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TOWARDS THE MOON AND BEYOND: PREPARING FOR THE FUTURE OF CISLUNAR AND SOLAR SYSTEM EXPLORATION

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A new era of space exploration has begun, as the Artemis program marks a fundamental step for human spaceflight. All eyes are on the Moon: NASA has recently proposed a Lunar Orbital Platform Gateway concept as the basis for future space exploration. The Moon and the cislunar environment will serve as training grounds for extra-terrestrial settlements, hosting the next developments of the space industry. Such ambitious objectives require a dedicated framework of innovative methods and operational strategies. Researchers of the Space Advanced Concepts Laboratory (SaCLaB) at the Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO) develop state of the art tools and methodologies to push the limits of cislunar exploration. To prepare for tomorrow, one must strive for innovation at all stages of mission design: this paper discusses the vision of the SaCLaB about access to the cislunar environment and to the Moon, in-orbit operations and exploitation of lunar resources. Rethinking our journey to the Moon and beyond is an essential part of the equation. Natural properties of multi-body dynamics create low-energy transport pathways to our natural satellite and further regions of the solar system. Near Rectilinear Halo orbits, future hosts of the Gateway, have stability and accessibility properties suited for human presence and staging missions, but they require dedicated system dynamics methodologies for mission analysis and operational purposes. Low-thrust propulsion will play a major role to ensure more sustainable mission profiles for cargo, maintenance and resupplying missions to lunar settlements. In-orbit operations and servicing are essential for repeated lunar access and surface exploration. Rendezvous and Docking operations are paramount for assembly, servicing and crew/cargo exchange activities. Station-keeping and orbit maintenance in Lagrangian point orbits are also challenges to be overcome for extended human presence in the region. Multi-body dynamics theory and autonomous guidance and control systems can ensure that such operations are optimized in terms of fuel consumption and duration, while complying with the safety requirements and standards of tomorrow. Repeated access to the lunar surface requires new transfer vehicles and modules dedicated to transporting crew and cargo between lunar settlements and lunar orbits. Such systems will benefit greatly from recent advances in multidisciplinary optimisation and reusability studies. Finally, lunar surface operations, logistics for ISRU, energy management and life support systems are presented as building blocks for a future lunar settlement.

I. INTRODUCTION

In the current, very dynamic context of space exploration, ambitions towards the Moon, in short to medium term, have been clearly announced by the major space nations: the ARTEMIS programme for NASA and its historical partners (notably ESA, CSA, JAXA and Roscosmos) of the International Space Station, the Luna Russian program, the Chinese Chang’e programme and the Chandrayaan Indian Lunar Exploration programme. These ambitions are no more limited to national and international space agencies, as private investors, have now become key players to be considered in future roadmaps. Moreover, they might
potentially perturb the cislunar environment, visited so far only for scientific and technological purposes.

In these times, so rich in plans and programmes for exploration of the Moon and beyond, as outlined by the ISEGC (International Space Exploration Coordination Group) roadmap [1], ISAE-SUPAERO created in 2017 the SaCLaB (Space Advanced Concepts Laboratory), with the support of Airbus Defence and Space and ArianeGroup. The main objective of this multi-disciplinary research team is to conceive space missions with a time horizon of more than fifteen years. In this context, robotic and human space exploration has a privileged place.

This paper illustrates the progress of SaCLaB’s scientific reflections on some of the essential issues to be overcome to allow for a reasoned and sustainable exploration of the Earth-Moon space and to prepare for more distant missions to Mars and the asteroids. The studied scenario is placed in the context of robotic and human exploration of the Moon and its environment for scientific and resource exploitation purposes. The considered system architecture is assumed to be composed of:

- An orbital space station, acting as a gateway managing the arrival and departure flows of vehicles transporting crews and resupplies between the different destinations of the solar system (Earth, Moon, Mars, and the asteroids).
- Facilities on the Moon surface for habitat, resources production, transportation, communications, and scientific laboratories.
- Orbital constellations for communications, navigation, and observation.

This scenario is described in Figure 1, where distances are not to scale. This Figure could be completed with the numerous other families of trajectories that exist in the Earth-Moon system. Here, only the Near Rectilinear Halo Orbit (NRHO) is represented as an example.

This article is divided into two main parts, firstly dealing with the challenges related to transportation systems (with a focus on rendezvous and lunar lander) and secondly, on other challenges related to robotic exploration, human factors, and sustainability, in the cislunar vicinity and Moon surface.

II. TRANSPORTATION SYSTEMS

In the context of the scenario described in Figure 1, transportation operations are critical: they provide a link between the location s (transfers of crew, goods, experiments, etc.), to resupply and maintain the facilities, to explore and bring back to Earth samples and lunar in-situ products. All these activities will take place under non-Keplerian dynamics, due to the effect of different attracting celestial bodies and associated perturbations. Before going into the details of the challenges related to the means of transportation, the paper will first focus on the dynamics models used.

II.1 Systems dynamics:

II.1.1 The Circular Restricted Three-Body Problem

The selected scenario is mainly placed in the vicinity of the Lagrange points of the Earth-Moon system. Considered as sufficiently representative of this peculiar dynamical environment, the classical Circular Restricted Three-Body Problem (CR3BP) [2] is mostly employed in this paper to model trajectories towards, around and from Lagrangian points. This model describes the motion of a particle, P, with a mass \( m \), under the gravitational attraction of two massive bodies (\( M_1 \), the larger primary and \( M_2 \), the smaller primary), with respective masses (\( m_1 \) and \( m_2 \)). The massive bodies are assumed to be isolated: no other effect is considered. As \( m \ll m_1 < m_2 \), the particle is approximated as massless and the problem is “Restricted”. The two primaries are supposed to be on circular orbits about their common centre of mass. The equations of motion of the particle are described in a rotating reference frame referred to as “synodic”. It is centred on \( O \), the centre of mass of the system \( M_1-M_2 \) and with the x-axis directed from \( M_1 \) to \( M_2 \) and the y-axis in the plane of the primaries’ motion (see Figure 2), the z-axis completes the right-hand system.
Masses, distances, and time are normalized respectively with the sum of the primaries’ masses, the distance between them and their angular velocity around their barycentre. The unit of time is chosen such that the period of the orbits of the primaries is 2π. The universal constant of gravitation, G, becomes then $G = 1$.

The only remaining parameter in the system of equations is the mass parameter, $\mu$, defined as:

$$\mu = \frac{m_2}{m_1 + m_2}$$  \hspace{1cm} (1)

so that $\mu \in \left[0, \frac{1}{2}\right]$ when $m_2 < m_1$.

When the position vector of the particle is given by $r = (x, y, z)$, its equations of motion in the CR3BP [3], using Newton’s law are:

$$
\begin{align*}
\ddot{x} - 2\dot{y} &= \frac{\partial U}{\partial x} \\
\ddot{y} + 2\dot{x} &= \frac{\partial U}{\partial y} \\
\ddot{z} &= \frac{\partial U}{\partial z}
\end{align*}
$$  \hspace{1cm} (2)

where the effective potential, $U$, is given by:

$$U(x, y, z) = \frac{x^2}{2r_1} + \frac{y^2}{2r_2} + \frac{1 - \mu}{\mu} \frac{x^2 + y^2 + z^2}{2}$$  \hspace{1cm} (3)

where:

$$
\begin{align*}
r_1 &= \sqrt{(x + \mu)^2 + y^2 + z^2} \\
r_2 &= \sqrt{(x - 1 + \mu)^2 + y^2 + z^2}
\end{align*}
$$  \hspace{1cm} (4)

are the distances from the particle to the primaries $M_1$ and $M_2$. The dot (‘’) denotes the time first derivative (velocity) and the double dot (‘’’) denotes the time second derivative (acceleration). The state of the particle is given by: $X = (x, y, z, \dot{x}, \dot{y}, \dot{z})$.

II.I.III Lagrangian points and orbits in the CR3BP

The system (2) admits five equilibrium points, referred to as Lagrangian or libration points, $L_i, i = 1 \ldots 5$ or Earth-Moon Lagrangian (EML) point in the Earth-Moon system. From the literature [2, 4, 5, 6], several families of orbits exist, both planar and three-dimensional, usually designated as: Lissajous orbits, Horizontal Lyapunov orbits, Vertical Lyapunov orbits, Halo orbits, including Near Rectilinear Halo Orbits. This paper mainly focuses on NRHO orbits, which are three-dimensional and periodic, characterized by a close perilune passage above one of the lunar poles. NRHOs’ perilune radii are ranging from 1850 km to 17350 km about EML2, with orbital periods of about 6 to 10 days and from 900 km to 19000 km about EML1 with orbital periods of 8 to 10 days. EML2 NRHOs are shown in Figure 3.

Being interesting for their Sun eclipse avoidance and constant Earth visibility properties, they have been identified as possible candidates for the future Gateway location [6]. The current baseline is a 9:2 synodic resonant NRHO with an orbital period of about 6.5 days, with a perilune radius of approximately 3250 km and a vertical extension of about 70000 km.

II.I.III Invariant manifolds

The concept of unstable and stable manifold is exploited to determine transfers from (or to) the orbits about the primaries to the vicinity of the Lagrangian points as well as to periodic solutions. As three-dimensional structures of the CR3BP, invariant manifolds constitute continuous surfaces or tubes in the position and velocity six-dimensional space. Largely studied in the literature [8,9,10], these invariant
structures are used to design staging orbits and to identify low-energy trajectories. Many strategies have been proposed for transfer solutions between the Earth, the Moon and the Lagrangian points, minimizing fuel consumption and time of flight such as indirect transfer [11], Weak Stability Boundary [12, 13] or lunar flyby [14], for Earth-to-EML2 [15] or Earth-to-Moon transfers [16].

Figure 4 showcases an example of stable and unstable invariant manifold originated from an EML2 Halo Southern orbit (with $A^C_2 = 8000$ km in purple and $A^T_2 = 10000$ km in blue).

A schematic of the main characteristics of the SEMpy library is reported in Figure 5.

Figure 4: Invariant Manifolds in the normalised synodic frame [18].

**II.1 IV Numerical tools**

The SaCLaB has developed SEMpy (which stands for Sun-Earth-Moon in Python), a Python 3 open-source astrodynamics library with a focus on mission analysis and trajectory design [17]. Initially developed for the Sun-Earth-Moon system, it was subsequently expanded for interplanetary trajectory optimisation and mission design to asteroids. It offers numerical orbit construction routines based on differential correction of semi-analytic orbit expansions and pseudo-arc length continuation schemes. The toolbox includes built-in validated databases, including Halo orbits, NRHOs, Distant Retrograde Orbits (DRO) and Lyapunov. The user can choose between interpolation routines for a fast generation of the desired orbit from the database or use the orbit construction routines.

The SEMpy library interfaces with SPICE library for orbit propagation in high-fidelity ephemeris and with the OPENMDAO and DYMOS libraries for continuous optimal control problem solving. This method has proven to be very promising, especially for on-board implementation.

**II.11 Rendezvous in non-Keplerian dynamics**

In the context of human and robotics space exploration, rendezvous and Docking (RVD) operational activities are mandatory and critical for the deployment, utilization and maintenance of the different assets. JC. Houbolt [18] defined them as:

"The problem of rendezvous in space, involving, for example, the ascent of a satellite or space ferry as to make a soft contact with another satellite or space station already in orbit."

However, the RVD problem in non-Keplerian environments has rarely been addressed [19] and no RVD has yet been performed to this date in the vicinity of Lagrangian points. Even if dynamics in such regions are more complex, they also come with strong advantages. Moreover, all the considerations discussed in this chapter can be applied to the undocking and departure phases, which will be also frequent and critical.

The target is the space vehicle already in orbit and the chaser is the arriving one. The Rendezvous then consists in all manoeuvres and trajectories performed by both vehicles to get safely closer before a soft contact (no collision, no destruction).

**II.11.1 Rendezvous phases**

The different phases and manoeuvres of a typical rendezvous mission from launch to docking have been
extensively studied, from the Apollo missions to the International Space Station (ISS) resupply missions. They are mostly named: launch, transfer, orbital injection, phasing, and proximity manoeuvres (including homing, closing and final approach).

Rendezvous can be followed by either docking or berthing, depending on the nature of the chaser. Most recently, the International Rendezvous System Interoperability Standards [20], published in 2019, present the RDV decomposed in three main phases:

- The **transfer phase** starts at trans-lunar injection and ends when the chaser has reached an operational orbit in cislunar space, so as to bring it from the terrestrial environment to the Earth-Moon environment.
- The **far rendezvous** allows the chaser to approach the target from its phasing orbit to a distance of 100 km from the target. This phase does not require the use of relative navigation and space-to-space communications.
- The **close rendezvous** includes approach operations from a distance of less than or equal to 100 km and ends with the physical contact between the chaser and the target. The docking follows. The chaser engages relative navigation and moves through increasingly narrow approach corridors using navigation sensors. In the considered studies, it is assumed that the target is fully collaborative: it participates and facilitates the rendezvous.

**II.II.R Rendezvous challenges**

Rendezvous in the cislunar environment can present important operational and conceptual challenges compared to traditional rendezvous attempts. These technological challenges may concern particular phases of the rendezvous, or the definition of the GNC (Guidance, Navigation and Control) system characteristics, such as its autonomy or safety.

Rendezvous on a periodic orbit about Earth-Moon Lagrangian points (EML) requires a very accurate management of the motion of both vehicles and relies only on modeling. Therefore, it is necessary to develop semi-analytical tools to model the relative motion between the chaser and the target, in a high-fidelity dynamical environment (with perturbations such as the influence of the other massive celestial bodies, solar radiation pressure, etc.), and optimize local legs and global strategies.

Using the SEMpy library, the SaCLaB team was able to conduct complex analyses of the Guidance, Navigation and Control system of a chaser to rendezvous a space station on a 9:2 EML2 Southern NRHO [21]. The need is to have a systemic approach to ensure an optimal, but also robust and safe strategy, to prepare future space operations of completely autonomous rendezvous, considering the increasing traffic flow according to the scenario previously presented. This is the reason why close rendezvous convex guidance [21] has been successfully explored. The algorithms allow simulating nominal and contingency situations, guaranteeing target and chaser safety and trying further attempts. Although this method has been validated by simulation, it is recommended to test this approach in orbit with a pioneer mission that would embark its guidance laws and qualify them in flight.

The challenges listed here are not exhaustive, as one could also mention the ones to be met in terms of standardized docking port, autonomous navigation (there is no navigation constellation around the Moon yet) or the optimisation of low-cost transfer times, particularly for the transfer of fuel produced with lunar resources (which are not stable for very long duration) [22] or utilization of electrical propulsion [23].

**II.III Lunar landers**

Among all the vehicles that will carry out rendezvous operations with the station in orbit around a Lagrange point, there are the lunar landers. Indeed, these vehicles could have for mission to make round trips between the surface of the Moon and the orbital station for the transport of crews, goods, samples, or products.

**II.III.I Definition and historical overview**

A lunar lander is defined to be a space vehicle designed to arrive softly on the Moon surface and not to crash. A distinction is made between crew landings and uncrewed landings. Finally, there are many objects that were intentionally crashed on the Moon at the end of their mission, but they are out of the scope of this paper.

The SaCLaB has developed an internal database with data extracted from NASA Space Science Data Coordinated Archive (NSSDCA) [24] to gather information about past lunar missions. Figure 6 presents some results of exploiting this database for lunar lander missions.

Only 4 nations have until now succeeded to softly land on the Moon, this representing 39% of the robotics attempts and 86% of the crew landing attempts. This demonstrates the complexity of designing a lunar lander and its mission. The new race to the Moon and the commercial exploitation of its resources creates the need for landers with an optimized architecture and mission profile. They need to be reusable and potentially modular to lower their operational cost and their footprint on the lunar environment. This raises, in particular, the question of reusability in the design of
these complex space systems, which are essential for robotic and human exploration.

**II. III. II Multidisciplinary design and architecture optimisation**

As previously discussed, a lunar lander is a complex space system, with a large number of design variables. Its physical architecture and mission are the result of a multi-disciplinary optimisation (MDO) process. All its functions and sub-systems must be carefully selected and designed to fulfill the mission requirement and the environmental constraints. Therefore, physical models need to be introduced to build an MDO tool. The four main disciplines to be considered are: propulsion, trajectory, thermal and structure [24], as presented on Figure 7.

In the scenario presented (Figure 1), the reusable lunar lander will perform round-trip transfers between the orbital station and the Moon's surface.

**Optimisation:** Among all the potential optimisation metrics commonly used in the aerospace literature (maximization of the payload mass, minimization of the mission cost, etc.), this study proposes to select the minimization of the average mass, $M_{av}$, of the lander as the cost function. The mass to be sent from Earth in the cislunar region is directly related to the overall cost of the mission and must be minimized. The cost function can be computed as follows [25]:

$$J = M_{av} = \frac{M_{total} + N_{reuse} \times M_{expansible}}{1 + N_{reuse}} \quad (5)$$

where:
- $N_{reuse}$ is the number of reutilizations of the lunar lander.
- $M_{total}$ is the total mass of the lunar lander.
- $M_{expansible}$ is the necessary mass to recondition the lander before next use (propellant, expanded stages, etc.).

The cost function computation will depend on the four disciplines listed earlier, to which belong the design parameters listed on Figure 7. The level of fidelity of each disciplinary model will depend on the level of knowledge and on available technologies. The objective is to have a metric and a methodology that ensure the comparison of the potential architectures and propose a preliminary concept of the lunar lander. It will be characterized by a number of stages (for example, in the Apollo mission concept there were 3 stages: service module, ascent and descent stages), a number of locations (for example: NRHO, intermediate lunar orbits, Moon surface…), etc.

![Extended design structure matrix for a lunar lander.](image)

**Propulsion:** Reusing the lunar lander implies refuelling. Consequently, only liquid-fuelled propulsion system can be considered and have to be assessed according to the studied scenario. One of the main outputs of the propulsion model is the computation of the mass of the engine, to be integrated in the lander total mass.

**Trajectory:** The lunar lander has to be optimized for several roundtrips between the cislunar region and the Moon surface. An intermediate Low Lunar Orbit (LLO) is recommended to manage rendezvous, refuelling, etc. and to reduce useless mass. Actually, some components do not need to land or to dock with the orbital space station. There are four main arcs of trajectory to be considered:

- Descent: from NRHO to LLO, from LLO to lunar surface,
- Ascent: from lunar surface to LLO and from LLO to NRHO.

Some arcs have to be modelled with the CR3BP, while the others can be limited to a planar restricted two-body problem around the Moon. Common approaches the literature impose predetermined transfers (between LLO and the Moon), alternating ballistic and propulsive arcs, and therefore sub-optimal.
Recently, the SaCLaB team has studied a more flexible strategy based on optimal control, considering a variable thrust, to fully explore the variables domain and find a global optimum [26].

**Structure and mass analysis**: For a given mission (inhabited/robotic, duration on the Moon surface, etc.), the structure (thickness, surface, number of stages, …) and its associated mass will also depend on the technical choices for the propulsion (size of the tanks, fuel mass, etc.). In Figure 9 it can be seen that despite identical specifications, the three competitors of the NASA Artemis surface mission call for proposals have converged to very different solutions.

![Figure 8: Lunar landers size comparison. Credits: Everyday Astronaut.](image)

**Thermal control**: If cryogenic propellants are used due to their higher efficiency, the thermal control subsystem has to be carefully designed. Its characteristics impact the mass, the efficiency, and the operations. The choice of thermal control technologies, and therefore the subsystem’s mass, will depend on many parameters of the lander and its mission such as the propulsion type, the operational period, the number of reuses. As in other disciplines, a good compromise has to be found between the accuracy of the model and the computation time of the optimisation loop.

**II.III.III Lunar lander challenges**

The methodology presented for a multidisciplinary design and architecture optimisation of a reusable lunar lander allows for the comparison of technologies for a given set of mission profiles or the comparison of missions to a given architecture. Applying it to a scenario close to the one presented in this article, the SaCLaB team obtained an optimal solution for an architecture composed of two vehicles, six reuses and a total mass of about 46 t per mission [25]. This method required the development of a complex optimisation tool, allowing the assessment of an innovative or a disruptive technology.

The main challenges of future reusable lunar landers are autonomy, safety, and reusability. The study confirmed that mission performance (measured with the average lander mass per mission) is directly related to the number of reuses, which affects the optimisation variables. Higher reusability pushes the system to be heavier but more efficient. To improve reusability, it will be necessary to improve the system’s autonomy in order to simplify operations.

However, autonomy requires refuelling and, therefore, the management of fuel or its production in situ. The transport of fuel (and therefore the optimisation of its transfer), the management of sloshing and the transfer of liquids in space, already done in Low Earth Orbit (LEO) between the International Space Station (ISS) and its resupply cargos, still have not seen any cislunar applications. It therefore seems necessary to plan demonstrators in cislunar orbit for fuel management (transport, storage, fluid transfer).

Indeed, the exploration of the Moon cannot be based solely on the use of liquid oxygen and liquid hydrogen from the water in its soil, firstly because production has not yet been demonstrated in-situ (although there are promising works in laboratories on Earth) and secondly because sufficient yields for such traffic are not guaranteed. The energy required for such a level of production would correspond to the use of nuclear power, which is currently not allowed.

**III – THE OTHER CHALLENGES**

The first part of this paper focused on the technological challenges related to the space transportation of people, scientific instruments, or production goods. This second part presents other challenges such as autonomous robotic exploration, human factors and sustainability.

**III-I Robotic Exploration**

As discussed previously, scientific exploration and resources exploitation need rovers and robots, in particular to visit unknown, unstructured, extreme or even dangerous zones. Those complex systems will also be very helpful not only as precursors to deploy facilities before crews’ arrival but also for maintenance, logistics and safety. Once again, the key challenge is the autonomy. The main scientific and technical questions are how to conduct autonomous operations with task planning, failure management, path planning, mapping, and localizing in a new environment [27].

To get better knowledge on this topic, the SaCLaB prepared a rover and drone collaboration scenario, named CoRoDro, which stands for “COLlaborative ROver & DROne “to study lunar lava tubes exploration. Figure 9 presents its concept of operations. An analogue field campaign will be performed soon, in the frame of the IGLUNA, a European Space Agency (ESA) Lab
initiative, designed to support academic and innovative projects to prepare future space exploration.

III-II Human Factors

After robotics, the next challenge deals with human factors. Actually, to prepare long duration mission or permanent settlement on the Moon or Mars surface, the impact on Human behaviour has to be considered from the earliest stages of the design process. A true collaboration between human and robot has to be assessed. That is the reason why the SaCLaB team has set an experiment, named TELEOP, to measure the impact of isolation on teleoperation tasks. The experiment consists of a rover teleoperation, which includes multiple subtasks of different natures (rover guidance, visual search for landmarks or an appropriate lunar sample). First it is assumed that the effect of time will modify not only the crew’s performance but also their mood and their confinement feeling. Secondly, it was supposed that the occurrence of rare booster events like Extra-Vehicular activity has an impact on the motivation. This experimental protocol evaluates the subjective state of the operator thanks to questionnaires, the behaviour thanks to task performance (mainly response time and accuracy) and the physiological state (mainly cardiac activity). Figure 10 presents the protocol of the experiment.

This experiment was run several times in different analogue environment. The two main hypotheses were confirmed:
- the time affects the performances and the mood,
- the motivation is decreasing all along the mission.

The effect of the booster events on the motivation was observed. The first results show the importance of training and the need to propose adaptive training to crewmember’s profile [28] and [29].

III-III Sustainability

The last challenge to be discussed in this paper is sustainability. The increasing number of activities in cislunar region and Moon surface will generate a large amount of space debris, because of the densification of the space traffic and the diversification of the space actors. It is then important to think about debris mitigation and end of life management before the problem appears. In the cislunar environment, three main options exist for spacecraft disposal: impact on the lunar surface, transfer to a stable graveyard orbit, either around the Sun or the Earth, or Earth atmospheric reentry [7].

The selected strategies must take into account some constraints, as for example, to protect the historical & scientific areas on the Moon, and to avoid collision in cislunar region and in Earth orbit, or further interference with the Earth-Moon system in case of heliocentric disposal.

Figure 11 presents a map of crashing or landing sites on the Moon surface, with data up to August 2020, to be used as a reference to establish protected zones when evaluating disposal through lunar impacts. This is part of a current project aiming at collecting information about past and present lunar missions and show related data through a user-friendly interface.

Moreover, starting from cislunar CR3BP orbits (such as Halo, NRHO, DRO) grid searches are run to characterise the dynamical environment in search for self-similar behaviours and chaotic regimes. Thousands of initial states are propagated using SEMpy modules, and different strategies are compared. An example of the type of results obtained is provided in Figure 12.
following these preliminary assessments, the main recommendation is to ask for international regulations to avoid chaotic areas and behaviours, preventing the uncontrolled spreading of debris in the cislunar realm.

III – CONCLUSIONS

As a summary, this paper has shown many technological and organisational challenges to overcome in order to prepare a quasi-permanent installation on the Moon for scientific exploration and exploitation. Humankind will have to master the transfers between the different locations (Earth, Moon, cislunar orbits) in a regular way, to increase launch rates and operational capacities and improve the space rendezvous techniques with more safety and autonomy. In addition, the recurrent use of reusable lander seems indispensable. The central issue in such a scenario is the propellant management in space, its production, transport, and transfer. This challenge is entirely related to energy.

In a very dynamic context with an increasing interest for Moon human and robotic exploration, the environment becomes more and more challenging. In particular for space transportation, which will require safe and autonomous for rendezvous in cislunar region and reusable lunar landers. In both cases, the main recommendation is to test precursor missions in-situ beforehand, to validate the technical concepts.

Autonomy is the key issue with autonomous robotics as an essential asset for human activities. Human-robot collaborations must be taken into account for a better assessment of human factor. Finally, sustainability must not be neglected to avoid debris proliferation in Moon environment. Furthermore, this discussion can be extended on space transportation carbon footprint and on a rational exploitation of the Moon’s resource.

The studied scenario focuses on the Moon and its environment, considered as a gateway for more distant destinations. It would seem to be an interesting perspective to compare these results with Martian or asteroids scenarios.

As this paper cannot be exhaustive, it focuses on the research work carried out by the SaCLaB team in order to contribute to the reflections on future robotic and human exploration programmes on the Moon. It could be extended to even more interdisciplinary studies that would encompass disciplines such as economics, law, politics, but also the arts or medicine.

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