LEO using WSB with a transit time of about 4 months. The spacecraft will be refueled in LEO and the solar panel will be inspected and maintained before docking with the new payload.
6. LEO_2 parking orbit for refueling station: 1,200 km, circular orbit. This orbit is chosen for the refueling

Table 3: High level functional requirements for MOONPORT

ID	Importance	Requirement	Parent Req.
MP-F-010	M	The spacecraft shall be able to travel to LEO-LLO and vice versa	
MP-F-011	M	The spacecraft shall be able to operate in cislunar environment	MP-F-010
MP-F-012	M	The spacecraft shall be reusable	MP-F-010
MP-F-013	M	The spacecraft shall be refuelable	MP-F-010
MP-F-020	M	The spacecraft shall be operational by 2030	
MP-F-030	NH	The spacecraft should have at least TRL = 5	MP-F-020
MP-F-031	M	The spacecraft shall withstand the launch loads and vibrations	MP-F-030
MP-F-032	M	The spacecraft shall be able to interface the launcher through a COTS adapter	MP-F-030
MP-F-040	M	The spacecraft shall be able to deploy a payload of 8 tons in LLO	

station for safety reasons, as LEO is less congested starting from 1,000 km. Electronic shielding against proton charge is required because LEO_2 is located in the first Van Allen belt. The tug is refuelled in LEO_2 before moving to LEO_1 to dock with the next payload.

The Δv values per orbital transfer are summarized in Table 4. A similar WSB trajectory is illustrated in Fig. 5, which was designed in the context of a nuclear-thermal tug for lunar cargo transfer in [1].

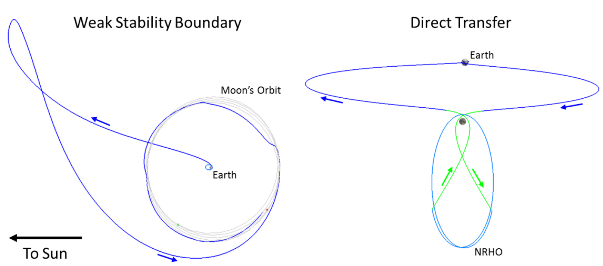

Fig. 5: Example of WSB trajectory for lunar transfer [1]

In the next paragraphs, LEO_1 will be identified as LEO to simplify the writing, unless otherwise stated. For these preliminary calculations a 5% Δv margin was applied for transfer from LEO to HEO due to the conventional Hohmann maneuver and ease of localization. However, a 10% margin was applied to the HEO to LLO transfer because of the complex WSB trajectory and, since the system is outside Global Navigation Satellite System (GNSS) radius, absolute navigation errors will contribute to the uncertainty in orbit determination. Finally, a 15% margin was applied to the foreseen plane changes, to account for further propellant expenditures involved in rendezvous and docking. Free return scenarios were excluded from this analysis to spare as much propellant as possible for the customer payload, which would have to perform the lunar capture manoeuvre on its own. Also, the use of a lunar swingby at departure from LLO would require a dedicated launch strategy, in contrast to the shared launch strategy selected. The expected lifetime of the tug for this configuration is 3 years. A total of 3 refueling missions can be conducted in LEO.

Table 4: Δv budget per orbital transfer

Phase	Margin	Δv [m/s]	Propulsion
LEO-HEO	5%	3,208	Chemical
HEO-LLO	10%	975	Electrical
LLO-LEO	10%	4,100	Electrical
Plane Change	15%	80	Chemical
Total		**8,363**	

3.3 Propulsion System

The choice of the monopropellant for the chemical propulsion system usually defaults to hydrazine due to the maturity of the technology, the low complexity of the propulsion system, and the ease of refueling. Nevertheless, the engine design shall be compliant with alternative greener propellants in the long term, to contribute to sustainable operation (water-based and In-Situ Resources Utilization (ISRU) propellants). Alternative in-space propulsion technologies have been investigated to replace hydrazine [8], but most of the TRLs still range between 5 and 7. As a consequence, MOONPORT proposes the use of the hydrazine-based TR-308 Dual Mode Liquid Apogee rocket engine from Northrop Grumman, which has a TRL = 9. This engine provides an I_{sp} of 322 s and thrust of about 500 N. A total of 3 units would achieve the thrust required for the Hohmann transfer in the first segment, which was estimated at around 1.5kN for the chemical burn performed in LEO.

Electric propulsion is used both to inject the spacecraft into LLO and to return the tug to LEO for refueling. The higher transfer time due to the low-thrust burn is not considered a critical factor for the targeted customer segment, which is formed by payloads unrelated to defense activities. The selected electric engine is the BHT-8000 Hall-effect thruster manufactured by Busek Co, which uses Krypton as the gas of choice, because of its lower cost when compared to Xenon. The main reason behind this decision was the high thrust, which would maximize the number of transfers performed within the operational life of the other electronics. However, the Hall thruster requires 8 kW of power. The maximum I_{sp} achievable for the same engine is 3,060 s with a thrust of 0.5 N. Pulsed plasma thrusters and magnetohydrodynamic thrusters were also considered to further reduce the transfer time, however most of such devices have TRL < 7, and therefore are not considered for MOONPORT.

The main energy storage unit is dedicated for powering the two propulsion systems, and the avionics equipment is powered by the secondary power unit. This allows for complete shut down of all avionics during the return trip, which thus prevents damage to these components during the crossing of the Van Allen belts, while the electric engines is still operative.

3.4 Rendezvous and Docking

A separate section is dedicated to the rendezvous and docking procedures, since there are very few companies that have successfully demonstrated this for commercial operations. In general, structural simplicity is prioritized for the docking mechanisms, avoiding the use of robotic arms to reduce the inertial perturbations and computational complexity. The Rapidly Attachable Fluid Transfer Interface (RAFTI) developed by Orbit Fab can be used for MOONPORT to support rendezvous and docking as well as refueling operations. It consists of a single docking port and allows for six degrees of freedom localization based on a single image. Visual approach by docking is performed based on the input of monocular cameras, using deterministic and low-computation filtering techniques. The distance to the docking port is determined based on the reference area of known infrared markers, and validated with laser rangefinders.

Robust algorithms for rendezvous and docking must be designed to minimize the effects of measurement uncertainty because of sensor degradation while crossing the radiation belts. Artificial neural networks and learning-based approaches are currently excluded as viable options, because they are neither easily certifiable nor stable. Anticipating the legal implications discussed in Section 4, it is cheaper to provide insurance for the customer if certified technologies are used. Instead, a Model Predictive Control approach based on visual feedback is used for closed-loop guidance, and the trajectory is passed to a Mu-synthesis controller optimized for soft contact. The accuracy achievable by such a system is estimated to be in the order of 0.02° rotational and sub-millimeter distance measurement [9].

3.5 Spacecraft Main Subsystems

To delineate an initial estimate of the mass budget of the spacecraft, the values are optimized for maximum energy storage and production. The use of electric propulsion helps to reduce the dry mass of the overall propulsion system and thus allows for the allocation of more mass for the Electrical Power System (EPS). It is often assumed that 70% of the total dry mass budget is taken up by the propulsion and EPS subsystems in a chemical space tug [10].

Since 62% of the Δv budget is covered by electric propulsion, the estimated dry mass budget for a fully chemical tug (40% propulsion) was scaled down accordingly, assuming that Krypton is three times more efficient to store than alternative chemical propellants, according to the dry mass ratio of a fully chemical and a fully electric propulsion system. This results in only 23% of the total dry mass taken up by the propellant tanks, piping and the engines themselves. The remainder, up to 70%, is allocated to the power system for enhanced production and storage capabilities. Table 5 reports the

Table 5: Spacecraft mass budget

Subsystem	Dry Mass Fraction	Mass [kg]
Propulsion	23%	279.7
Power	47%	536.9
Structures	15%	180
AOCS & OBDH	7%	77
Communications	1%	11.5
Thermal Control	4%	48
Harnesses	3%	36
Total + margin	**100%**	**1169.1**

estimated mass budget for all subsystems. AOCS and OBDH stands for Attitude and Orbit Control Systems and On-board Data Handling, respectively. The conceptual spacecraft, without a payload, is shown in Fig. 6.

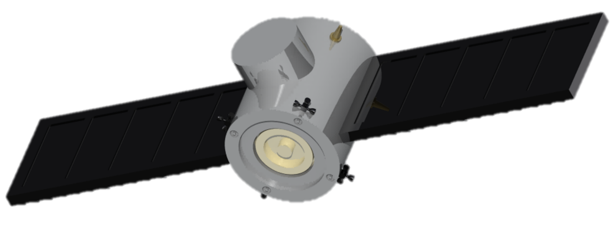

Fig. 6: Conceptual spacecraft design

The tug is six-axis stabilized and uses an accelerometer, GNSS and laser rangefinders for the translational degrees of freedom. Sun sensors, star trackers and gyroscopes are used for the rotational degrees of freedom, depending on the operational mode. Cameras are used for both distance and rotation measurements. Four control moment gyros are used for redundancy and increased precision, as well as eight clusters of hydrazine micro-thrusters for de-saturation and emergency manoeuvres. All actuators have to be placed strategically, in order to be at an effective distance from the centre of gravity, both when the tug is operating on its own, and with the payload attached. The controllers are gain-scheduled, based on whether the payload is docked or not, and on the strength of the local gravity field.

A central tube configuration consisting of monocoque skin with stiffeners was selected to reduce the weight of the main structure, while supporting the critical stresses along the main axis of inertia during docking and thrusting. The structure is built primarily with aluminium and carbon-fibre reinforced plastic, while the thrust frame for the main engines is reinforced with titanium. The Krypton tanks follow a conventional Composite Over-wrapped Pressure Vessel structure, consisting of a titanium liner, made from two welded domes, which are then over-wrapped with a graphite fiber-based composite, to which annealing of the welded liners is applied prior to composite wrapping [11]. Conversely, the hydrazine tanks are manufactured entirely out of titanium alloys such as Ti6AlV because of the lower manufacturing cost and lower pressurization requirements.

3.6 Power System

This section describes the power requirements and resulting power budget for the mission. The following subsystems have been considered for the power budget: EPS, Communication and Data Handling (CDH), Telemetry Tracking and Command (TT&C), Thermal Control, AOCS and propulsion subsystem. The resulting power budget is shown in Table 6.

Table 6: Power budget

Consumer	Power [W]
EPS	151.20
CDH	234.60
TT&C	25.70
Thermal Control	158.76
AOCS	339.15
Propulsion (Electrical)	7,896.00

For the calculation of the power budget, three modes where considered. In the Standby mode, the TT&C is on 10% duty cycle and the propulsion unit is off. In the Downlink mode the TT&C is on 100% duty cycle and the propulsion unit is off. In the Maneuver mode the TT&C is on 10% duty cycle and the propulsion unit is 100% on. The average power consumption, power generation for each mode, along with the depth of discharge after shadowing are listed in Table 7. DoD stands for Depth of Discharge.

The final design results in a battery pack with energy of 70.56 kW and a total solar panel area of 27 m^2 divided over 4 panels.

Table 7: Power modes used to calculate power budget

	Standby	Downlink	Maneuver
Average Power Consumption [W]	1,000.09	1,254.56	9,685.69
Average Power Generation [W]	9,223.20	9,223.20	9,223.20
DoD after shadowing	-1.88%	-2.35%	-18.16%

3.7 Van Allen Belts

The radiation environment in the Van Allen belts causes higher damage to the power systems in low-thrust transfers. For instance, the amount of radiation that a spacecraft receives with the pure electrical ascension of 200 days is equivalent to an exposure of 6.7 years in GEO. Given that a satellite's lifespan is circa 15 years, this means that exposure through the belts cuts the operational lifespan of a satellite in half [12]. In the context of MOONPORT, the return transfer to the Earth causes the spacecraft to experience higher radiation exposure, as transit through the Van Allen belts is slower.

Two Van Allen radiation belts are located in Earth's orbit. The inner belt consists of mainly protons from an altitude of 1,000 to 8,000 km, with a peak particle density at around 3,000 km [13]. The outer belt consists mainly of protons and electrons and extends between 12,000 and 25,000 km with a peak at around 17,000 km. Radiation in this second belt is lower compared to the first. The orbit inclination is crucial in terms of radiation absorption, and lower inclination orbits are less exposed compared to high inclination ones. A low inclination orbit is used in MOONPORT.

Several techniques have been proposed and implemented to countermeasure such high radiation exposure. Shielding the most critical electronic instruments from protons and heavy ions is the most used option. Critical components include the Inertial Measurement Unit (IMU), on-board computers, sensors, and other critical subsystems. Usually aluminum panels of 3 mm thickness are used for this purpose, increasing the total mass of the spacecraft. However, high-energy particles such as protons can still pass through the shield [13]. Folding the solar panels to reduce the exposure to the high-energy particles would lead to a similar outcome. Innovative solutions consider gallium nitride and zinc oxide as building materials for electronic components [14]. Such materials work as standard semiconductors but with much stronger bonds, showing the potential for self-healing when hit by highly charged particles. MOONPORT identifies these innovative materials as possible solutions for radiation mitigation.

4 Legal Implications

From a policy and legal perspective, the project does not present any insurmountable challenges or particularly controversial aspects. However, in light of the commercial nature of the undertaking as well as the technological novelty of the proposed service, there are a number of legal issues that need to be dealt with at the level of international and national law, as well as concerns regarding the contractual relations with potential customers.

International space law is a set of treaties and recommendations developed under the auspices of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) to regulate space activities. The most important document is the Outer Space Treaty (OST). Although such treaties are directly binding only for States and not for private entities, the rules thereby established are indirectly relevant for the project, as States parties have the obligation to ensure their compliance by all the non-governmental entities under their jurisdiction. To ensure that national space activities are conducted in compliance with international law, several States have adopted ad-hoc regulatory frameworks commonly known as national space legislations [15]. Their purpose is to provide legal certainty to private space operators and implement policy choices for the development of a national space industry [16]. For the applicability of MOONPORT we recommend full compliance with applicable national space law. Lack of compliance would cause reputational damage, financial sanctions, and in the worst case the denial or withdrawal of the operator's license.

Disposal and de-orbiting procedures applied when reaching the end-of-life of a space asset are not fully clarified by the legal framework. In fact, the issue of space debris is not specifically addressed by space treaties. However, several non-binding documents have been developed in order to ensure the long-term sustainability of space activities. Among these, it is relevant to mention the 2002 Space Debris Mitigation Guidelines approved by the IADC (IADC guidelines) and revised in September 2007, and the 2007 Space Debris Mitigation Guidelines of UNCOPUOS (UNCOPUOS guidelines) endorsed in Resolution A/RES/62/217 by the General Assembly of the United Nations. These guidelines are not mandatory but rather based upon voluntary adherence by States, and address mission planning and the construction of a satellite or orbital vehicle [17]. It is recommended that the technical design, operation and disposal of MOONPORT's spacecraft complies with the applicable guidelines as implemented in the relevant jurisdiction.

The business case foreseen for MOONPORT could potentially involve several co-operating States. The ratification of the space treaties by the involved States Parties would regulate important aspects such as responsibility, licensing, authorization and liability for the space assets. For instance, Article VI of the OST states that States Parties are responsible for national activities in outer space on an international level. The activities of non-governmental entities in outer space shall require authorization and continuing supervision by the appropriate State. As a consequence, several States have established a domestic licensing system for the space activities carried out under their responsibility. Private entities under their jurisdiction must apply to the competent national authority to obtain a license before commencing any space operation. The main purpose of these authorizations is to ensure the safety of the population, to minimize possible risks, and to avoid interference with other space activities. As a rule, the conditions imposed for the release of a license are related to the consistency with the international obligations of the State, the United Nations treaties, and other relevant directives [18].

Referring to the ConOps presented in Section 2.4.1, MOONPORT requires some legal clarifications for the rendezvous and docking operations. In fact, it is important to identify the liable State Party in case of collision between two spacecrafts while performing rendezvous and docking. As a consequence, liability and insurance are two important aspects to be considered within MOONPORT's activities. Although liability is covered briefly by Article VII of the OST, third-party liability for damage caused by private space actors is taken on by States under the Space Liability Convention (LIAB) and passed on to the former under the applicable national space laws [19]. These laws normally establish an express right of redress of the government against the negligent private entity, however limiting it by statutory or discretionary caps on liability. Above such caps, the operator is no longer liable and the State assumes the guarantee.

Space insurance is unique and represents a very small part of the insurance market. However, it is essential for the smooth running of space activities. There are two types of insurance in the space industry, the first one is for property damage and the second one is for civil liability, also referred to as third-party liability. The latter concerns the prejudices caused to others, and it is the most relevant in light of the activity performed by MOONPORT. This is a compulsory insurance against third-party risks, which is usually a requirement to get the space access licensed. This provision has the dual function of granting a full and immediate compensation to the victims, and guaranteeing the restoration of the State in the event that it has been held liable under the space treaties [20]. The minimum insurance coverage required is commonly related to a fixed amount or to the ceilings on liability. Whereas manned missions are not insurable because of the high risk related to the human presence, for non-human activities it is possible to insure the pre-launch phases as well as the launch and life in orbit of the spacecraft. The insurer must consider the technical concepts of the mission and make a detailed risk analysis in order to consider all the solutions [21]. Third-party insurance is a common requirement attached to the national licensing of space activities. We recommend the incorporation of a State that offers advantageous regulatory conditions for the performance of MOONPORT's activities. Elements such as the length and complexity of the authorization process, the conditions attached to the license, the caps on liability, the mandatory insurance requirements, as well as the general attitude of the regulator towards space business should be taken into account.

A final aspect investigated in this work is related to the frequency allocation. Safe and efficient communications are a key component of the business. It is therefore necessary to clarify the regulatory conditions for the establishment and operation of communication uplink and downlink between the ground control station and the spacecraft Telemetry, Tracking, and Command (TT&C) subsystem. In the context of MOONPORT, the TT&C link should cover great distances for a long period of time and should be highly reliable. For this reason, it has unique technical requirements that affect the selection of the bandwidth, the conditions for band sharing, coordination, protection from interference, and other regulatory and frequency management matters [22]. The use of the radio spectrum is regulated at an international level by an international treaty called the Radio Regulations, and is supervised by the International Telecommunication Union (ITU). When planning and implementing the TT&C link, it is recommended that its fully compliance with the technical provisions of the Radio Regulations is ensured, so that the service does not cause and does not suffer harmful interference from other space radio services using neighboring frequency bands. A specific challenge is that currently, there are no frequency bands specifically allocated to commercial space missions by ITU. The only category of service recognized by the Radio Regulation that would suit the technical needs of the project is the "Space Research Service (SRS)", currently used by the international space scientific community. However, the use of this allocation for MOONPORT is hindered by two obstacles. Firstly, there may be friction with the definition and original purpose of such allocations, which appears to exclude commercial use. The Radio Regulations define SRS as "a radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes" (RR 1.55). The second obstacle is the spectrum actually allocated to the space research service (approximately 500 MHz), which is already currently considered insufficient for the future increase of space research missions by space agencies [23]. It is therefore recommended that a proactive approach is taken, by pushing for the adoption of a suitable regulatory solution, such as negotiating new spectrum allocations for the SRS in the short term, and creating new categories of space communication services for commercial use over the long term.

5 Conclusions

This research tackled several challenges and offered a solution for on-orbit mobility and manipulation in space. Extensive research and analysis allowed for the inclusion of the anticipated market demand into the MOONPORT solution. A significant market opportunity for this cislunar transportation service was identified, primarily for cargo and potentially future crewed missions. The market and opportunities analysis discovered multiple emerging opportunities to deliver customers from LEO to LLO through more cost-effective means than those that are currently available in the space transportation marketplace. Additionally, the competitive landscape analysis reviewed various approaches that current in-space transportation companies offer and has concluded that there is a gap in the existing market for which MOONPORT can provide a solution.

The technology analysis surveyed the currently operational and advanced propulsion concepts that met the needs of the MOONPORT in-space transportation solution. Rendezvous and capture techniques and the associated technologies were also assessed to evaluate the ideal approach to capture multiple customer spacecraft with the same vehicle. The selected chemical-electric propulsion system included a cluster of TR-308 Dual Liquid Apogee rocket engines from Northrop Grumman for the chemical aspect, and BHT-8000 Hall thrusters from Busek Co. for the electric aspect. The use of chemical-electrical propulsion in this conceptual phase allowed for the optimization of the mass of the spacecraft, the time spent in the Van Allen belts, the launch cost, and transportation time between LEO and LLO.

Considering legal aspects, a possible expansion of the business was identified, as well as the possibility of providing services across the globe, launching from suitable countries which actively implement a national legal framework for space activities.

Future work aims to define a preliminary design of the spacecraft subsystems to show the feasibility of the project within the identified business case. The solution proposed by MOONPORT also provides a good framework to tackle the challenges of the NewSpace economy and may be an attractive business opportunity for emerging startup activities.

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Acronyms

AOCS Attitude and Orbit Control Systems

CDH Communication and Data Handling

CLPS Commercial Lunar Payload Services

ConOps Concept of Operations

COTS Commercial Off-the-Shelf

ECSS European Cooperation for Space Standardization

EPS Electrical Power System

ESA European Space Agency

GEO Geostationary Orbit

GLS Gateway Logistics Services

GNSS Global Navigation Satellite System

HEO High Earth Orbit

IADC Inter-Agency Space Debris Coordination Committee

ITU International Telecommunication Union

JAXA Japan Aerospace Exploration Agency

LEO Low Earth Orbit

LIAB Space Liability Convention

LLO Low Lunar Orbit

MOONPORT Moon On-Orbit Nexus Providing Orbital Rendezvous and Transportation

NASA National Aeronautics and Space Administration

OBDH On-board Data Handling

OST Outer Space Treaty

SRS Space Research Service

SWOT Strengths, Weaknesses, Opportunities, and Threats

TLI Translunar Injection

TRL Technology Readiness Level

TT&C Telemetry, Tracking, and Command

UNCOPUOS United Nations Committee on the Peaceful Uses of Outer Space

WSB Weak Stability Boundary

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