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Repetitive-Use Rocket-Crane/Rover System (R3S) for Planetary Surface Missions

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This study proposes a concept for a Repetitive-Use Rocket-Crane/Rover System (R3S) for surface missions (e.g. geological or resource survey, infrastructure development) on the Moon. The system consists of a rocket crane module, that can perform multiple point-to-point take-offs and landings on the Moon's surface, and rovers that can sample multiple locations in a site, where the crane has landed. The rovers detach and attach themselves to the crane module repeatedly to be carried to the next site. A pre-existing detachable cargo pod concept for electrical vertical take-off and landing (eVTOL) logistics will be applied for the latching mechanism between the crane module and the rover. The early stage feasible use case is to search for H_2O-rich resources on the lunar surface: the combination of the crane and rover will allow a wide-area multi-site survey in a single mission, complementing each of their drawback. In addition to the focus on the initial Moon H_2O quest, this study will discuss the use expansion of the R3S in the context of sustainable lunar exploration, and towards Mars development in a broader timeline.

I. Nomenclature

g_e	=	Earth gravity acceleration: 9.806 m/s^2
g_m	=	lunar gravity acceleration: 1.625 m/s^2
h_{Apg}	=	apogee altitude (m)
ImLEO	=	initial mass in low-Earth orbit (kg)
I_{SP}	=	specific impulsion (s)
m	=	mass (kg)
n_{LX}	=	number of locations designed to be explored
T	=	thrust in vacuum (kN)
TtWR	=	thrust-to-weight ratio
V	=	velocity (m/s)

Subscripts

Crn	=	crane
CS	=	conventional lander-rover system
DS	=	deceleration stage
Eng	=	engines
Ldr	=	lander

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Prop	=	propellant
R3S	=	R3S (Repetitive-Use Rocket-Crane/Rover System)
Rov	=	rover
Str	=	structure

II. Introduction

Exploring the Moon is considered to be one of the key next steps in space exploration. Indeed, the Moon holds valuable information about the development of the Solar System, is a potential site for astronomical observations, contains resources such as water and precious metals that could be used both on Earth and in space, and ultimately, could be a first extraterrestrial human base. Experience and data acquired on the Moon could furthermore be useful for the exploration of Mars and other bodies. However, exploring the Moon extensively relies on significant infrastructure over long durations. One of the first objectives on the Moon will be to find and extract water ice. The location of regions in which water might be found is only approximatively known, and its form and condition even less. [1]. Significant transport capacity to scout and drill for water will therefore be needed. A modular crane using a payload attach and release system for transporting instruments, rovers, infrastructure and resources could thus support the exploration of the Moon, as soon as the first reconnaissance missions, considering its high ground investigation capacity. In addition, multiple take-offs and landing (MTOL) systems could be a step in the directions of sustainable exploration of space. Previous attempts at providing an extraterrestrial reusable surface mobility system was the Lunar Flying Vehicle (LFV), which Bell Aerosystems designed for the Apollo missions [2], but this was discarded in favor of a rover allowing to effectively transport astronauts near the landing site. The main difference is the addition of the R3S modular feature. As the Bell's concept had human as its payload which can only be deployed on the surface for an extremely short length of time, and also requires to be recovered at any cost[*], the purpose and context will be vastly different from the concept shown in this study. In addition, a simple recovery design for the payload will be required if we assume there is no human intervention for the docking procedure.

In this paper, a space crane infrastructure concept based on the existing method for docking the PUPA™ repetitive payload attach system that is under development by Yamato will be described. Furthermore, the system's ability to investigate a terrain and its impact on mission design will be investigated. The expansion of possible use case of the R3S will be discussed regarding future timeline. First, the initial use case of this system will be discussed from a concept standpoint. Then, other possible use cases beyond that initial scenario will be discussed, regarding the thoughts of modularity and interfaces. This paper's objective is to highlight the potential of an interoperable and reusable transportation system in the context of space exploration.

III. Method

The mobility concept proposed in this paper is a crane for moving equipment such as rovers, resources, pieces of infrastructure, possibly even humans, from a point on the Moon to another, thus placing said resources at their respective use location at a given time. This crane is not defined in terms of size, mass or means of locomotion in our approach, but is essentially defined as being reusable, which is enabled by an adapted interface allowing to attach and detach any equipped payload.

For the crane module, concepts proposed in Reference [3] for Martian exploration will be redesigned and applied for this mission (Figure 1). While the original idea in the reference mentioned above is proposed for a timeline in which human activities are already performed on extraterrestrial bodies (on Mars in this case) and in-situ propellant production is available, the concept proposed in this study is for the nearer future. It is admitted that human activity is not yet established permanently on the Moon or Mars, and in-situ propellant production is not available. Furthermore, a certain level of interest from industry to move to the next stage, which includes further exploration of the Moon, is admitted.

The mechanism to load and unload the rover multiple times with both high reliability and limited energy supply will be one of the crucial elements of the concept proposed here. Yamato Holdings, Japan's largest parcel delivery provider, has developed a mechanism to attach and detach. PUPA™ (Pod Unit for Parcel Air-transportation) is a cargo pod to be used for future logistics service using electrical vertical take-off and landing (eVTOL) aircrafts [4]. The PUPA docking system (PDS) enables an easy and self-sustaining (i.e. does not require any ground support vehicle)

[*] The concepts proposed by Bell also included to be used as a lifeboat when the Ascent Stage of the Lunar Module fails and the astronauts loose the primary mean to return to the Command Module orbiting the Moon.

docking between the PUPA™ and the tail-sitter eVTOL aircraft (Bell APT70) with just horizontal motions (Figure 2). As the PUPA and PDS are being developed to have enough robustness on broad flight profiles, such as impact at landing, transition of flight direction between vertical and horizontal, side winds, gusts, and turbulence, so as to obtain high availability of the logistics service it is to be applied, it is expected to achieve certain level of system robustness as airworthiness that can be applied onto a heavy-use space craft with minimum modification in the near future (Figure 2)†. Applying this PDS into the R3S, the reloading mechanism could be simple enough to be used for multiple times on the Moon or Mars with low failure rate, which no existing space crafts have executed as their mission so far.

Figure 1 An illustration of a Martian Crane landing a crew module.

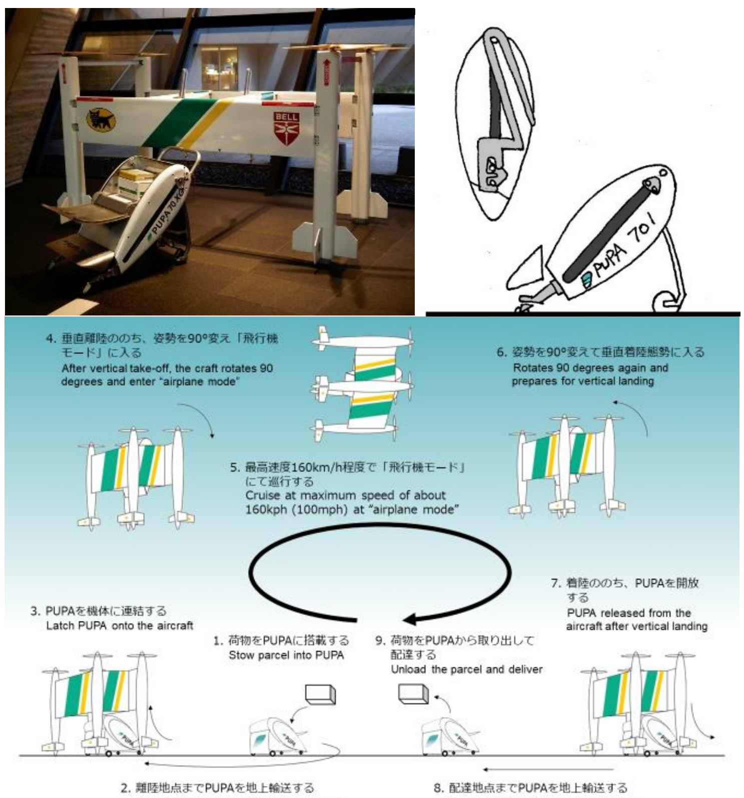

Figure 2 PUPA™ in front of Bell APT70 (above left), the illustration of PDS (above right), and mission profile of PUPA and Bell APT70 (bellow).

† Since the eVTOL aircraft PUPA is designed to be attached onto (Bell APT70) is an unmanned tail-sitter logistics aircraft, it is to be tilted for maximum 90 degrees together with the airframe in transition between VTOL mode and cruise (aircraft) mode. In addition, no passenger to aboard could make the aeromechanical system accept larger impact at landing.

Considering these concepts, the mission profile of the R3S will be defined. This study will also break the system into components regarding the constraints and gains unique to the idea. Once the system breakdown is completed, the variables that define the mass of each component the most will be discussed so as to construct a reference model that can shared between conventional lander + rover system and R3S. The function of approximation for the feasibility boundary between the conventional system and the R3S will be constructed as the main objective of this research (Figure 3).

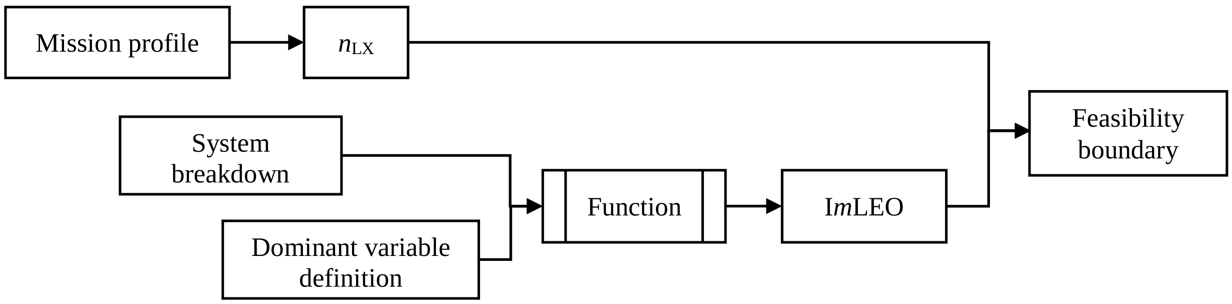

Figure 3 The structure of this study

A. Mission profile

The basic idea of sending a reusable a set of a rover and a rocket craft that can visit many locations (or, "make an excursion trip") on the surface of the Moon or Mars within its lifetime is that it could be more economical than sending rovers by use-and-discard cruise craft and lander for each mission. Therefore, the mission profile will be simply to be sent to the Moon or Mars, hop on the surface for certain times within its lifetime, and deploy and recover the rover as the crane conducts landing. Therefore, the gain of R3S per mission will be simply stated as n_{LX}, while that of the conventional lander-rover system is simply 1.

B. System breakdown

In this section, the R3S will be broken down into components so as to construct a reference model that will allow to used information from the conventional lander-rover configuration as a reference regarding the mass system, allowing to understand the potential of the R3S concept. First, the space craft can be roughly divided into 3 units: rover, crane/lander, and deceleration stage, while the last unit is special to R3S (Figure 4).

Since the fundamental configuration of the rover does not differ much whether or not to the rover is applied with PDS or not, despite the method to keep the rover onto the space craft is entirely different from the conventional "put-on" style. Hence, the mass of the rover will be assumed as the same between conventional system and R3S (see Appendix for the discussion on the PDS rover design that lead the conclusion here). For further discussion, we will use the mass for the rover as $m_{Rov} = 430$ [kg] referring the latest NASA's VIPER (Volatiles Investigating Polar Exploration Rover) concept [5].

As we refer the VIPER concept for the rover, we will also refer to its delivery system as a typical lander model. In June 2020, NASA has contracted with Astrobotic for the use of the company's Griffin lander to be used for delivery of the VIPER [6]. According to the company's website[‡], the Griffin lander is capable of performing trans-lunar injection, trajectory correction, lunar orbit insertion, and powered descent. The launch mass of the Griffin lander is not yet published as for the writing of this paper, and therefore will be calculated. From the understanding above, we will assume as follows, where m_{Ldr} is its wet mass at launch and will include the mass of propellant that will be consumed for cruise, lunar orbit insertion, descent, and landing.

$$\mathrm{I}m\mathrm{LEO}_{CS} = m_{Rov} + m_{Ldr} \tag{1}$$

Crane and lander share the feature as a space craft that will decelerate the system in the terminal phase of the landing and consume the impact by itself so as to protect the rover while at landing. The difference between these concepts is that the former will conduct landing and taking-off for multiple times, while the latter is only to land for once at arrival to the Moon. This will initially require propulsion module that can be used over time. In addition, the

[‡] https://www.astrobotic.com/griffin, retrived 14 November, 2020.

crane concept requires robustness on the structure (whose definition in this study to include both the structural frame and landing gears) and prevents the crane from adopting crushable shock absorbing mechanism, such as the one used on landing gears of the Apollo Lunar Module (LM) [7] .These requirement that originates in reusing the system could somewhat increase the m_{Str}/m_{Rov} rate if we are to assume that the force of impact of landing is the same.

On the contrary, the decent stage that is original for the R3S in lunar application could solve this problem in a different orientation. The initial landing on the Moon will be vastly different from the succeeding ones as the space craft has to decelerate from lunar orbiting velocity down to zero. This requires a deceleration engine module that is only required for this process, as one applied onto the conventional lander. Thus, the engine of the deceleration suits that of a conventional lander. What is different is that in R3S, we already have the structure needed to sustain the impact of landing on the crane. This means that if the space craft can be decelerated into the height and velocity where the lander should bare for the second-or-later flights, we can discard the deceleration stage there and leave the structure of the crane to bare the initial landing impact. In this sense, the deceleration stage can be omitted with landing gears, and its structure can be simplified down to the level that can only bare the continuous and relatively small negative acceleration during deceleration burn. At this low level of force, it could be also possible to sustain the acceleration stress largely by the pressure of the propellant tank. On the contrary, as the conventional lander still has to keep its shape even after landing in order to deploy the rover and maintain communication as a base, its structure is designed strong to sustain the entire spacecraft including the heavy deceleration engine unit. The idea of applying deceleration stage for R3S can also be summarized as a reverse multi-stage rocket. To make clear comparison with the Griffin lander, let us assume that the deceleration stage will also perform trans-lunar injection and lunar orbit insertion just like the cruise stage of the Luna 9 [8], despite it can be possible to split these performances for an additional cruise craft and separate before power decent. For clarification, the deceleration stage will not be included in the definition scope of the R3S: m_{R3S} does not include m_{DS}, and we will define:

$$m_{R3S} = m_{Rov} + m_{Str} + m_{Eng} + m_{Prop} \tag{2}$$

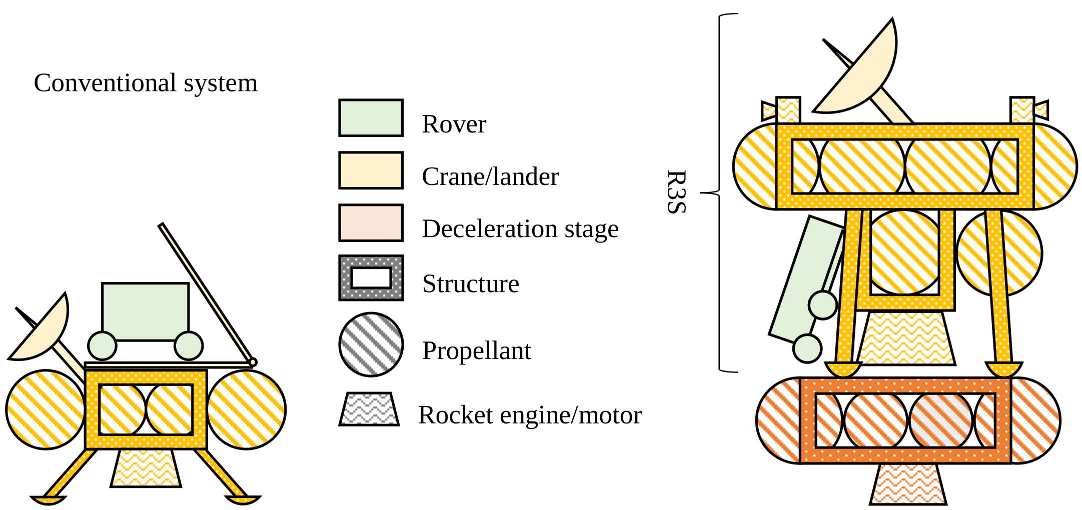

Figure 4 Reference model for conventional lander-rover system and R3S

C. Dominant variable

1. Propellant

The largest concern on whether the R3S is economical as intended or not comes from the simple fact that if we are to use the crane over times, the crane has to carry propellant it will consume for its entire life expectancy. Regarding this issue, we will construct a simple numerical model to state the mass system related to the number of flights.

In order to make the function as simple as possible, we will make the flight profile assumption as bellow:

1. The flight takes place on the Moon.

2. Each flight distance is assumed to be exactly 100 km[§]. The flight will take the simplest configuration to initially ascent for several ten to hundred meters, then kicked into 45 degrees angle by a rocket motor, burn the main engines for ballistic flight, change aptitude and decelerate in the terminal phase of ballistic flight, and land inside the allowed site window vertically (Figure 5). Hence, we have $h_{\mathrm{APG}} \cong 50{,}000$. The roundness of the Moon as a sphere is not considered here as points 100 km apart on the Moon only makes about 3 degrees of central angle.

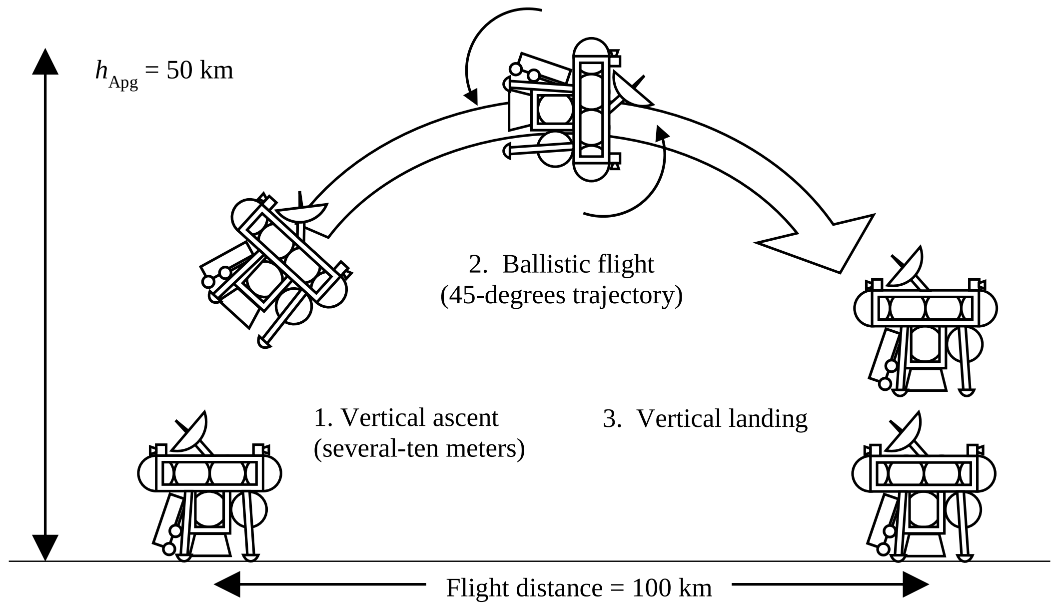

Figure 5 Typical flight profile of the crane

Based on these assumptions, the rough calculation on the mass system will be described. Let us describe the mass of the crane and the rover at the apogee level of its a-th time flight $m_{a+0.5}$, while its mass before and after the flight will be stated respectively m_a and m_{a+1}. For clarification, the landing procedure at arrival at the Lunar surface after jettisoning the deceleration stage will be called as "arrival landing", and the first flight will take place after the arrival landing: the mass at arrival landing can be stated as $m_{0.5}$. Regarding the flight profile, the burns on both ends of the ballistic flight will be initially considered.

Given the I_{SP} of the engine, the velocity to be earned for the start and reduced for the end on the flight is stated as Eqs. (3) and (4) by modifying the Tsiolkovsky equation. These velocities are equal as there exist no reduction during the flight, and also can be calculated by the angle of the trajectory (45 degrees), $h_{\mathrm{Apg}} = 50{,}000$, and g_{m}, as Eq. (5).

$$V = I_{\mathrm{SP}} g_{\mathrm{e}} \ln \frac{m_a}{m_{a+0.5}} \tag{3}$$

$$V = I_{\mathrm{SP}} g_{\mathrm{e}} \ln \frac{m_{a+0.5}}{m_{a+1}} \tag{4}$$

$$V = \sqrt{2 g_{\mathrm{m}} h_{\mathrm{APG}}}\sqrt{2} \cong 570 \text{ [m/s]} \tag{5}$$

From equations (2), (3), and (4), we can have the mass ratio before and after the flight as:

[§] This distance was established regarding that the record of maximum distance a rover has ever traveled on the lunar surface is the Lunokhod 2's 37 km. Far exceeding this distance, we have to send two sets of lander-rover system if we are to explore points 100 km apart with the conventional configuration.

$$\frac{m_n}{m_{n+1}} = \exp(116.2732/I_{\mathrm{SP}}) \tag{6}$$

Regarding the deceleration stage, its function is to accelerate for trans-lunar orbit, decelerate the system from arrival velocity down to 0 m/s at point high above the lunar surface so that the crane can then manage speed reduction for landing as it is designed in further flights. Reference [9] proposes an energy-saving lunar delivery flight to have the total ΔV for trans-lunar orbit and lunar orbit insertion as 3,462 m/s, as the inserted lunar orbit altitude is 600 km. If we adopt this flight pattern, by assuming the lunar orbiting velocity of altitude of 600 km as 1,448 m/s, the total change in velocity will be $\Delta V_{DS} = 4{,}910$ m/s. The mass system regarding R3S and its deceleration stage can be stated, by modifying the Tsiolkovsky equation again as:

$$\frac{m_{DS}}{m_{R3S}} = \exp(500.7138/I_{\mathrm{SP}}) - 1 \tag{7}$$

2. Rocket engine

Eq. (6) indicates that larger I_{SP} will make the value of m_a/m_{a+1} smaller, that will broaden room for the justification of R3S. However, the value of I_{SP} differs on the type of engine that will also have different sets on its unit dry mass and thrust. In order to understand the capability of engines in the current level technology, we have collected available sets of values for major engines used or planned for lander or upper stage rockets as Table 1. As we take a look into this, it seems that the sweet spot for the application of R3S exists around dry mass from 80-200 kg, TtWR of 20-40, and I_{SP} of 300-320, typically referring Bell/Rocketdyne LMAE used on the Ascent Stage of the LM. However, as there is still a dispersion, the value of m_{Eng} will not be determined at this point.

Table 1 Capabilities of engines used or planned for lander or upper stage rockets

Engine	Cycle	Used spacecraft	m_{Eng}, kg	T, kN	TtWR	I_{SP}, s
RD-0146 [10]	Expander cycle	KVTK	261	98	38.4	463
LMDE [7]	Pressure-fed	Descent Stage (LM)	158	45	25.5	310
LMAE [7]	Pressure-fed	Ascent Stage (LM)	91	16	17.4	310
TR-201 [11] [12]	Pressure-fed	Delta (2nd Stage)	135	44	33.3	303
MR-80B [13]	Monopropellant	Curiosity lander	168	4	2.2	225

* Goal value

Hence, when we substitute the value of the I_{SP} as 310, we will obtain from Eq. (6) as:

$$\frac{m_a}{m_{a+1}} = 1.455 \tag{6-bis}$$

Therefore, the mass of the rover and crane of R3S in total at arrival at lunar orbit, excluding the deceleration stage, will be stated as:

$$m_{R3S} = (m_{Rov} + m_{Eng} + m_{Str})\, 1.455^{\,n_{\mathrm{LX}}-0.5} \tag{8}$$

In addition, if we substitute the value of RD-0146 as $I_{\mathrm{SP}} = 470$ for the deceleration stage into Eq. (7), we will have:

$$\frac{m_{DS}}{m_{R3S}} = 2.902 \tag{7-bis}$$

3. Structure

Since this is a high-level study to examine the feasibility of the R3S concept, deep consideration on the structure will not be conducted here. Since it requires a complicated terramechanical study to actually predict the acceleration of landing onto the Moon, regarding the dynamic interaction with regolith [14], how m_{Str} might be affected by m_{R3S} will be discussed regarding the Descent Stage of the LM instead. Since this space craft has conducted 6 landing onto different locations on the Moon without any failure, we can somewhat rely on this design.

The reinterpretation of the LM Decent Stage breakdown and their value are shown in Table 2. After obtaining the actual value of m_{Str}/m_{R3S} as of LM, this value will be calibrated for 110%, regarding that the actual structure on the crane might obtain somewhat more mass than that on the single use LM, because of the needs for robustness for repetitive use, as discussed earlier. Non-structural components such as batteries, cooling system, and aptitude control units are inclusive in this m_{Str}, but this is not a big issue as we also need such subsystems on the R3S as well in reality.

Table 2 Mass system of components as of LM [7]

Mass system	Corresponding mass subsystem in LM	Note	Value as of LM [kg]
m_{R3S}	Ascent/Decent Stages total mass at launch.		16,375
m_{Rov}	Mass of Ascent Stage at launch	Regarded as payload	4,990
m_{Crn}	Mass of Decent Stage at launch.		11,612
m_{Prop}	Mass of Decent Stage propellant.		8,845
m_{Eng}	Decent Stage main engine (LMDE) dry mass.		179
m_{Str}	The rest of the mass on the LM	Non-structural components inclusive	1,990
		${}^{m_{Str}}/_{m_{R3S}}$ (original)	0.134
		${}^{m_{Str}}/_{m_{R3S}}$ (110% calibrated)	0.147

By substituting the value of $m_{Str}/m_{R3S} = 0.147$ from the above, Eq. (2), and also $m_{Rov} = 430$ into Eq. (8), we have:

$$m_{R3S} = \left(430 + m_{Eng}\right)1.455^{\ n_{\mathrm{LX}}-0.5}\frac{1}{1-0.147}$$

$$= 1.173\left(430 + m_{Eng}\right)1.455^{\ n_{\mathrm{LX}}-0.5} \tag{9}$$

Regarding Eq. (7-bis), the ImLEO of the R3S system will be:

$$\mathrm{I}m\mathrm{LEO}_{R3S} = m_{R3S} + m_{DS} = (1 + 2.902)\ m_{R3S}$$

$$= 3.404\left(430 + m_{Eng}\right)1.455^{\ n_{\mathrm{LX}}-0.5} \tag{10}$$

4. Lander (for comparison)

Since the launch mass of the Griffin lander is not published yet, the ImLEO for the Griffin-VIPER system will simply obtained by substituting $n_{\mathrm{LX}} = 1$ and $m_{Eng} = 82$ into Eq. (11): as the mass system on the structure and deceleration system should differ between R3S and the conventional system, their difference will be assumed to be offset mutually. Also, since the actual thrust of the Griffin (15.6 kN) is close to that of the LMAE (16 kN), we will roughly use the mass of the LMAE. Therefore, we will obtain:

$$\mathrm{I}m\mathrm{LEO}_{CS} = 2{,}139\ [\mathrm{kg}]^{**} \tag{11}$$

D. Discrimination

An indication of the potential economic feasibility of the R3S will be determined if the ImLEO$_{R3S}$ at its n_{LX} will be smaller than n_{LX}ImLEO$_{CS}$. In addition, regarding the engine, the thrust has to be enough to decelerate the crane

** Regarding that the Peregrine Lander, which is the smaller ancestor of the Griffin Lander, had its ImLEO as 1,283 kg with 265 kg of payload [19] that makes its payload to wet-mass ratio as 21%, this calculation result that provides one for the Griffin as 20% seems to be in proper range from this approach as well.

down to 0 m/s while descending from 50 km above lunar surface. Therefore, the discrimination of the feasibility of the R3S will be:

$$\begin{cases} \mathrm{I}m\mathrm{LEO}_{R3S_{n_{\mathrm{LX}}}} \leq n_{\mathrm{LX}} \mathrm{I}m\mathrm{LEO}_{CS} \\ T_{Eng} \geq 1000\ g_{\mathrm{m}} \mathrm{I}m\mathrm{LEO}_{R3S_{Eng}} \end{cases} \tag{12}$$

IV. Results

Table 3 shows the result of the study and I*m*LEO of the R3S concept. Referring the lightest two engines from Table 1, the result shows that despite the poor TtWR of the LMAE compared to TR-201, the application of LMAE has efficient mass-saving performance with having 9,588 kg of I*m*LEO with $n_{\mathrm{LX}} = 5$.

The I*m*LEO should be still slightly under the real value as the structure is designed heavily to sustain the initial mass at arrival of the lunar surface and hence excessive for the later part of its life. However, we can allow the crane to either shorten the flight distance eventually, or to design the structure in modularity so that the crane can strip-off unnecessary structures as it proceeds its journey. Therefore, we can assume that the most efficient R3S for lunar application will have around 10 tons of I*m*LEO.

Table 3 Feasibility and I*m*LEO [kg] of R3S regarding m_{Eng} and n_{LX} (N/F: not feasible)

Engine	T, kN	m_{Eng}, kg	n_{LX}				
			2	3	4	5	6
LMAE	16	91	3,112	4,529	6,589	9,588	N/F
TR-201	42	113	3,244	4,720	6,867	9,992	N/F

V. Discussion

A. Mission

1. *Early-stage mission: lunar H_2O quest*

The possibility of finding H_2O resource on lunar surface has been regarded as one of the major milestones in lunar and planetary exploration, as its success will enable an economic in-situ propellant production and contribute to revolutionary leap in further spacecraft operation efficiency and flight cost. However, the chance of finding H_2O land that can feasibly be used for propellant production is unknown but considering its significance for future exploration of the Solar System, attempting several locations may be worthy. Furthermore, the terrain is likely to not be easily accessible by rover and more hazardous for a dedicated mission, considering that most water is expected to be located in the slope of craters at the Poles. In order to minimize the risk and increase the probability of success, a more economical mean to enable repeated survey should be required. In addition, existing design and concept should be reapplied where possible so that the resource for its development can be saved. Major challenges, which will need to be accounted for in the design of a mobility system, are landing precision, avoidance of hazardous landing sites and attachment and detachment in hazardous sites or land connection between a safe landing site and an area of interest. Furthermore, on the Moon specifically, dust could degrade the structure, the attaching mechanism or render a site unusable due to its extreme volatility and abrasiveness.

The R3S concept might prove useful, as it is designed to hop on the lunar surface and move among multiple locations with limited terrain and travel constraints. The rovers equipped with a compact drilling device and an H_2O detector will travel for a very short distance from where the crane has landed, which enables the system to search for H_2O land in a particular area without hopping too many times for short-distance travels. By complementing the drawbacks of rocket motor and rover, respectively the low energy efficiency for short-distance travel and weakness against rough terrain, the system can conduct a dig-until-you-find style survey within a targeted area, just like a drilling ship or mobile oil rig whose purpose is to wander around and detect matter.

2. *Further applications*

It is possible to imagine that the design of the crane could also evolve with each new mission. For example, if we admit that the first missions of finding water until its extraction and its transformation into fuel materialize, this will induce the construction of an inhabited or automated base equipped with an extraction system and refueling. Thus, the longevity and the means of action of the infrastructure could be improved considerably, with regards to the limiting factors of the first reconnaissance missions. Examples of missions for R3S could include not only pure scientific research purpose but also industrial applications to deploy ground mobility for surface development wherever and whenever needed, such as; construction machines, utility, or to tug space crafts or container units on the surface for a short distance. The concept could also be adapted to Mars and beyond in the long term.

The crane could represent a supporting tool in each of the stages that will prepare for a permanent presence and operations carried out since this last. This means that the PDS rovers can be designed to have longer life expectancy than the crane. In the state of surface development, heavy construction machines should be extremely precious on the Moon or Mars as the logistics of such equipment will be totally different from on the Earth. It could be more economical to keep the machine there and resend a crane to transport them on the surface, rather than sending multiple machines from the Earth every time.

On the other hand, if we can refuel the crane on the surface, its efficiency will boost. Therefore, the initial early-stage mission stated in the previous section should justify sustainable concepts such as R3S furthermore in further phases, as it should accelerate the development of in-situ propellant production. However, even at the state of in-situ propellant production is not established, there might be a possibility to increase the mass efficiency of the R3S by delivering propellants along with parts, supplies and further equipment from orbit into the site the system is to be going (Figure 6). There might be no room of feasibility to conduct this on the moon, but regarding Mars that we can use aerobreaking for decelerating the propellants delivered, this might be one solution. Additionally, the mobility of the PDS rover will allow lower accuracy of delivery as it can bring the propellant to the crane by driving on the ground. This concept needs to be examined in further studies.

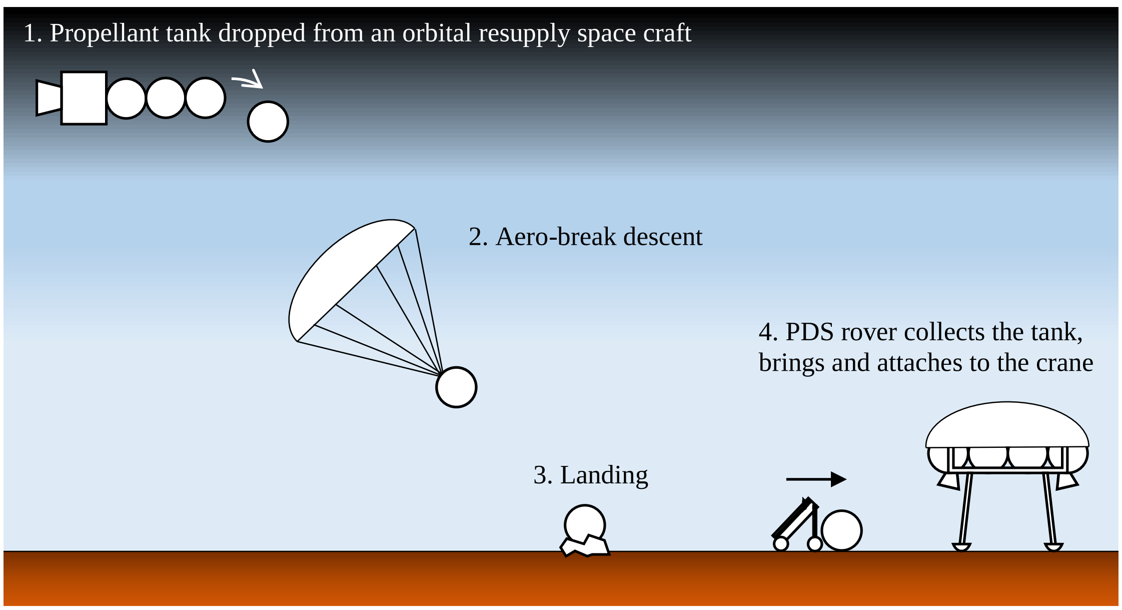

Figure 6 Mid-mission refueling plan for Martian R3S

The crane could potentially be used for different types of missions. However, it is important to clarify that this crane can take different shapes in terms of size, mass, payload capacity, etc. Even the mode of travel could vary from propulsion, large wheels, twist/jump system. The concepts that are common to all are the presence of a complementary, reusable mobility concept, modularity and standardization of interfaces between the crane and the payload(s).

Using multiple rover, such as discussed in Reference [15], can be an option to expand the use of the R3S. The rover should be designed for a specific area and can be adapted to explore the target on a case-by-case basis. The malfunction of rovers negatively impacts the mission but is not critical. In this case, each rover can be designed more specifically regarding the mission or the areas to be explored. The multiple rovers deployed in an area can also be used for relay operation and potentially broaden the area for exploration. This idea is worth considering in further studies as R3S that is to conduct multiple landing onto different location within its lifetime has higher chance of accident, and thus the importance on redundancy is relatively even higher than conventional lander-rover configuration. This is particularly interesting for visiting specific sites in a relatively small and easy to navigate area, with significant uncertainty as to either findings or possible error.

B. Propulsion

The calculation process to observe the feasibility boundary referred to the rocket engines already substantiated in the current level technology in order to prove the concept regarding early-stage application that can take in the near future. However, as the equations shows, better engine capabilities on m_{Eng}, TtWR, and I_{SP} could improve the figures vastly.

As for the proximate timeline, additional discussion on smaller engines with the same range of I_{SP} will be required as it will provide the option for distributed propulsion that could improve controllability as argued in Ref. [3]. Moreover, distributing the engines might also enable to discard some of them that exceeds the mass of the system at one point during the mission, and keep the propellant burn rate small even in the later part of its life on the surface.
Regarding the farther future, it should be helpful to consider the use of engines that are not brought into production or application, such as nuclear thermal engine, to enhance the idea of R3S.Future Work

Future work could be to conduct more in-depth feasibility studies. Indeed, there are many other factors on which a multiple take-off and landing system must prove their added value, such as cost, probability of success, resource consumption and scheduling. Furthermore, the functionality of such a system would be heavily impacted by the efficiency of technologies and capabilities such as landing precision, robustness of attach mechanism, landing terrain flexibility and infrastructures with which it is to be coupled. Candidate missions that could benefit from a reusable and modular transportation system may be identified as a consequence. Furthermore, once possible mission will have been identified, architectures for the mobility system and associated mission designs could be investigated. Indeed, there are many ways to design a modular and reusable mobility system for space applications and the optimal strategy, and its performance, will depend on mission objectives and constraints.

VI. Conclusions

In conclusion, the concept study shows that the R3S concept could be mass efficient considering multiple trips, which would be beneficial especially when considering multi-location, long-duration or sustainable missions. The exploration of the Moon could be a first candidate mission for using multiple take-off and landing systems, nevertheless other missions such as on Mars might also benefit from similar systems. The two key attributes described are reusability and modularity, enabled by a repetitive attachment and detachment system, such as the PUPA developed by Yamato for Earth applications. The specific design of a system, however, would depend on the mission objectives, constraints and available technologies. For example, systems could also hop on the surface or drive. Ultimately, with increasingly long-duration, multiple location and interconnected missions planned, sustainable concepts should be considered.

Appendix: PDS rover design

A. Undercarriage

First, the configuration of the undercarriage will be discussed, as this will determine the existing rover model we can refer to for the basic characteristics (e.g. size, mass, speed) of the rover we are to discuss.
Autonomous planetary rover requires a specially designed suspension due to two reasons: it has to overcome various type of rough terrains, and its traveling speed is significantly slow compared to other all-terrain vehicles (e.g. off-road vehicles, tanks, the Apollo LRV[††]). To cope with this problem, several types of suspension has been developed and installed onto rovers. There exist three types of rover suspension that have been realized as follows (also see Figure 7):

1. Double bogie

Double bogie (8 wheel) configuration was adopted for the Lunokhod series. Paired drive wheels on a bogie directly mounted onto the body will follow the pitch of the terrain. There seems to be no function to balance the extraction of the wheels on both sides regarding three dimensional terrain, as it is designed to be able to continue traveling even if only two drive wheels on each side (50% of the drive wheels equipped) are powered [16]. Although this configuration provides high redundancy, this also means that the vehicle has to have double the power source if all the wheels can

[††] Apollo LRV (Lunar Roving Vehicle) used a double wishbone suspension that is a common configuration with high-speed automobiles used on Earth [18].

follow the terrain, which should make the mass of the rover significantly large. Nevertheless, as both Lunokhod 1 and 2 were manually controlled from Earth, it seems that this redundancy was necessary at that time.

2. Rocker-bogie

Rocker-bogie is a configuration that substitutes one bogie with a wheel on each side of the double bogie configuration, and also balances the following of the wheels on both sides by differential [17]. This will both decrease the weight of the rover system by both decreasing the number of the drive wheels and the maximum output of each drive wheel as they are designed to always follow the terrain. Rocker-bogie configuration has been used in the series of NASA-launched mars rovers (Sojourner, Spirit, Opportunity, and Curiosity), and the Chinese Yutu series.

3. Active suspension

Active suspension will be applied for the currently planned NASA VIPER [5]. If the extraction of each wheel can be adjusted separately by computer, the number of the drive wheel can be minimized. As a consequence, the VIPER actually has only 4 driving wheels. However, this requires computing resource for maintaining the aptitude of the rover while at travel.

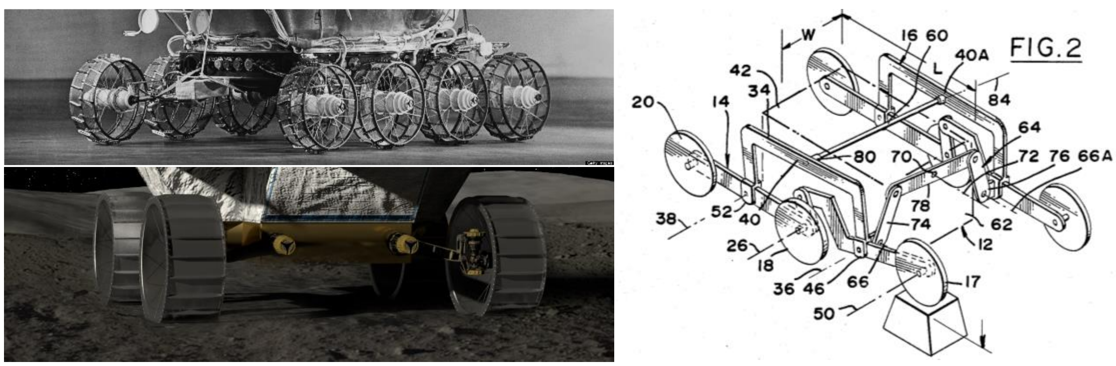

Figure 7 Suspensions for rovers: double bogie, rocker-bogie, and active suspension (from the left above, clockwise). Image credit: NASA/GSFC/Arizona State University; US Patent No. US4840394A; NASA.

Regarding the use of PUPA docking system (PDS), one design constraint that is new to planetary rover arises: the roll angle of the rover has to be adjusted to align with the rocket crane for re-docking. Though this can be done independently from suspension, it would be better if the suspension could provide this function as it will decrease the number of moving parts on the entire system, make the mass lighter, and increase reliability.

When a PDS-applied ground vehicle approaches the flying platform, it has to adjust the height of the spider to fit the adaptor. When these systems are planned to be used on an artificial plain surface (e.g. helipads), this problem can be solved without moving parts by simply adjusting the heights of the ground vehicle and the flying platform in advance, and adding tolerance to small error. However, when these systems are to be deployed into natural terrain, the requirement for an active height adjustment arises, especially when assuming the use on terrains with convex or concave.

In addition, it is required to align both port and starboard spiders at the same time. The most preferable solution is to match the roll angle of the rover with the rocket crane, as it will also enable the pins on the spiders to be caught by the adaptor perpendicularly as intended. Therefore, the rover is preferable to take an arbitrary roll angle within a certain range, regardless of the terrain.

Regarding the discussion above, this paper proposes an active suspension for PDS rovers. As rocker-bogie and active suspension are the two major modern suspension method for modern space rovers, the former does not fit the requirements for PDS-applied rovers as it cannot adjust its rolling aptitude unless applied with some mechanism to release the differential connecting the systems on both sides. Therefore, the VIPER will be referred for the basic configuration of the undercarriage of the PDS rover.

B. Body

Regarding the configuration of the PDS rover to be hoisted onto the rocket crane in an angled position, it would be preferable to make the footprint of the rover on its Y-Z plane small as possible, as it will enable the frame of the rocket crane smaller and lighter as a consequence. Regarding this requirement, the body of the PDS rover is decided to be pitched like the original PUPA. In this paper, the pitched-up front will be regarded as the traveling forward since it will provide clear site of the near ground for the camera mounted on the belly side, although there's no preference on directivity from a structural standpoint. When at docking with the rocket crane, the rover will move towards the opposite direction of the traveling direction.

As the body is pitched, how to place the forward wheels far from the body will be an issue. Theoretically, connecting left and right forward wheels with the body individually with arms and make the arm also serve as a pitching active suspension arm is conceivable. When doing so, the number of actuators can be decreased as that for the forward wheel active suspension can also be used to fold the arm for flight. However, as it requires long forward arms, the maximum required torque for the actuators will increase, and therefore requires more mass for the rover and more power for its traveling: on the other hand, this large torque is not required for folding the arm for flight as it can be done after the forward wheels leave the ground as the rover get hoisted. Therefore, this study will take a simpler approach to first add a front-wheels-extraction and connecting the wheels to it via traditional short active suspension. The pivot to connect the extraction with the body will be placed on the front end of the body. This will provide a vertical surface on the front of the vehicle that can be used as a platform for multiple purposes: e.g. add a solar panel, install a mechanism to lift an object like a forklift, place sensors. Therefore, the side view of the rover will be like an oblique style lambda of the Greek alphabet (Figure 8).

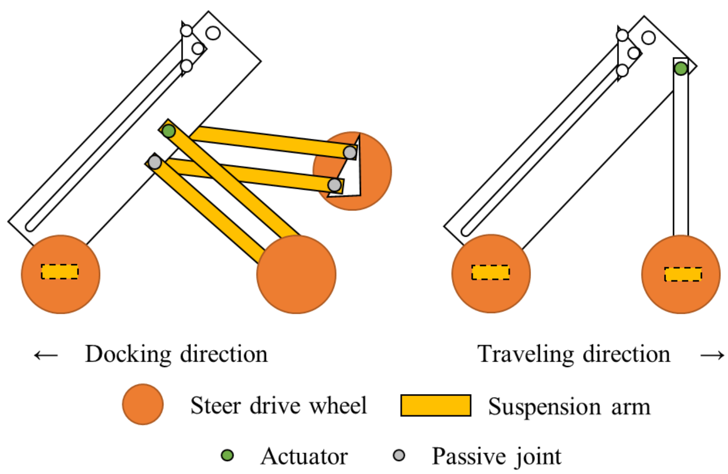

Figure 8 Possible configuration of the rover: with forward long pitching suspension arms (left; declined), and with traditional active suspension on a front-wheels-extraction (right; adopted).

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